

MEASURING AND IMPROVING MENTAL ROTATION ABILITY IN THREE
DIMENSIONS: A HOLISTIC INVESTIGATION

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ZEYNEP PİRİ

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submitted by **ZEYNEP PİRİ** in partial fulfillment of the requirements for the degree
of **Doctor of Philosophy in Computer Education and Instructional Technology**,
Middle East Technical University by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Soner Yıldırım
Head of the Department, **Computer Education and
Instructional Technology**

Assoc. Prof. Dr. Göknur Kaplan
Supervisor

Examining Committee Members:

Prof. Dr. Kürşat Çağıltay
Computer Science and Engineering, Sabancı University

Assoc. Prof. Dr. Göknur Kaplan
Computer Education and Instructional Technology, METU

Prof. Dr. Ömer Delialioğlu
Computer Education and Instructional Technology, METU

Assoc. Prof. Dr. Tuğba Öztürk
Computer Education and Instructional Technology, Ankara
University

Assist. Prof. Dr. Erkan ER
Computer Education and Instructional Technology, METU

Date: 03.04.2023

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname

Zeynep Piri

Signature :

ABSTRACT

MEASURING AND IMPROVING MENTAL ROTATION ABILITY IN THREE DIMENSIONS: A HOLISTIC INVESTIGATION

Piri, Zeynep

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Mental rotation ability involves visualizing the results of manipulating two or three-dimensional objects in the mind. Improving this ability is important for many aspects of daily and professional lives. Therefore, it is a common objective that mental rotation ability, which is decisive for employment and professional success in many fields including defense, engineering, medicine, architecture, and the Arts, should be developed for individuals of all ages and from all educational levels (Hu et al., 2017; Gold et al., 2018; Paruchuri et al., 2020). This study aims to measure and develop mental rotation ability in a three-dimensional environment and explore the training experience of the users in this novel environment. In accordance with the study aims, a mixed-method design was employed. While the quantitative part involved the investigation of the effect of stimulus dimensionality on mental rotation performance and the training effectiveness of the Mixed Reality-based training module, the qualitative part addressed the question of how the training experience was perceived by the participants.

In this study, Purdue Spatial Visualization Test: Rotation was transferred to Microsoft HoloLens 2 environment to be used as the measurement tool. Secondly,

a Mixed Reality-based application for mental rotation training has been developed with the help of software developers specialized in immersive platforms. In this application, participants can watch rotation animations accompanied by audio narrations, perform gesture-based rotations within interactive animations and solve rotation problems of various complexity by navigating around holographic objects. 47 students at Kastamonu University completed the three-dimensional mental rotation training. Before and after training, the mental rotation ability of half of the participants was measured with the two-dimensional test on the computer, while the other half was measured with a Head-mounted Display device. The effectiveness of the mental rotation training and the effect of stimulus dimensionality on mental rotation performance and cognitive load was examined using the experimental method. Furthermore, semi-structured interviews were conducted for understanding this training experience better.

This is the first study that measures the effectiveness of a three-dimensional spatial ability training module using a complete three-dimensional spatial ability test in an immersive environment. The results show that three-dimensional training improved mental rotation ability measured by both two-dimensional and three-dimensional tests. No relationship was found between the sense of presence in the immersive training environment and mental rotation ability improvement. There is no difference in mental rotation performance between two-dimensional and three-dimensional tests. The cognitive load in the three-dimensional test was lower than in the two-dimensional test. While the mental rotation ability of females was lower than males before training, this gender difference disappeared after training. The interviews showed that the training received positive responses and that the representational and interactional affordances of the training environment were appreciated by the participants.

Keywords: Mental Rotation Ability, Spatial Ability, Three-dimensional Learning Environments, Cognitive Ability Training, Mixed Reality, Augmented Reality

ÖZ

ZİHİNSEL DÖNDÜRME BECERİSİNİ ÜÇ BOYUTLU ORTAMDA ÖLÇMEK VE GELİŞTİRMEK: BÜTÜNSEL BİR ARAŞTIRMA

Piri, Zeynep
Doktora, Bilgisayar ve Öğretim Teknolojileri Eğitimi
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Zihinsel döndürme (mental rotasyon) becerisi, iki veya üç boyutlu objelerin manipüle edilmesinin sonuçlarını zihinde canlandırabilmeyi kapsayan bir yetenektir. Bu becerinin gelişmesi günlük ve profesyonel hayat için büyük önem taşımaktadır. Savunma, mühendislik, tıp, mimari, sanat gibi birçok alanda istihdam ve mesleki başarı için belirleyici olan zihinsel döndürme becerisinin her yaşta ve eğitim düzeyinde bireyler için geliştirilebilir olması amaçlanmaktadır (Hu vd. 2017; Gold vs., 2018; Paruchuri vd., 2020). Bu çalışma zihinsel döndürme yeteneğinin üç boyutlu ortamda ölçülmesini ve geliştirilmesini ve bu yeni ortamda kullanıcıların eğitim deneyimlerini açıklamayı amaçlamaktadır. Araştırmanın amaçlarına uygun olarak karma araştırma yöntemi kullanılmıştır. Araştırmanın nicel bölümü, Katışık Gerçeklik (Kaplan, 2023) temelli eğitim modülünün uyaran boyutluluğunun zihinsel döndürme performansı üzerindeki etkisinin ve verilen eğitim etkililiğinin araştırılmasını içerirken, nitel bölüm, eğitim deneyiminin katılımcılar tarafından nasıl algılandığı sorusunu ele almaktadır.

Bu doğrultuda, ölçme aracı olarak kullanılmak üzere 30 maddelik Purdue Uzamsal Canlandırma Testi: Döndürme'nin bilgisayarda revize edilmiş versiyonu üç boyutlu

Katışık Gerçeklik ortamına (Microsoft HoloLens 2) aktarılmıştır. İkinci olarak, zihinsel döndürme becerisini artırmak üzere Katışık Gerçeklik ortamına yönelik bir uygulama geliştirilmiştir. 3 oturumdan oluşan bu zihinsel döndürme eğitiminde katılımcılar sesli anlatımlar eşliğinde döndürme animasyonlarını izleyebilmekte, etkileşimli animasyonlar ve hareket tabanlı etkileşim ile döndürme yapabilmekte ve çeşitli karmaşıklık düzeylerinde döndürme problemlerini holografik şekillerin etrafında gezinerek çözebilmektedir. Üç boyutlu zihinsel döndürme eğitimini Kastamonu Üniversitesi'nde öğrenim gören 47 öğrenci tamamlamıştır. Eğitimden önce ve sonra grubun yarısının zihinsel döndürme becerisi bilgisayar ortamında iki boyutlu testle ölçülürken, diğer yarısı için ise Katışık Gerçeklik gözlüğü kullanılmıştır. Geliştirilen zihinsel döndürme eğitimin etkililiği ile uyaran boyutluluğunun zihinsel döndürme performansı ve bilişsel yüke etkisi deneysel yöntem kullanılarak incelenmiştir. Ek olarak, bu eğitim deneyiminin daha iyi anlaşılabilmesi için yarı-yapılandırılmış görüşmeler gerçekleştirilmiştir.

Bu çalışmada üç boyutlu bir uzamsal yetenek eğitimi modülünün etkililiği ilk defa aynı sürükleyici ortamda bütün bir üç boyutlu uzamsal yetenek testi kullanılarak ölçülmüştür. Sonuçlar katılımcıların aldığı üç boyutlu zihinsel döndürme eğitiminin hem iki boyutlu hem de üç boyutlu testlerce ölçülen zihinsel döndürme becerisini artırdığını göstermektedir. Sürükleyici eğitim ortamındaki bulunuşluk hissi ile zihinsel döndürme yeteneği gelişimi arasında bir ilişki bulunmamıştır. İki boyutlu ve üç boyutlu testler arasında zihinsel döndürme performansı açısından bir fark bulunmamaktadır. Üç boyutlu testte bilişsel yük iki boyutlu testten daha düşüktür. Eğitim öncesinde kadınların zihinsel döndürme becerisi erkeklerden daha düşükken, eğitim sonrası cinsiyetler arası fark kaybolmuştur. Yapılan görüşmeler sonucunda, zihinsel döndürme eğitiminin olumlu karşılandığı ve etkili bulunduğu görülürken, bu yeni eğitim ortamının olanak sağladığı görüntüleme ve etkileşim biçimleri katılımcılar tarafından takdir edilmiştir.

Anahtar Kelimeler: Zihinsel Döndürme Becerisi, Uzamsal Beceri, Üç Boyutlu Öğrenme Ortamları, Bilişsel Beceri Eğitimi, Karma Gerçeklik, Artırılmış Gerçeklik, Katışık Gerçeklik

To All My Beloved Ones

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TABLE OF CONTENTS

ABSTRACT.....	v
ÖZ	vii
ACKNOWLEDGMENTS	xi
TABLE OF CONTENTS.....	xiii
LIST OF TABLES	xvii
LIST OF FIGURES	xix
LIST OF ABBREVIATIONS.....	xxi
CHAPTERS	
1 INTRODUCTION	1
1.1 Problem Statement	4
1.2 Purpose of the Study	6
1.3 Significance of the Study	7
1.4 Definition of the Terms.....	8
1.5 Research Questions	9
2 LITERATURE REVIEW	11
2.1 Spatial Ability	11
2.2 Mental Rotation Ability	12
2.2.1 Mental Rotation Strategies.....	13
2.3 Dimensionality	15
2.4 Mixed and Augmented Reality	16
2.5 Measuring Mental Rotation Ability in Three Dimensions	18
2.6 Gender Differences in Mental Rotation Ability.....	23
2.7 Mental Rotation Ability Training in Three Dimensional Environments	25
2.7.1 Learning Content and Features of 3-D Mental Rotation Training Environments	31
2.7.2 Representation Devices Employed in 3-D Mental Rotation Training	34
2.7.3 Manipulative Types Employed in 3-D Mental Rotation Training.....	36
2.7.4 Interaction Devices Employed in 3-D Mental Rotation Training.....	36
2.8 Immersive Learning Environments and Presence.....	39

2.8.1	Feeling of Presence in 3-D Mental Rotation Training	40
2.9	Cognitive Theories Informing the Study	41
2.9.1	Cognitive Load Theory.....	41
2.9.2	Cognitive Fit Theory	44
2.9.3	Situated Cognition	45
2.9.4	Theories of Visual Imagery	45
2.10	Summary.....	46
3	METHODOLOGY	49
3.4	Research Questions	49
3.5	Study Design	50
3.5.1	Mixed Method Design.....	51
3.5.2	Variables of the Study	52
3.6	Participants	53
3.7	Usability and Pilot Studies	54
3.8	Procedure.....	55
3.9	Apparatus.....	60
3.10	Instruments	60
3.10.1	The Revised Purdue Spatial Visualization Test: Rotations.....	61
3.10.2	Presence Questionnaire	67
3.10.3	Cognitive Load Scale	67
3.10.4	Interviews	67
3.11	The MR-based Mental Rotation Training Application	68
3.12	Data Analysis Procedure	78
3.13	Reliability	79
3.14	Validity	80
3.15	Ethical Considerations.....	81
4	RESULTS.....	83
4.1	Research Question 1	85
4.1.1	Research question 1a	85
4.1.2	Research Question 1b.....	86
4.1.3	Research Question 1c	88
4.1.4	Research Question 1d.....	91
4.2	Research Question 2	94

4.2.1	Research Question 2a	96
4.2.2	Research Question 2b	96
4.2.3	Research Question 2c	99
4.2.4	Research Question 2d	99
4.3	Research Question 3	101
4.3.1	Mixed Reality Tool for Spatial Training	102
4.3.2	Cognitive Aspects	108
4.3.3	Affective Aspects	113
4.3.4	Technical Aspects	116
4.4	Summary	119
5	DISCUSSION	121
5.1	Effectiveness of Mixed Reality-based Training	123
5.1.1	Gender Difference in Mental Rotation Ability Before and After the Training 125	
5.2	Effect of Stimulus Dimensionality and Complexity	127
5.2.1	Effect of Stimulus Dimensionality	127
5.2.2	Effect of Stimulus Complexity	129
5.3	Cognitive Load in Measuring Mental Rotation Ability	131
5.3.1	Cognitive Load in Different Dimensionalities	131
5.3.2	Cognitive Load and Mental Rotation Ability Improvement	133
5.4	Sense of Presence and Effectiveness	134
5.5	Mixed Reality-based Training Experience	135
5.6	Limitations	137
6	CONCLUSION	139
6.1	Implications on Education and Training	140
6.1.1	Built-In Measurement In Immersive Spatial Ability Training	140
6.1.2	Effective Spatial Ability Training with Short Sessions	140
6.1.3	Easily Modifiable Tool For Different Education Levels	142
6.1.4	Alleviating Cognitive Overload In Three-Dimensional Environments	142
6.1.5	Promoting Equal Gender Representation In Spatial Ability-Related Careers 142	
6.2	Implications on Research	143

6.2.1 Documenting The Effectiveness Of 3-D Training With 3-D As Well As 2-D Tests	143
6.2.2 Increasing The Range Of Sensory Input For Effective Spatial Ability Training	144
6.2.3 Offering Design Guidelines For Mixed Reality-Based Learning Environments.....	144
6.3 Suggestions for Future Spatial Ability Training Systems	146
6.4 Summary.....	148
REFERENCES	149
A. Consent Form	163
B. Demographic Survey	165
C. Cognitive Load Scale	167
D. Presence Questionnaire	168
E. Interview Questions.....	171
CURRICULUM VITAE (Only For Doctoral Thesis).....	173

LIST OF TABLES

TABLES

Table 2.1 Input devices used in 3-D mental rotation training.....	39
Table 3.1 PSVT:R Item Complexity Index.....	66
Table 4.1 Sample demographics (n = 47)	83
Table 4.2 Descriptive Statistics of 2-D and 3-D Test Groups	85
Table 4.3 Difference between 2-D and 3-D Mental Rotation Scores	85
Table 4.4 Mental Load in 2-D and 3-D Test Groups	86
Table 4.5 Mental Load Difference by Test Dimensionality	87
Table 4.6 Mental Effort in 2-D and 3-D Test Groups.....	87
Table 4.7 Mental Effort Difference by Test Dimensionality	87
Table 4.8 Mental Rotation Scores by Gender (Pre-test)	88
Table 4.9 Difference Between Male and Female Test Scores	89
Table 4.10 Gender Difference by Test Versions	89
Table 4.11 Gender Difference After Training	91
Table 4.12 Success Rate by Item Complexity	92
Table 4.13 Success Rate in Test Items by Stimulus Complexity	93
Table 4.14 Descriptive Statistics of Pre-test and Post-test Scores.....	94
Table 4.15 Mental Rotation Ability Before and After Training	94
Table 4.16 Mental Rotation Ability Before and After Training by Test Group	95
Table 4.17 Mental Rotation Ability Improvement by Dimensionality	95
Table 4.18 Mental Rotation Ability Improvement by Gender.....	96
Table 4.19 Improvement of Success Rate by Item Complexity	97
Table 4.20 Mental Rotation Ability Improvement by Stimulus Complexity	98
Table 4.21 Relationship between Mental Rotation Ability Improvement and Sense of Presence	99
Table 4.22 Relationship between Mental Rotation Ability Improvement and Cognitive Load.....	100

Table 4.23 Demographic Information of the Interviewed Subsample	101
Table 4.24 Themes and Categories	102
Table 4.25 Categories of the <i>Mixed Reality Tool for Spatial Training</i> Theme.....	103
Table 4.26 Categories of the <i>Cognitive Aspects</i> Theme.....	108
Table 4.27 Categories of the <i>Affective Aspects</i> Theme	113
Table 4.28 Categories of the <i>Technical Aspects</i> Theme.....	116
Table 6.1 The Implications of the Study	139

LIST OF FIGURES

FIGURES

Figure 1.1 Symbolic Mental Representations of Rotation.....	1
Figure 2.1 Virtuality Continuum.....	17
Figure 2.2: Sample item from the Mental Rotation Test (Vandenberg & Kuse, 1978)	18
Figure 2.3: Sample item from the Cube Comparison Test (Ekstrom et al., 1976) .	19
Figure 2.4 Sample item from Card Rotation Test (Ekstrom et al., 1976).....	19
Figure 2.5: Sample item from Purdue Spatial Visualization Test: Rotation (Guay, 1976)	19
Figure 2.6 Representation devices used for 3-D mental rotation training: a) Head Mounted Display (Kozhevnikov et al., 2008), b) Projector screen (Wang et al., 2011), c) Tablet (Gecü-Parmaksız & Delialioğlu, 2020), and d) Holographic Display (Lee et al., 2016).....	35
Figure 2.7 Interaction devices used for 3-D mental rotation training a) Touchscreen (Zander et al., 2016), b) Wireless pen (Kauffman et al., 2008), c) Virtual Physical Manipulative (Ha & Fang, 2018), and Gesture-based Interaction (Ariali, 2020)...	38
Figure 3.1: Variables of the Study	52
Figure 3.2: Airtap Gesture (https://docs.microsoft.com/th-th/dynamics365/mixed-reality/guides/hl1)	56
Figure 3.3: Taking 3-D PSVT:R on HoloLens 2	57
Figure 3.4 Flow of the study	58
Figure 3.5: Microsoft HoloLens 2	60
Figure 3.6: Item from Revised PSVT:R	62
Figure 3.7: 2-D PSVT:R Item.....	62
Figure 3.8: Examples of 3-D Models.....	63
Figure 3.9: Sample Item from 3-D PSVT:R	64
Figure 3.10: Shepard and Metzler type mental rotation task (on the left). An example item from the PSVT:R (on the right).....	65

Figure 3.11: Color use in menu items. Test Instructions (left) Score Screen (right).	69
Figure 3.12: Storyboard and screen pairs example.	70
Figure 3.13 The denotation of the canonical axes used in the present study	70
Figure 3.14 Design of Training Content.....	71
Figure 3.15: Improvement with 3-D Mental Rotation Training.....	72
Figure 3.16: Content Flow of the Mental Rotation Training.....	72
Figure 3.17: Rotation Practice Screen	73
Figure 3.18: Passive Animation Example	75
Figure 3.19: Interactive Animation Example	76
Figure 3.20 Rotation Problem Example	77
Figure 4.1: Mental Rotation Ability Scores by Gender.....	89
Figure 4.2: Mental Rotation Ability Scores/Test Dimensionality by Gender	90
Figure 4.3: Stimulus Complexity and Success Rate.....	93
Figure 4.4: Mental Rotation Score Improvement by Item Complexity.....	98
Figure 5.1 Summary of the Key Features of Training Experience.....	137

LIST OF ABBREVIATIONS

AR:	Augmented Reality
HMD:	Head Mounted Display
MR:	Mixed Reality
PSVT:R:	Purdue Spatial Visualization Test: Rotation
VR:	Virtual Reality

CHAPTER 1

INTRODUCTION

The importance of spatial ability as a type of cognitive ability has been recognized better in recent years. Perceiving, understanding, and manipulating three-dimensional spatial information is fundamental for problem-solving in many science-related careers (Stieff et al., 2005). Spatial ability level obtained with psychometric measures is a strong predictor of performance in STEM education programs (Uttal et al., 2013). However, it is still far from being addressed sufficiently in formal education when compared to other cognitive skills such as verbal and mathematical skills.

Mental rotation ability, a type of spatial ability, involves visualizing the results of manipulating two or three-dimensional objects in the mind. It is basically the answer to “What happens when an object is rotated that way?”. Performing mental rotation requires generating the whole process involved in changing the orientation of a given stimulus (Figure 1.1).

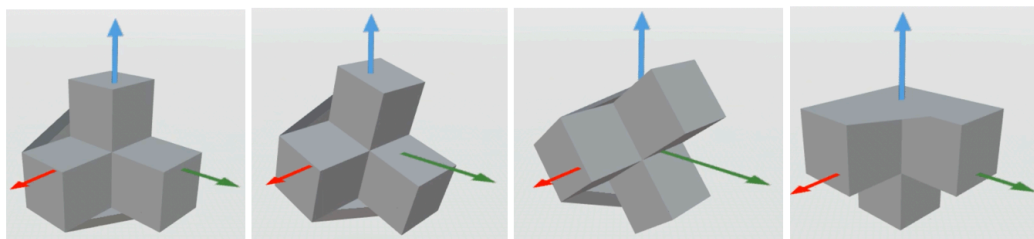


Figure 1.1 Symbolic Mental Representations of Rotation

Mental rotation ability not only facilitates many everyday activities such as driving and navigation but also is important for academic and professional success in several areas such as defense, engineering, architecture, and arts. For example, mental

rotation ability was found to increase the effectiveness of in-service programs in medical education (Jamil et al., 2019). Mental rotation training allowed better comprehension of applied anatomy. Accurate measurement of mental rotation ability can enable making career decisions more effectively, alleviating the individual performance differences in this ability with technology-enhanced interventions is considered to increase the potential for success in several career types (Sorby, 2009). Mental rotation ability is associated with the largest gender difference reported among the types of spatial abilities (Maeda & Yoon, 2013). Typically, women have been found to perform poorer than men in traditional measurement environments with 2-D stimulus. Reducing the gender difference in this type of ability can increase the inclusion of women in many career types (Reilly et al., 2017). On the other hand, 3-D tasks often denied a gender difference in mental rotation ability (Parsons et al., 2004; Toptaş et al., 2012). Therefore, another topic for investigation is whether the absence of gender difference could extend to the performance in a complete standardized test of mental rotation.

Mental rotation tasks can become more difficult based on the complexity of the geometry of the target object (Ha & Fang, 2018) and the rule of rotation to be performed including the angle of rotation and the required number of rotation moves (Shepard & Metzler, 1971). The effect of stimulus complexity on mental rotation performance in 2-D online tests was investigated using eye-tracking method (Chen & Yang, 2014). Knowing how characteristics of stimuli might affect performance can be useful for the design of effective training for this ability. In this study, we investigate how stimulus complexity influences performance and how Mixed Reality-based training affects performance in test items with different levels of complexity.

The subjective feeling of “being there” in a simulated environment is called presence. This feeling can arise from the immersiveness of an environment and the possibility of interaction (Berki, 2019). The feeling of presence was theoretically linked with spatial ability on the grounds that easily creating a mental model of the spatial environment is likely to induce feelings of being actually located in that space

(Wirth et al., 2007). However, no relationship was found between mental rotation ability and a sense of presence (Coxon, 2016). Therefore, new studies involving different simulated environments are needed that address such a relationship.

Cognitive load during training is a critical aspect to consider as mental rotation is challenging for most learners. While immersive 3-D technologies can display content with high degrees of realism, realistic displays are not necessarily the best option in all cases (Smallman & John, 2005). In this vein, they receive criticisms about increasing cognitive load due to the richness of visual data and high immersion (Makransky et al., 2019). In their systematic review of the impact of AR on cognitive load and performance, Buchner et al. (2021) found that AR seems to be less cognitively demanding and leads to higher performance. Similarly, studies on 3-D mental rotation training suggest that, to say the least, 3-D MR training does not impose a greater cognitive load on learners than 2D training (Piri & Cagiltay, 2023). Lower cognitive load may not always lead to better performance, therefore, the relationship between them should be investigated.

Mixed Reality is an umbrella term that involves more than one type of technology including Virtual Reality and Augmented Reality. Mixed Reality environments enable real-world users to interact with virtual objects integrated into their view of the real world (Kumar et al., 2017). Mixed Reality (MR) applications are being increasingly used in fields such as science, engineering, and manufacturing (Potkonjak et al., 2016; Ibanez and Delgado-Kloos, 2018; Wang et al., 2021). Their capability to merge real and virtual objects is explored to find how they can be leveraged most effectively for learning or cognitive training purposes. Using 3-D representational technologies, low spatial ability students can improve their spatial ability to be better prepared for STEM programs (Martin-Dorta et al., 2014)

The potential of Virtual Reality and Augmented Reality technologies for spatial ability training and measurement was recognized very early (Rizzo et al., 1998). However, these technologies were primitive in the late 1990s and they have been gradually improving in terms of user comfort, resolution, and processing capabilities. Increased employment of three-dimensional learning environments including

Augmented Reality applications has facilitated the use of such tools for spatial ability improvement (Omar et al., 2019). These types of environments enable exploring spatial ability with higher fidelity stimuli. However, there are some research gaps in the literature regarding both the measurement and training of spatial ability which will be outlined in the next section.

1.1 Problem Statement

Typical mental rotation tests involve 2-D isometric stimuli that look three-dimensional. In such tests, participants must transform the two-dimensional drawings into three-dimensional equivalents in their mind first, perform the required mental transformations, and then find the two-dimensional equivalent of the three-dimensional mental image they created as a result of these transformations. These transformations are seen as redundant for measuring an ability that entails thinking in 3-D (Strasser et al., 2010). Therefore, such actions induce a heavier and extraneous cognitive load on the individual (Lee et al., 2016). In tests carried out in three-dimensional environments, it is possible to eliminate the dimension transformations that are not essential for the mental rotation process.

There is a growing opinion that a skill that involves three dimensions should be measured in three dimensions rather than two dimensions for more accurate measurement (Ariali, 2020). While 2-D computer-based testing might be limited for testing mental rotation ability, 3-D applications can provide a more valid environment (Kozhevnikov et al., 2008).

With Mixed Reality technology becoming increasingly reliable, 3-D testing can provide a more authentic assessment of skills in/for the workplace. Parsons et al. (2004) argued that it is possible to obtain more reliable, valid, and precise information about the cognitive processes that underlie mental rotation using this technology. Additionally, when compared to the dominantly used desktop-based VR and AR applications for spatial ability training, HMD-based (Head Mounted

Display) applications can provide a more immersive learning and testing environment. With this aforementioned aim, in this study, the Purdue Spatial Visualization Test: Rotations (PSVT:R), a complete psychometric spatial ability test, was transferred to the three-dimensional environment.

Following the recognition of the importance of mental rotation ability for academic success, many training interventions have been designed and implemented to improve this ability in individuals of different age groups and grade levels. Methods used to address this ability involved game-based learning (Terlecki et al., 2008), web-based learning (Rafi & Samsudin, 2009), computer-aided drawing (CAD) software (Erkoç et al., 2013), robotics (González-Calero et al., 2019), augmented reality (Hoe et al., 2019), and virtual reality (Ariali, 2020). Most of the early interventions entailed 2-D representations in the learning content, which may hinder understanding the mental rotation processes of 3-D objects.

With technological advances, three-dimensional visualization tools have become more common and accessible. When three-dimensional (3-D) realistic figures are used, necessary visual information such as volume, dimensions, texture, and perspective, which are not available in two-dimensional drawings, are presented to the individual (Yue, 2008). In addition, three-dimensional training helps enhance attention by facilitating visualization (Wang et al., 2011).

Immersive 3-D systems are particularly effective tools for spatial ability training as they can improve transfer to real-life spatial tasks (Kozhevnikov & Dhond, 2012). With animations that allow users to visualize and manipulate three-dimensional virtual objects synchronously, Augmented Reality technology can enhance mental rotation ability in a way that traditional two-dimensional materials cannot (Hoe et al., 2019). Therefore, 3-D mental rotation training can overcome some of the limitations of two-dimensional training systems. The increasing accessibility of immersive technologies may cultivate the design of more authentic mental rotation training systems. However, until five years ago, most mental rotation training interventions employed 2-D paper-based or digital representations (Lin & Yeh, 2019). Tüker (2019) highlighted the scarcity of research on the use of Virtual Reality

(VR) and Augmented Reality (AR) systems for spatial ability training. With the growing demand for the use of three-dimensional learning environments, it is possible to examine this type of spatial ability with more authentic stimuli; and purposefully and promptly remediate it to the levels required for academic success.

1.2 Purpose of the Study

The ecological validity of the conventional paper-and-pencil tests that measure spatial ability was questioned by many researchers (Marusan et al., 2006; Hartman et al., 2006; Merchant et al., 2013). Some attempts were made in transferring spatial ability tests into 3-D environments (Cohen & Hegarty, 2012; Ventura et al., 2013) for assessing cross-section inference and spatial navigation. While there are a few studies conducted to measure mental rotation ability in three-dimensional environments, no study was found that delivered Purdue Spatial Visualization Test: Rotation in such environments to measure mental rotation ability.

Therefore, the first purpose of this study is to assess mental rotation ability using truly three-dimensional stimuli. To provide tools for evaluating learning that takes place in immersive environments, we developed a test that can be administered in Mixed Reality environment. This testing tool was also used for measuring the effectiveness of the training module explained below.

The second purpose of this study is to design and develop a Mixed Reality application for mental rotation training. In their meta-analysis which showed that spatial ability can be trained, Uttal et al. (2013) argue that part of the training effect occurs due to ‘the acquisition and appropriate application of strategies or rules’. Taking students’ ability to learn spatial strategies and the characteristics of MR technology into account, this application involved tasks with different degrees of complexity and it aims for increasing success in mental rotation tasks in a three-dimensional learning environment.

1.3 Significance of the Study

The interactive mental rotation ability training system developed in the present study leverages the characteristics of immersion, fidelity, and active learner participation (Mikropoulos and Natsis, 2011) in Mixed Reality technology to create an effective learner experience. It employs Mixed Reality goggles to display high-resolution three-dimensional content, enables motoric manipulation, and viewing objects from different angles in a realistic manner. Real-time 3-D presentation employed in the training module integrates the learning content into the physical world. This system aimed to provide a more intuitive interaction opportunity with gesture-based technology and to simulate physical rotation with high fidelity. The design of the training module assumes that mental rotation ability can be improved by accurately describing the rotation processes. Although there have been studies in which three-dimensional mental rotation systems using gesture-based interaction have been developed, these are predominantly game-based applications for elderly individuals (Lee et al., 2016; Hoe et al., 2019).

Mental rotation ability can be developed by helping the learner create more accurate mental models (Rafi & Samsudin, 2009). In this study, the three-dimensional training module contains holographic objects to deal with mental rotation ability as it is handled in the real world without being exposed to the "dimensionality crossing" (Horan & Rosser, 1984 as cited in Neubauer et al., 2010) experienced in 2-D environments.

Until the present times, the use of three-dimensional environments for training mental rotation ability was mainly through desktop-based applications and with simple visual stimuli. Hence, as Molina-Carmona (2018a) pointed out, the current study aimed to address this ability using more challenging stimuli (containing more complex objects to be rotated and rotation sequences), employing a standard psychometric test, and advanced technology. In this study, the testing tool and the training environment targeting mental rotation ability were developed for a Mixed Reality headset (i.e., *Microsoft HoloLens 2*).

The effectiveness of the mental rotation training system developed in this study is demonstrated with both two-dimensional and three-dimensional measurement tools. Although there are many statements in the literature that measuring spatial abilities in a three-dimensional environment will increase validity (Mikropoulos & Natsis, 2011; Cohen & Hegarty, 2014); to the best of our knowledge, so far there is no other study that used a complete mental rotation ability test containing real three-dimensional (holographic) stimuli as a pre- and post-test to determine the effectiveness of a three-dimensional educational material. In this study, one of the new assessment methods is discussed since such methods will likely be needed more as three-dimensional learning environments become increasingly widespread. PSVT:R, which is a standardized spatial ability test as opposed to a single mental rotation task, was converted into a three-dimensional test and employed to measure the effectiveness of the developed system.

1.4 Definition of the Terms

The definition of the terms used in this study is provided below.

Spatial Ability: “the ability to generate, retain, retrieve, and transform well-structured visual images” (Lohman, 1996).

Mental Rotation Ability: “the ability to mentally rotate two- or three-dimensional objects based on the principle of the transformation of spatial information” (Zander et al., 2016).

Mixed Reality: “refers to the class of all displays in which there is some combination of a real environment and virtual reality (Drascic and Milgram, 1996).

Dimensionality: In this study, two types of dimensionalities are included. Lamb’s (2016) description of two-dimensional and three-dimensional are employed. In two-dimensional environments, manipulations can be made in the x- axis and y- axis while in three-dimensional environments manipulations can be made in the x- axis, y- axis and z-axis of the Cartesian coordinate system.

Training: A systematic technology-enhanced program targeted to improving a particular cognitive ability.

1.5 Research Questions

In this study, we explored the use of Mixed Reality technology for measuring and improving mental rotation ability. Specifically, this study investigates mental rotation performance and cognitive load in environments with different dimensionalities. In this respect, PSVT:R, a test measuring mental rotation ability, was transferred to the Mixed Reality environment and administered to university students. The three-dimensional measurement tool and the two-dimensional measurement tool were compared to examine whether stimulus dimensionality has an effect on mental rotation performance. The effectiveness of the Mixed Reality training module in improving mental rotation ability was investigated.

The research questions driving this study are presented below.

- 1) What is the effect of the dimensionality of the measurement environment?
 - a) What is the effect of dimensionality of the test stimuli (2-D vs. 3-D) on mental rotation performance?
 - b) What is the effect of the dimensionality of the test stimuli (2-D vs. 3-D) on cognitive load?
 - c) Is gender difference observed in mental rotation performance in the test environment?
 - d) How does stimulus complexity affect mental rotation performance?
- 2) Can mental rotation ability be improved with a Mixed Reality-based training application?
 - a) Does the 3-D mental rotation training lead to a difference between male and female mental rotation ability improvement?

- b) Does mental rotation ability improvement remain the same for different levels of stimulus complexity?
 - c) Is there a relationship between feeling of presence and mental rotation ability improvement in the 3-D training environment?
 - d) Is there a relationship between cognitive load and mental rotation ability improvement in the 3-D training environment?
- 3) How are the mental rotation experiences in the three-dimensional training environment?

The remainder of this thesis is structured as follows. First, the relevant theoretical and empirical work that frames the current study is presented. Then, the experimental methodology is described. Next, the account of the results from the analyses performed on the collected data is given. A discussion of these results based on the framework provides a basis for the implications anticipated for different stakeholders. Finally, the conclusion captures the contributions of the study and presents some suggestions for researchers, practitioners, and developers.

CHAPTER 2

LITERATURE REVIEW

This chapter presents an extensive review of the literature that frames this study. It explains spatial ability with existing typologies and delves into one of the spatial ability types, mental rotation ability. It recaps the research that used 3-D environments for measuring and improving mental rotation ability. It provides information about immersive learning environments and gesture based-interaction. It elaborates on the variables focused on in this study, gender, stimulus dimensionality, cognitive load, and feeling of presence. Finally, it explains the theories that inform the conduction and interpretation of this study.

2.1 Spatial Ability

Spatial ability involves the production, retention, recall, and transformation of visual images in the human mind (Lohman, 1996). There are several categories and interchanging terms used in spatial ability research which can be confusing. Carroll (1993) carried out a comprehensive factor analysis to determine the major sub-categories of spatial ability. The five sub-categories are as follows:

Visualization: “Ability in manipulating visual patterns”. This ability focuses on how complex and difficult visual stimuli can be handled by the individual.

Spatial Relations: “Speed in manipulating relatively simple visual patterns”. Mental rotation ability is related to this particular factor.

Closure Speed: Speed in identifying an obscured visual pattern, without knowing what the pattern is.

Flexibility of Closure: Speed in identifying an obscured visual pattern, knowing what the pattern is.

Perceptual Speed: Speed in finding unobscured visual patterns or comparing patterns accurately.

Yılmaz (2009) highlighted three more spatial ability sub-categories that may be overlooked in some classifications. *Spatial Orientation* refers to “one’s ability to imagine the appearance of an object from different perspectives.” *Dynamic Spatial Ability* involves problems with a moving stimulus. *Environmental Ability* is related to integrating information about natural and artificial objects around an individual. Each type of spatial ability emphasizes different aspects of the process of image generation, storage, retrieval, and transformation (Lohman, 1996).

Spatial abilities are critical for understanding and excelling in several domains including geometry (Hannafin et al., 2008), chemistry (Harle & Towns, 2011), and engineering mechanics (Ha & Fang, 2018). As learning most science subjects require understanding spatial relationships, some studies suggested embedding spatial training (i.e., allowing manual manipulation of representations) in learning environments. However, spatial ability training has only received adequate attention in the present decade. As the importance of spatial ability has been recognized in a wide range of professional disciplines, this type of reasoning has been increasingly addressed in formal education curricula.

2.2 Mental Rotation Ability

As a type of spatial ability, mental rotation refers to the ability to imagine the consequences of manipulating two or three-dimensional objects. Understanding the specific cognitive processes involved in mental rotation is critical for valid measurement and successful training of mental rotation ability. Therefore, background information about mental rotation research will be presented.

In the first empirical study investigating mental rotation, Shepard and Metzler (1971) assigned 1600 pairs of stimuli to 8 adult subjects. The subjects were to judge whether the pairs depicted the same object from different perspectives or completely different objects. Mirror images were also used for preventing subjects from making decisions with the help of some distinctive features of the objects without performing mental rotation. The results showed that the response time in the mental rotation task increased linearly when the angular difference between the objects in the pair of stimuli increased, which is known as the *Angular Disparity Effect*.

Just and Carpenter (1985) were the first scholars who attempted to theorize the cognitive processing differences involved in mental rotation. They described the sub-processes of mental rotation as *Search, Rotation, and Confirmation*. Using computer models to simulate low and high spatial ability groups, they were able to uncover large performance differences resulting from small differences in mental rotation processes.

Based on Cartesian coordinate systems, Just and Carpenter (1985) put forward the concept of *Cognitive Coordinate Systems* with “at least one implicit origin and some directional axes” on which humans base their perceptions about physical objects. The authors argue that recognition, retrieval, and spatial processing (including mental rotation) of visual information are largely based on the individuals’ choice of cognitive coordinate systems. For the case of mental rotation, this choice influences how the next steps in the mental rotation task will be performed.

2.2.1 Mental Rotation Strategies

According to Just and Carpenter (1985), there are four alternative strategies to use in a mental rotation task:

- 1) Mental rotation around standard axes: Subjects using this strategy often use the canonical axes x , y , and z . In the use of this strategy, the frame of reference is external to the to-be-rotated object.

- 2) Mental rotation around task-defined axes: Some subjects purposefully choose an arbitrary axis useful for performing a particular rotation task. Finding such a task-defined axis for mental rotation implies the use of a cognitive coordinate system.
- 3) The comparison of orientation-free descriptions: Features of the to-be-rotated object can be directly compared regardless of the orientation of the whole object. For example, subjects may reason ‘The sharp end of the object is on the top when its flat surface is at the bottom’.
- 4) Perspective Change: This strategy entails mentally changing the position of the self (observer). Encoding object’s and their own positions into a cognitive coordinate system, subjects imagine how the object would appear if they looked from different angles.

Another distinction was made between ‘holistic’ and ‘analytical’ mental rotation strategies. In holistic strategy, the object is handled as a whole while the rotation task is being performed in the mind. On the other hand, individuals who use the analytical strategy analyze the object first and refer to a part of the object for rotation (Sorby, 2009). The holistic strategy generally produces better results under a time restriction and is usually employed more by males than females. The reliability of spatial ability tests is related to the test items requiring a holistic strategy as much as possible (Yoon, 2011).

Using eye-tracking data, Just and Carpenter (1985) illustrated that as opposed to high spatial ability subjects, low spatial ability subjects never used the task-defined axes in mental rotation. However, using the non-standard trajectory where possible is often the most efficient way to solve rotation tasks. In another study, Chen and Yang (2014) analyzed students’ cognitive activities during mental rotation tasks using an eye-tracking methodology. Accuracy in mental rotation tasks was correlated with eye movement patterns. Specifically, high performers engaged in more observing, recognizing, memorizing, and imagining activities. On the other hand, low performers were likely to rotate using an aid such as hands.

2.3 Dimensionality

The phrases “three-dimensional” and “3-D” are used vaguely in the literature. To illustrate, systems displaying figures that represent isometric views of objects with a “3D” effect in a 2-D environment are often described as “3-D” in the literature. However, we describe an environment as “3-D” only if it employs 3-D models that can be viewed from all angles. Two-dimensional and three-dimensional environments are essentially different in terms of how visual information is presented. The effect of stimulus dimensionality on spatial ability performance was investigated by Hartman et al. (2006). Relevant to the purpose of the present study, he put forward the possible advantages of a VR-based (3-D) test over a paper-based (2-D) test:

- a) Allowing more valid assessments,
- b) Eliminating the ambiguity of isometric figures,
- c) Removing inherent biases (such as gender difference).

Hartman et al.’s (2006) anticipation was that there would be no significant performance differences between the 2-D and 3-D versions of the test.

Spatial tasks that require deriving three-dimensional representations from two-dimensional images are claimed to cause ‘dimensionality crossing’, which may increase task complexity, especially for females (Horan & Rosser, 1984 in Neubauer et al., 2010). Many studies pointed out the topic of ‘dimensionality crossing’ which refers to the difficulty to infer the visual features of 3-D objects accurately from representations in 2-D environments.

According to Yue (2008), when three-dimensional realistic figures are used, useful visual information absent in two-dimensional figures such as volume, dimensions, texture and perspective can be presented to the learner. On the contrary, they are oversimplified when converted to isometric 2-D figures. Yue (2008) realized the importance of using realistic stimuli in mental rotation tests and added some visual information to PSVT:R figures. Although mental rotation performance was

increased when compared to the isometric drawings, this superiority was marginal. The authors argued that this was because it was not possible to obtain a realistic presentation of three-dimensional objects on a two-dimensional computer screen.

The fact that the mental rotation processes are affected by dimensionality and immersion was revealed by Kozhevnikov et al.'s (2008) study. In 2-D and non-immersive 3-D environments, they found that rotations around axes x and z required longer response time than the rotations around axis y . This suggested that in these environments objects are encoded in terms of horizontal and vertical relations inherent in their structure. On the other hand, rotations around the x -axis took shorter than the rotations around the z -axis in the immersive 3-D environment. The difference in processing visual information in such an environment may stem from vestibular feedback.

2.4 Mixed and Augmented Reality

Mixed Reality (MR) is an umbrella term that involves more than one type of technology including Virtual Reality and Augmented Reality. Mixed reality refers to “the class of all displays in which there is some combination of a real environment and virtual reality” (Drascic and Milgram, 1996). Being a complex concept, the definition of Mixed Reality has fluctuated over time, reflecting the contemporary technological trends and dominant linguistic meanings and narratives (Mystakidis, 2022). Therefore, as Augmented Reality evolved to include interactive affordances, Mixed Reality is sometimes characterized as a combination of AR and VR.

Milgram and Kishino (1994) proposed the concept of the ‘*virtuality continuum*’ (Figure 2.1). Real environments perceived by human senses are found at one end of this continuum. At the other end is virtual reality which is characterized by total immersion in a completely ‘*synthetic*’ world. Any environment that combines real and virtual information is referred to as mixed reality and can be anywhere within the continuum depending on the dominant type of information it contains (i.e., real

or virtual). The authors noted that the degree to which Mixed Reality tools can display the *world* within is related to *Reproduction Fidelity*. They considered real-time, high-fidelity 3-D animation as the peak of this concept. For *presence*, they set the highest degree as “real-time imaging” at which the user senses the environment as they are in unmediated reality.

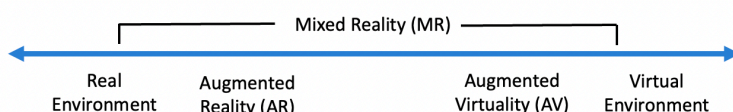


Figure 2.1 Virtuality Continuum

Augmented Reality is a technology that enables presenting an interactive combination of real-life objects and virtual information in three dimensions (Azuma et al., 2001). Especially in HMD-based AR applications which contain special screens that are mounted on the head and contain cameras, speakers, and trackers; information is presented to the user in a highly contextualized and immersive environment. With these ‘goggles’, head and eye movements suffice to engage with the learning material which makes them more immersive than other options that require carrying around a device. (Santos et al., 2013).

Since the beginning of the 2000s, the majority of AR research in educational settings employed portable devices such as tablets and mobile phones. Although sometimes seen as cumbersome because of the necessity of carrying around and holding against physical objects to view AR content, these mobile devices allowed considerable flexibility in terms of time and location of instruction. On the other hand, HMDs emerge as a ‘hands-free’ option that can receive commands from the user in the form of hand gestures.

MR devices increasingly become lighter, more affordable, and more reliable which makes them a more convenient option for delivering instruction. VR and AR-based immersive environments have been increasingly employed for cognitive ability testing in recent years with normal and diagnosed participants (Kim et al., 2021). They are used for both evaluating executive functions of people from different age groups and rehabilitating the elderly for helping them manage activities of daily life. VR/AR is used to assess and enhance spatial ability by allowing interaction with virtual objects (Uz-Bilgin et al., 2021). Since they are likely to be widely used in the future, focusing on educational MR applications could enable a smoother transition for that period. Also, this study can contribute to improving cognitive ability using MR technology in addition to studies that mainly focused on user satisfaction with such environments (Molina-Carmona et al., 2018a).

2.5 Measuring Mental Rotation Ability in Three Dimensions

Since mental representations cannot be measured directly, tests or tasks are used for making inferences about spatial performance (Hegarty et al., 2006). Typical mental rotation tests involve multiple choice questions of varying complexity on 2-D paper. A list of the most widely used traditional mental rotation tests is provided below:

- 1) Mental Rotation Test: This 24-item test entails Shepard and Metzler-type objects (Vandenberg and Kuse, 1978)

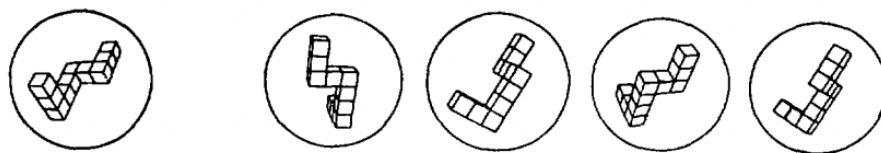


Figure 2.2: Sample item from the Mental Rotation Test (Vandenberg & Kuse, 1978)

- 2) Cube Comparison Test: This 21-item test comprises cubes with letters and numbers on the surfaces. (Ekstrom et al., 1976)

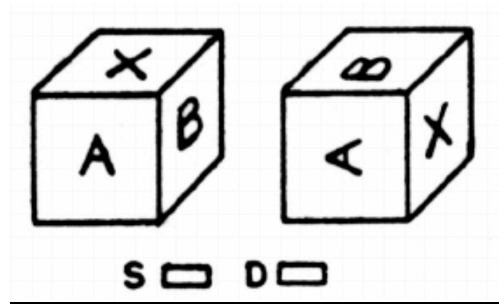


Figure 2.3: Sample item from the Cube Comparison Test (Ekstrom et al., 1976)

- 3) Card Rotation Test: (Ekstrom et al., 1976), adapted to Turkish by Delialioğlu (1996)

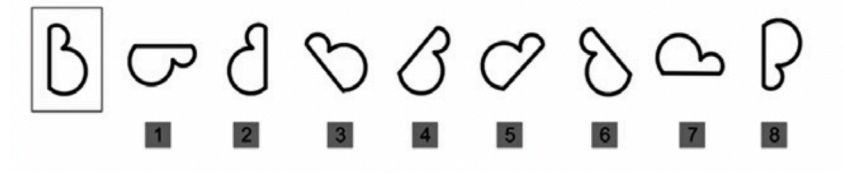


Figure 2.4 Sample item from Card Rotation Test (Ekstrom et al., 1976)

- 4) Purdue Spatial Visualization Test: Rotations: (Guay, 1976)

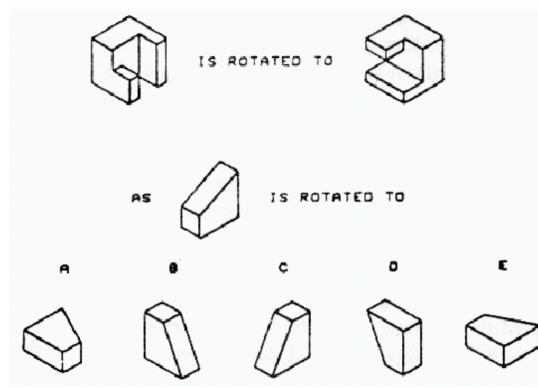


Figure 2.5: Sample item from Purdue Spatial Visualization Test: Rotation (Guay, 1976)

Although most of the widely used mental rotation tests measure this ability in 2-D, the majority of the real-life interactions that require mental rotation involve three-dimensional objects. Furthermore, unlike many real-life spatial tasks, conventional

mental rotation tests entail the processes of transformations from 2-D to 3-D and after performing mental transformations, re-transforming to 2-D (Kaufmann et al., 2008). Performing mental rotation tasks that contain two-dimensional objects and three-dimensional objects requires different skills (Yoon, 2011). When considering the ambiguity caused by 2-D isometric drawings, both the reliability and the construct validity of these psychometric tests become questionable (Hartman et al., 2006).

The primary distinction between 3-D environments and 2-D environments is the addition of depth information. Three-dimensional display with sufficient depth information is achieved by presenting slightly different images to each eye, a technology known as “stereoscopy”. Participants mentally rotate stimuli presented with stereoscopic disparity faster and more accurately. This may result from the reduced ambiguity of stimuli (Burles et al., 2019). Stereoscopy can influence cognitive processes entailed in rotation as well as perceptual processes. Employing the eye-tracking method, Karacan et al. (2010) found that with increased familiarization with the three-dimensional environment, users become better at perceiving changes.

In the first study that aimed to measure mental rotation ability in three dimensions, Rizzo et al. (1998) developed a semi-immersive Virtual Reality application based on the figures in the Mental Rotation Test. They transferred the complete traditional 2-D MRT to the 3-D Virtual Reality environment. The authors described the stimuli as “hologram-like 3D objects floating above the projection screen”. With the Virtual Reality Spatial Rotation (VRSR) system the authors aimed to standardize the stimuli presented to the learners and precisely measure the responses. The system enabled them to observe the problem-solving processes of the learners better.

The VRSR was concerned with both measurement and rehabilitation of mental rotation ability. The study compared the VR-based MRT with the paper-based MRT. However, the whole procedure required the 40 participants to take both versions of the test twice within 2 hours. Although this was done to measure the effect of a

mental rotation training containing 100 items similar to the MRT items, the '*testing effect*' is likely to have affected the overall results.

Parsons et al. (2004) also used the VRSR to investigate the gender differences in paper-based and VR-based MRT performance. This system that contained stereo glasses and magnetic head and hand trackers could be defined as "*first generation*" Virtual Reality. The system allowed a trial-and-error approach as it proceeded to the next question when an object is rotated correctly. Because proceeding with the wrong answer was not possible, the authors used time and efficiency in task solutions as independent variables instead of mental rotation accuracy.

Although the authors expected to find performance differences in both test formats, they found that in the VR-based format female students scored no less than male students. This was interpreted as the possible process-driven effect of the dimensionality of the stimuli on the cognitive processes involved in mental rotation. Alternatively, students might have changed their approach to the mental rotation task based on dimensionality. According to Parsons et al. (2004), a 3-D version of the same stimuli is more complex than the 2-D version and therefore, induces more cognitive load on the learner. On the other hand, from an alternative viewpoint, it may be argued that as 3-D presentation provides additional visual information such as depth; it may help the learner to perform the rotation task more easily.

Kauffman et al. (2008) developed D-STAR, a testing as well as a spatial ability training tool in a VR environment. Whereas students were required to construct the answers actively as opposed to choosing among multiple choices, there was no time limit for completing the test. Also, the figures used in the application were relatively simple. Price and Lee (2010) used tasks designed by modifying existing items of spatial ability tests to compare performance in solving 2-D paper-based vs. 3-D Virtual-Reality based mental rotation tasks. A 3-D display was prepared by projecting stimuli on a GeoWall.

Neubauer et al. (2010) compared mental rotation tasks presented in 2-D screen and AR-based 3-D projector in terms of gender differences in performance. This study

employed a set of Shepard-Metzler figures as the stimuli as opposed to a complete mental rotation test. The 3-D testing environment led to higher accuracy and shorter response times in the tasks than the 2-D environment. The authors argued that 3D presentation of the stimuli ‘releases’ the information processing load for all individuals, but more strongly for females since, unlike the 2-D environment, their performance in the 3-D testing environment was not lower than that of males. Although the mode of presentation (2-D vs. 3-D) influenced female mental rotation performance, the effect size was low. The authors stated that their use of Augmented Reality lacked immediate feedback and was limited to the 3-D presentation of stimuli with no possibility of moving around objects or grasping them.

Developments in VR technologies enabled the transfer of the MRT into a VR headset, Oculus Rift (Foroughi et al., 2015). In this study, the effects of gender and the sense of presence on mental rotation ability were examined. A mild correlation was found between mental rotation ability and perceived presence. Nevertheless, using the keyboard for interaction with the HMD-based application might have influenced the perceived presence. Jeng and Liu (2016) developed a multimedia version of the same test which involves interactive 3-D test items. When compared to the static form of the computerized MRT, this interactive test reduced the gender difference in mental rotation ability by especially boosting female performance.

In a recent study, Guzsvinecz et al. (2020) compared the administration of 3-D spatial ability tests (MCT, MRT, and PSVT) applied in desktop-based and HMD-based VR environments. Real-time data about user actions were collected during testing. The study found that HMD-based testing led to better performance and diminished gender differences. In this study, the tests and the environments in which they were applied were compared whereas the three-dimensional tests developed were not used as a pre- and post-test for learning material.

Lochhead et al. (2022) developed the Immersive Mental Rotation Test (MRT) to examine the effect of dimensionality and background complexity in the virtual environment on mental rotation performance. Conducted remotely, they

administered MRT in Oculus Quest to participants who owned these particular glasses and observed them online. Importantly, they modified the original test choices by excluding the distractors to encourage mental rotation rather than piecemeal approaches. Both versions of MRT were delivered with the VR headset.

Literature in the last decade highlights the importance of measuring spatial ability in three-dimensional (3-D) environments. Up-to-date 3-D technologies may enhance quality or fidelity which can facilitate test performance in turn (Foroughi et al., 2015). Mixed Reality, which allows overlaying virtual objects onto the real world (Allcoat et al., 2021), can be a suitable environment for spatial ability testing. Such 3-D environments are likely to be used for measuring the effectiveness of state-of-the-art cognitive training applications. Tests administered in traditional environments are not compatible with learning experiences in immersive environments. There is a research gap in the measurement of mental rotation ability as it is dominantly measured using stimuli with 3-D effects in 2-D environments (paper, computer screen, etc.). Apart from the few studies reported above, mental rotation ability was dominantly measured using two-dimensional stimuli in previous studies. Additional studies including emerging technologies are needed to explore the effect of dimensionality on mental rotation performance.

The studies outlined above point out certain features for a 3-D immersive test: the majority of the reviewed studies employed simple stimuli for measuring mental rotation ability. It is recognized that the stimuli should induce an appropriate level of challenge for undergraduate students. Allowing user interaction, especially motoric manipulation could contribute to future studies. Also, appropriate time should be allowed between the test and training sessions.

2.6 Gender Differences in Mental Rotation Ability

Mental rotation is the spatial ability type in which the most salient gender difference is observed (Maeda & Yoon, 2016). In conventional mental rotation tests, males

typically outperform females. Whereas some argue that the performance gap is due to socio-cultural and environmental factors, others suggest that hormonal or neurological differences may be the reason. Nevertheless, unstandardized administrations of the tests (i.e., increasing or decreasing the time allocated in the instructions, excluding some of the test items) can result in different effect sizes that compromise the test validity. Especially when insufficient time is allocated the mental rotation performance of females is more likely to be affected negatively than that of males.

As far as three-dimensional testing environments are concerned, a few studies compared the mental rotation performance of two genders. Some studies found a gender difference in mental rotation performance in a VR environment (Kaufmann et al., 2008; Foroughi et al., 2015). On the contrary, whereas Parsons et al. (2004) and Toptaş et al. (2012) observed gender differences in the 2-D paper-based test, they indicated that the gender gap was not evident in the 3-D VR format. Jamil et al. (2019), Bell et al. (2018), and Moreau (2013) also reported that 3-D training diminishes the gender gap in mental rotation performance. Likewise, Neubauer et al. (2010) found that the superiority of male performance disappeared completely when three-dimensional models are used as stimuli and concluded that this is due to the released information processing load. Rafi et al. (2005) noted that although males still performed faster than females, no gender difference was found in terms of accuracy in the VR-based mental rotation training in their study. Arendasy et al. (2011) found that the 3-D presentation of stimuli developed by the authors benefited females more than 2-D representations and narrowed the gap between male and female performance.

Overall, it is possible to say that the evidence base of gender difference in mental rotation ability in 3-D environments is not as well-established as in 2-D. The fact that three-dimensional environments allow for motor manipulation may explain why this difference was not observed in these environments. Alternatively, the elimination of the “dimensionality crossing” problem may be the reason for enabling females to show their actual performance in 3-D mode.

Since the literature reports pronounced differences between the mental rotation abilities of males and females, the latter emerges as a disadvantaged group concerning many spatial ability-related careers. Ha and Fang (2018) and Chang et al. (2018) found that females benefited more than males from 3-D mental rotation training. Some comparison studies have shown that males show equal improvement in traditional learning and 3-D training environments (Rafi et al., 2005). Ha and Fang (2018) claim that 3-D touch-based training may help alleviate the prevalent gender difference in mental rotation ability reported in the literature. Yeh et al. (2014) reported that females who used a motion controller improved more than males.

Overall, the literature shows that the greater room for improvement in underachieving groups is more easily filled with such technologies. There are efforts for developing mental rotation training exclusively for females as they may have different learning needs in this domain (Alqahtani et al., 2017). If smaller gender differences can be achieved consistently with 3-D, training targeting females may become more prevalent. In this respect, a 3-D mental rotation training program that benefits females as much as males can be a step towards eliminating the considered difference.

2.7 Mental Rotation Ability Training in Three Dimensional Environments

Mental rotation tasks are challenging for most people since they place substantial demands on both storage and transformation functions (Lohman, 1996). Therefore, mental rotation ability takes considerable time and effort to improve. According to Uttal et al. (2013), mental rotation performance improves partly because learners become faster at rotating the object in their minds. Training for this ability can be of different durations, from supplementary activities for university-level courses covering a whole semester (Sorby, 2009) to targeted single sessions (Ariali, 2020).

Early mental rotation training interventions mostly employed methods and materials including paper-and-pencil, solid models, 2-D CAD software, and video games.

Studies aimed to improve mental rotation ability by using three-dimensional stimuli in various technologies such as brain-computer interfaces (Poor et al., 2011), tangible models corresponding computer graphics (Ha & Fang, 2013), computer-assisted drawing software (Erkoç et al., 2013) and robotics-based instruction (Gonzalez-Calero et al., 2019).

In recent years, few studies aimed to improve mental rotation ability in immersive three-dimensional learning environments. The effectiveness of these platforms was compared against their 2-D counterparts as well as physical model-based training (Kornkasem & Black, 2015). Cantero et al. (2012) noted that replacing the aluminum material with AR-based material could result in a more standardized and effective procedure. Similarly, better improvement in mental rotation ability was found using 3-D software than training with wooden blocks (Kornkasem & Black, 2015). A comparison between the learning effectiveness of desktop-based and HMD-based AR in mental rotation training revealed that cabled HMD may be perceived uncomfortable because it can interfere with user movement and inhibit the feeling of immersion (Martin-Gutierrez et al., 2011).

VR studies: Kozhevnikov et al. (2008) carried out research for understanding the effect of varying degrees of immersion on mental rotation performance. The authors used similar stimuli to Rizzo et al.'s VRSR in that it required judging whether the two Shepherd and Metzler-type figures are the same or different. With the counter-balancing technique, 16 participants took the 24-item mental rotation test in two-dimensional (desktop), non-immersive three-dimensional (anaglyphic glasses), and immersive three-dimensional environments (HMD). The authors report that the highest mental rotation performance was observed in the immersive three-dimensional environment. This superiority was explained in relation to the differing visual information and presentation capabilities of different environments. Different presentations lead to different 3-D images and 3-D transformation processes in the participant's mind. Due to the widened 'effective visual field-of-view, immersive environments encourage the use of a more 'ego-centric' frame of reference. Importantly, this type of reference is 'more reflective of real life' (Lee et al., 2016)

in the sense that it is used in everyday rotation activities. Thus, it is suggested that mental rotation studies using 2D computer screens might be insufficient for mirroring the real-life patterns occurring in natural 3-D environments. Recent studies proved that the tasks presented to the individual in a frame that can be taken as a reference (i.e. the computer screen) affect mental rotation performance (Bilge & Taylor, 2017). Therefore, environments that include both three-dimensional and realistic shapes can be effective tools for mental rotation ability training.

Rafi and Samsudin (2009) employed the 3-D interactive virtual environment, *Desktop Mental Rotation Trainer (iDeMRT)*, and compared it to training with 2-D printed materials. Using 3-D animations facilitated the construction and refining of mental models of rotations and the devising of the steps for correct rotation by the participants. The undergraduate students who used the iDeMRT could explore the environment, watch animations and receive feedback on their learning. The authors found that although this group did not improve in mental rotation speed, they did show greater improvement in mental rotation accuracy than the 2-D training group.

Alqahtani (2017) displayed one of the first attempts to go beyond the Shepard and Metzler figures and employed PSVT:R figures as a basis for the VR-based mental rotation training application. Specifically, she was interested in the use of different mental rotation strategies. In the training levels where the analytical strategy based on piecemeal analysis was applied, colored object surfaces and axis arrows were used. In the levels priming holistic strategy, original shapes without color were used. In this study, PSVT:R was not used as a measurement tool, and half of the test items were selected as training content. The implementation with 38 female engineering students illustrated the effectiveness of the VR training tool in improving mental rotation ability. Although students could rotate and navigate the 3-D figures with the desktop-based VR tool, the training could be improved by the flexibility and interaction opportunities that HMD-based applications entail.

Hu et al. (2017) developed a learning environment for training mental rotation ability with a 3-D multimedia approach. The authors applied 10 items from PSVT:R as a

pre-test and post-test and developed a training module by generating questions similar to the test items. The training module allowed students to rotate the test object manually while the reference object can be rotated synchronously with the test object. The 3-D controller allowed rotation in the x and y axes. The training was effective in improving mental rotation ability. The authors suggest that careful design of multimedia and interaction can reduce cognitive load and offer an embodied experience when engaging in a mental rotation task.

Ha and Fang's (2018) study employed a tool named *virtual and physical manipulatives* (VPM), that allows students to interact with physical manipulatives and observe the real-time changes in the corresponding on-screen virtual manipulatives (3-D models). A sensor board is attached to the physical manipulative and sends real-time orientation information to the virtual manipulative on the computer screen. This is an effective system that provides immediate feedback to manual manipulation actions from the screen and resulted in higher improvement in mental rotation performance for females. Immediate feedback can improve future mental rotation performance by decreasing errors (Rodan et al., 2016).

In another study, Molina-Carmona et al. (2018a) compared the effectiveness of desktop-based 2-D and HMD-based 3-D applications on the mental rotation performance of Multimedia Engineering Students. They used simple polyhedral 3-D models similar to the PSVT:R figures for training. The HMD-based training was found to be more effective than the desktop-based training which suggests that the degree of immersion can influence mental rotation training effectiveness. Nevertheless, the authors suggested that the use of more advanced devices such as Microsoft HoloLens could offer better immersion.

Lin and Yeh (2019) developed two different versions of VR-based mental rotation training: the first program enabled motion control using a controller for learners to rotate the 3-D objects from the Vandenberg and Kuse Mental Rotation Test and the second only allowed passive observation of the 3-D animated videos presenting the rotation of the same objects. The learning activities involved judging if the two

objects were the same or different. The motion-control program was found to be more playful, useful, and easier to use than the observation-only training program. However, improvement in mental rotation performance was not addressed in this study. The authors suggest the use of VR in mental rotation training for increasing motivation in female students while adjusting task difficulty for addressing male students' perceived playfulness.

Ariali (2020) developed a module for improving mental rotation ability with a virtual reality application in which hand movements are detected with Leap Motion. While the modified MRT test items were used and feedback was not given in the test part of this module, the training part focused on skill development by providing feedback. In the VR-based test unit, users could answer multiple-choice questions with hand gestures. The author found a correlation between the scores in paper-based and VR-based MRT.

AR studies: Studies that compare the effectiveness of 2-D training and 3-D AR-based mental rotation training (Lee et al., 2016; Omar et al. 2019) indicate that 3-D mental rotation training is more effective than traditional 2-D training. However, these studies employed less immersive AR devices such as desktop-based and mobile AR. Bell et al. (2018) have shown that their mobile game-based AR application is effective in improving mental rotation ability, especially for students with low spatial ability. Gecü-Parmaksız and Delialioğlu (2020) revealed that AR-based virtual manipulatives are more effective than physical manipulatives in improving preschool students' mental rotation ability.

Lee et al. (2016) argued for using 3-D rather than 2-D stimuli in mental rotation training programs for the elderly for both affective and cognitive reasons. They stated that using 3-D stimuli can be beneficial for reducing cognitive load and increasing interest during rotation tasks. Using a holographic projector that allows representation for multiple persons to view, their mental rotation system involved game-based activities for rehabilitating the mental rotation abilities of the elderly. A Leap Motion controller was used for recognizing participants' hand and finger

movements for performing rotations. The authors described this process as an ‘overt simulation’ of mental rotation. The 3-D training for the elderly led to higher accuracy and shorter response times than the 2-D training. However, it should be noted that their training was simplified by using only part of the MRT due to the participants’ conditions.

Roca-Gonzalez et al. (2017) found that using AR-based training is effective in improving a set of spatial abilities including rotation. Mobile Augmented Reality was used for teaching orthographic projection to engineering students and proved more effective than conventional 2-D methods in improving mental rotation ability (Omar et al., 2019). 2-D images on paper were used for projecting their 3-D representations using mobile Mixed Reality Applications (Tumkor, 2018). Learners without prior game or CAD experience improved in mental rotation scores the most after the implementation.

In their meta-analysis, Kaplan et al. (2021) found that the target population and the task being trained upon can influence whether an XR environment is an effective medium for training. Overall, the above research found that using 3-D environments is effective for fostering mental rotation ability regardless of the technology and target group used. The only exception is Adams et al. (2016) study which found that playing the game Portal for a short duration (75 minutes) was not sufficient for improving mental rotation ability. They argued that focusing on student creation within the game world to accommodate different perspectives could benefit spatial ability. Also, some studies suggest that 3-D mental rotation training is more effective than 2-D physical model and guidebook training (Yurt & Sünbül, 2012; Lee et al., 2016) and other traditional approaches (Rizzo et al., 1998; Rafi & Samsudin, 2009; Neubauer et al., 2010; Zander et al., 2016; Ha & Fang, 2018; Hoe et al., 2019; Kok & Bayaga, 2019; Kuit & Osman, 2021). On the other hand, two studies found 2-D and 3-D mental rotation training to be equally effective. Erkoç et al. (2013) showed that 2-D paper-based isometric drawing is as effective as 3-D CAD training in mental rotation ability development. Dokumacı Sütçü (2020) reported that 3-D computer-based spatial games were not superior to the original physical versions of these

games in improving mental rotation ability. However, these studies did not involve an immersive technology-based environment. Paruchuri et al. (2020) found that 3-D training is not more effective than 2-D and attributed this to denying free exploration in the 3-D VR environment. Considered together with the results of other studies reporting the superiority of 3-D environments, this implies that the effectiveness of 3-D systems stems from supporting views from multiple angles by allowing manipulation of the virtual objects. Nevertheless, the way people can switch between different angles is also important. While in PC-based interventions this is done by pressing buttons or dragging 3-D objects to see the other sides; in more immersive systems naturally walking around the object is possible.

Reviewing the studies that aimed to improve mental rotation ability in 3-D environments, we devised a training module for improving students' mental rotation ability using truly 3-D stimuli (i.e., closer to real life), employing an immersive Mixed Reality device, and allowing gesture-based interaction. Moreover, the effectiveness of this module is evaluated both with a traditional measurement tool and within the same MR environment.

2.7.1 Learning Content and Features of 3-D Mental Rotation Training Environments

There is a certain degree of agreement that mental rotation ability can be improved by supporting learners in constructing better mental representations (Kornkasem & Black, 2015; Dere & Kalelioğlu, 2020). Hence, it is critical to focus on cognitive processes involved in mental rotation. Moreau (2013) noted that 2-D and 3-D mental rotations entail different cognitive processes. The results of their study revealed that whereas 3-D training enhances performance in both 2-D and 3-D tasks, 2-D game-based training improves performance solely in 2-D tasks.

Desktop-based 3-D mental rotation training comprises various tasks, such as producing virtual 3-D models of physical models, generating 3-D objects using

isometric drawings (Martin-Dorta et al., 2008; Cantero et al., 2012), writing down the angle and direction of rotation before performing the rotation (Kornkasem & Black, 2015), viewing 3-D objects from different angles (Kadam et al., 2012), playing games in three dimensions (Moreau, 2013; Dokumacı Sütçü, 2020) and predicting alternative orientations (Jamil et al., 2019).

3-D desktop platforms support students in developing mental rotation ability by enabling synchronous rotation of reference objects and test objects (Hu et al., 2017), playing with physical manipulatives while observing the real-time changes in the corresponding on-screen virtual manipulatives (Ha & Fang, 2018), 3-D animations and visual aids such as colored surfaces (Wang et al., 2020). 3-D mental rotation training software facilitates multiple-angle views, easy manipulation of stimuli, and gradual presentation of rotations. These methods may enhance understanding by better visualization of the gradual conversion from one object orientation to the other. According to Samsudin et al. (2011) the ability to zoom in and out, twist, pan, and roll in the VR environment may lead to better visualization of objects. Alqahtani et al. (2017) addressed analytical and holistic mental rotation strategies by using color and visual aids such as axis arrows. Also, it is noted that 3-D environments allow participants to visualize rotations of 3-D objects and eliminate the unnecessary 2-D to 3-D transformational processes required in 2-D environments (Kauffman et al., 2008) which is called “dimensionality crossing”.

The methods employed in VR-based systems for improving mental rotation ability include interaction with 3-D virtual objects (Rafi et al., 2005; Ariali, 2020), construction of answers to rotation tasks (Kauffman et al., 2008), interactive animations (Wang et al., 2011) that provide a step-by-step illustration of the mental rotation process (Alpiste et al., 2019), game-based construction of 3-D models (Martin-Dorta et al., 2014), strategy teaching (Alqahtani et al., 2017) and consumption and creation of 360-degree videos (Baumgartner et al., 2022). There are VR-based interventions that entail material similar to standardized mental rotation tests (Rizzo et al., 1998; Ariali, 2020). Zhou et al. (2022) created a unique

system that uses shapes and letters to enable interaction between users and virtual objects in a desktop-based VR application.

Some research on VR-based mental rotation training compares different systems based on interactivity (Samsudin et al., 2011) and modes of delivery (Martin-Gutierrez et al., 2015); while others investigate their effectiveness against 2-D materials (Rafi & Samsudin, 2009), physical models (Yurt & Sünbül, 2012), computer training (Molina-Carmona et al., 2018a) as well as no training (Alqahtani et al., 2017). Interactive VR was found to facilitate transfer to drawing performance better than non-interactive 3-D or 2-D printed materials (Samsudin et al., 2011). Controlling the movements of to-be-rotated figures was found to be more effective than passively observing animations (Wang et al., 2011). Employing simple 3-D graphics, clear axis labels, and animated rotations, Flanders and Kavanagh (2013) effectively improved mental rotation performance while also enhancing self-confidence. Recent systems allow learners to explore each step in the mental rotation process corresponding to their manipulations (Yeh et al., 2014).

Some AR applications aim to improve mental rotation ability using game-based approaches. Lee et al. (2016) incorporated AR with 3-D holography to rehabilitate the mental rotation ability of the elderly with a task in which participants used gestures to turn a virtual key at certain angles to open a holographic chest. 3-D hologram use does not require wearing an HMD and allows simultaneous use by multiple participants. Underlining the inefficiency of common 2-D mental rotation training for older adults, the authors argued that holographic training would be helpful in both reducing cognitive load and increasing interest. Also targeting older adults, Hoe et al. (2019)'s system, ARSVT, incorporates 3-D animation with real-time motoric manipulation. Hoe et al. (2019) argued that AR is more beneficial for mental rotation than VR as it can provide spatial visualization information about the surrounding environment, which helps make accurate judgments about the shapes of mental rotation stimuli. Bell et al. (2018) developed a mobile game featuring various interactions for rotating, comparing, and folding 3-D objects. Using AR enabled the better representation of the rotation of 3-D objects around the axes.

Although there are self-development efforts for training (Hu et al., 2017; Ha & Fang, 2018), targeted interventions among desktop-based 3-D mental rotation training tools are few (Sanandaji et al., 2021). Unlike traditional computer software, VR-based mental rotation training mostly involves applications developed specifically for enhancing this ability. The effectiveness of interactivity was observed across studies. According to research, mental rotation ability is enhanced by the technological capabilities of VR for visualization and more valid representation as well as instructional scaffolds integrated into these systems. Similar to VR, AR-based mental rotation training mostly involves targeted training applications. The research aims at enhancing this ability by addressing student interest in game-based learning. AR supports mental rotation training by enabling intuitive manipulation (i.e., gesture-based) of high-fidelity objects in a real-world context. Specifically, AR-based interventions are used for the drawing tasks of Engineering students and the rehabilitation of older adults.

2.7.2 Representation Devices Employed in 3-D Mental Rotation Training

Representation devices used in 3-D mental rotation systems show great variation due to the perpetual technological advances of our age. In 3-D virtual environments, users can focus on learning objectives and training for specific tasks in realistic situations, without the need to learn how to navigate a complex user interface (Yeh et al., 2014). Early research in this area involved projection screens and stereo glasses (Rizzo et al., 1998; Neubauer et al., 2010) as well as stereoscopic screens (Wang et al., 2011). Computers (Marusan et al., 2006); tablets (Zander et al., 2016; Gecü-Parmaksız & Delialioğlu, 2020), and mobile phones (Omar et al., 2019) were preferred as they are ubiquitous tools. Desktop-based AR and VR systems employed immersive technology within the limitations of the screen (Rafi & Samsudin, 2009; Flanders & Kavanagh, 2013; Roca-Gonzalez, 2017; Hoe et al., 2019). HMD-based training systems allow a more immersive and flexible representation of 3-D stimuli (Kozhevnikov et al., 2008; Kauffman et al., 2008; Alqahtani et al., 2017; Molina-

Carmona et al., 2018a; Tumkor, 2018). Some of the different representation devices employed in 3-D mental rotation training are given in Figure 2.6.

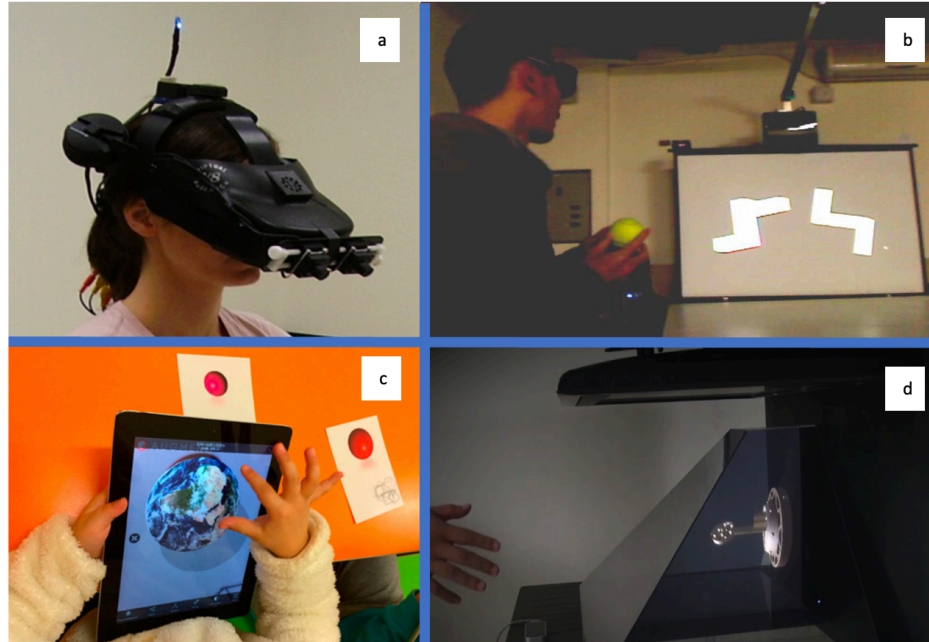


Figure 2.6 Representation devices used for 3-D mental rotation training: a) Head Mounted Display (Kozhevnikov et al., 2008), b) Projector screen (Wang et al., 2011), c) Tablet (Gecü-Parmaksız & Delialioğlu, 2020), and d) Holographic Display (Lee et al., 2016)

Virtual-Reality-based mental rotation training comprises tools with different representational and immersive capabilities including computer screens, stereoscopic displays, projector screens, and HMDs . AR-based training systems have been developed in the form of desktop-based and tablet-based applications (Gecü-Parmaksız & Delialioğlu, 2020; Thornton & Lammi, 2021), holographic displays (Lee et al., 2016), AR books (Roca-Gonzalez et al., 2017; Danakorn Nincarean et al., 2019), low-end and high-end HMD-based applications (Tumkor, 2018) and mobile applications (Bell et al., 2018; Omar et al., 2019; Gomez-Tone et al., 2020). Particularly, the 3-D holographic display employed by Lee et al. (2016) is a unique way of representation due to its ease of use by multiple persons. Different technologies offer different degrees of immersion and different ways of user-system interaction.

2.7.3 Manipulative Types Employed in 3-D Mental Rotation Training

By providing necessary information such as distance and volume accurately and through active interaction with life-like objects, 3-D training can overcome the limitations of 2-D representations (Omar et al., 2019). Instead of physical manipulatives, virtual manipulatives are used for technology-based 3-D mental rotation training. The use of virtual manipulatives is more effective in enhancing the mental rotation ability of preschool students than physical manipulatives (Yurt & Sunbul, 2011; Gecü-Parmaksız & Delialioğlu, 2020). Specifically, allowing children to engage with virtual manipulatives helps raise student interest and supports spatial cognition. Recently, the integration of concrete and physical manipulatives allowed exploring how rotating a real-world object changes the corresponding computer graphics in real-time (Ha and Fang, 2018). AR use was suggested to standardize stimuli as opposed to using physical stimuli (Cantero et al., 2012).

2.7.4 Interaction Devices Employed in 3-D Mental Rotation Training

A large variety of interaction devices and techniques were employed in 3-D mental rotation training. Mouse w/o keyboard was the most used input device due to ease of use and familiarity (Marusan et al., 2006; Rafi & Samsudin, 2009; Flanders & Kavanagh, 2013; Yurt & Sünbül, 2012; Roca-Gonzalez, 2017; Tumkor, 2018; Molina-Carmona et al., 2018). Various tracking devices were employed such as hand-held trackers (Wang et al., 2011), data gloves (Alqahtani et al., 2017), head trackers (Molina-Carmona et al., 2018a), and magnetic trackers (Yeh et al., 2014). Wireless pens (Kauffman et al., 2008), joysticks (Chang et al., 2020), and touchscreens (Gecü-Parmaksız and Delialioğlu, 2020) were also used for interaction. Ha and Fang (2018) used a physical manipulative with an integrated sensor board that sends real-time orientation information to the virtual manipulative.

Gesture-Based Interaction: Parsons et al. (2004) suggested that “the motor system is simply an output device for cognition”. Wiedenbauer and Jansen-Osmann (2008)

emphasized the processes common to manual rotation and mental rotation. Therefore, practicing manual rotation tasks can benefit mental rotation performance. Mental rotation ability can be improved by manual rotation training. This illustrates that motoric involvement may facilitate the mental rotation processes. Similarly, Gardony et al. (2014) argued that physical rotation training can improve mental rotation ability and guided participants to use a holistic rotation strategy as opposed to piecemeal strategies. Therefore, it might be useful to employ hand gestures for motoric involvement. Indeed, using gestures was found to support performing spatial tasks (Zander et al., 2016). In this study, a tablet-based application allowed manual manipulation of virtual mental rotation stimuli using the Arcball technique. This technique entails mapping 2-D touch input onto a virtual sphere that surrounds the stimuli. This mobile application was more effective in enhancing mental rotation performance and decreasing response time than a paper-based equivalent.

In a study comparing interaction devices in the rotation of virtual objects in Augmented Reality, Reifinger et al. (2008) found that gesture recognition, displaying the immediate reaction of the object to the individual's movements; was the fastest way of interaction and induced lower cognitive load than the other options of interaction. Gesture-based interaction can support users inexperienced in AR to familiarize themselves with the learning environment more easily. On the other hand, the probability of higher physical load should be considered as this type of interaction requires making head and arm movements when students perform gestures. Some of the different representation devices employed in 3-D mental rotation training are given in Figure 2.7.

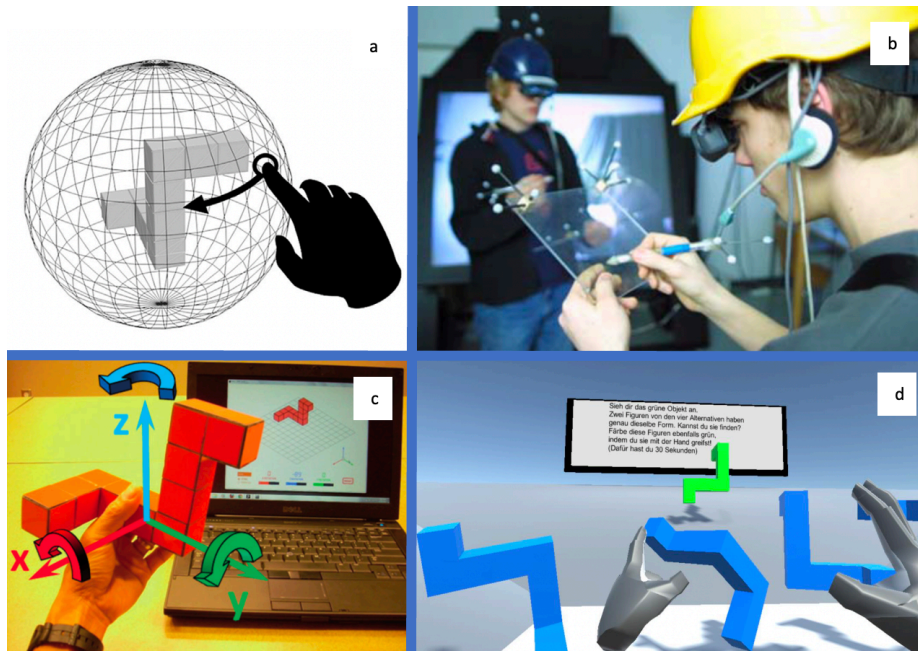


Figure 2.7 Interaction devices used for 3-D mental rotation training a) Touchscreen (Zander et al., 2016), b) Wireless pen (Kauffman et al., 2008), c) Virtual Physical Manipulative (Ha & Fang, 2018), and Gesture-based Interaction (Ariali, 2020)

In recent studies, gesture recognition has become prominent as an intuitive way of interaction (Lee et al., 2016; Tumkor, 2018; Hoe et al., 2019; Ariali, 2020). Zander et al. (2016) argue that gesture-based interaction contributes to spatial problem-solving by offloading information to facilitate the mental rotation process. In Hoe et al. (2019), participants used gestures to make 3-D virtual objects fall through a hole in the virtual floor. As seen in Table 2.1, although technological advances have introduced new input methods, earlier solutions such as the mouse and keyboard are still largely used due to their low cost, ease of use, and familiarity. Recent input devices carry concerns regarding user control, intuitiveness, and lowering cognitive load.

Table 2.1 Input devices used in 3-D mental rotation training

Input Device	Study
Mouse w/o keyboard	Marusan et al. (2006), Rafi and Samsudin (2009), Flanders and Kavanagh (2013), Yurt and Sünbül (2012), Roca-Gonzalez (2017), Tumkor (2018), Molina-Carmona et al. (2018a)
Hand-held trackers	Wang et al. (2011), Ha and Fang (2018), Yeh et al. (2014)
Data Gloves	Alqahtani et al. (2017)
Head Trackers	Molina-Carmona et al. (2018a)
Wireless Pen	Kauffman et al. (2008)
Joystick	Chang et al. (2020)
Touch-based Interaction	Gecü-Parmaksız and Delialioğlu (2020), Zander et al. (2016)
Gesture-based Interaction	Lee et al. (2016), Tumkor, (2018), Hoe et al. (2019), Ariali (2020)

2.8 Immersive Learning Environments and Presence

Immersion is the individual's subjective perception of having a realistic and comprehensive experience. Different environments can enable different degrees of immersion (Dede, 2009) which has implications for the user's cognitive processes. Immersion can be increased by "increasing the range of visual stimuli, such as the amount of visual field engaged and the fidelity of visual displays; providing three-dimensional spatialized sound, such as sound that is fixed around a moving body; using interfaces with a tight sensorimotor coupling for which changes in sensory stimulation respond naturally to body movements, such as head, hand, and other motions; and through other techniques that increase the sensorimotor realism of objects and settings in the virtual environment" (Bohil et al., 2011). Along with audial and visual immersion, fully immersive systems allow gesture-based interaction which is more intuitive and realistic than the keyboard or tangible user interfaces.

Desktop-based VR/AR environments are considered as low immersion while settings involving HMD are classified as high immersion (Makransky et al., 2019). In desktop-based applications, mental rotation processes are referenced by the frame formed by the computer screen (Bilge & Taylor, 2017). On the other hand, through the immediate feedback given to the head movements Head Mounted Display (HMD) allows a mental rotation process in which the user's eye movements are the reference as in real life rather than the frame that the computer screen forms. Immersive 3-D environments can update images when the head moves which allows a *retina-centered* frame of reference as opposed to *the scene-based* frame of reference users employ in 2-D and non-immersive 3-D environments (Kozhevnikov et al., 2008). Therefore, HMD involves more senses in the testing and learning experiences when compared to desktop-based VR applications.

According to Kozhevnikov and Garcia (2011), the most effective environments for spatial ability training and transfer to real life are immersive virtual environments. Compared with 2-D or 3-D non-immersive environments, Marunic and Glazar (2013) suggested that 3-D immersive virtual environments facilitate more efficient spatial ability training. Furthermore, Chang et al. (2018) reported that females expressed greater enjoyment and satisfaction in an immersive VR mental rotation training system. Immersiveness and interactivity were facilitated by physical motion control in this training. Molina-Carmona et al. (2018b) found that when compared to desktop-based training, HMD-based training is more effective in training mental rotation ability. While smartphones were used for easy implementation of VR technology, the authors noted that the limited effect on mental rotation performance in their VR-based training could be improved by using devices that increase the sense of immersion.

2.8.1 Feeling of Presence in 3-D Mental Rotation Training

Because of the cognitive processes caused by the immersion of the body and the senses of the user, the sense of being in the simulated environment can be increased,

which is called presence (Berki, 2019). In other words, the sense of presence arises from the immersiveness of the environment and the possibility of interaction. Although presence can sometimes be viewed as a by-product of immersion, it is rather a subjective concept that refers to the sense of being in a virtual environment.

Mikropoulos and Natsis (2011) argued that the feeling of presence is important as it enhances 'first-hand' learning experiences. It is assumed that the individual's perceptions of presence can influence the processing of surrounding spatial information. The degree of the sense of presence may depend on both technical variables and individual characteristics (Coxon et al., 2014). Immersive environments create a strong sense of presence with realistic images and thus contribute to the user's understanding and learning of spatial tasks more easily (Dan & Reiner, 2017). Head-mounted displays provide better spatial presence by allowing the field of view to be actively changed, rather than watching content statically (Chang et al., 2020). The use of a Head Mounted Display can increase the perceived presence. HMD-based VR was found to be more effective in improving mental rotation than desktop-based VR (Molina-Carmona et al., 2018a). There is a study that found a correlation between mental rotation performance and perceived presence (Foroughi et al., 2015). On the other hand, Coxon et al. (2014) could not find a relationship between mental rotation performance and presence.

2.9 Cognitive Theories Informing the Study

2.9.1 Cognitive Load Theory

Cognitive Load as a construct is defined as 'the load that performing a particular task imposes on the cognitive system' (Sweller et al., 1998: p.266). It is considered to have three sub-dimensions: mental load, mental effort, and performance. Mental load is imposed by the nature of the task or the environment whereas mental effort involves the cognitive resources that are allocated by the learner for understanding the task (Paas & Merrienboer, 1993).

According to Cognitive Load Theory, there are three separate sources of cognitive load involved in information processing: intrinsic cognitive load, extraneous cognitive load, and germane cognitive load. Intrinsic cognitive load is related to the inherent complexity of the learning material. Therefore, it is not possible to control it with instructional design decisions. Germane load refers to activities that lead to schema acquisition. In other words, it involves the effort related to information retrieval from long-term memory to working memory and deeper processing. Continuous refinement of schemas leads to performance improvements in the targeted skill. As learners gain schemas, the working memory load imposed on them in this particular domain is lowered. By definition, these two types of cognitive load are beneficial for learning. On the other hand, extraneous cognitive load refers to demands that are not essential to understanding the learning material. Hence, this type of cognitive load negatively affects learning and can be reduced by changing the way of presenting information and required learner actions to improve learning (Leahy et al., 2003).

Since the capacity of working memory is severely limited, instructional design decisions should be made for reducing extraneous processing (i.e., extraneous cognitive load), managing essential processing (i.e., intrinsic cognitive load), and fostering generative processing (i.e., germane cognitive load). Such endeavors require attention management: withdrawing learner attention from processes not relevant to learning while directing it to aspects related to learning (Sweller et al., 1998).

Measurement of cognitive load is not a straightforward process: High mental load can be compensated by making a higher mental effort on the learner's side to ensure a specific performance level. Based on the assumption that people can assess their cognitive processes and report on a numerical scale, subjective indices rely on asking students to rate the difficulty of the material via questionnaires or interviews.

2.9.1.1 Cognitive Load in Mental Rotation Training and Immersive Learning Environments

Cognitive load refers to the burden of performing a task on the cognitive system (Sweller et al., 1998). Mental load, one of the two components of cognitive load, is more task-oriented and indicates the load required by the task itself. Individual-oriented mental effort is the cognitive resources that a person can devote to the demands of the task. If there are multiple elements interacting with each other, cognitive tasks may expose the student to excessive cognitive load.

Thinking processes in mental rotation place high demands on cognition by requiring encoding a visual stimulus, constructing a visual image in working memory, transforming the image, and confirming the outcome by comparing the visual stimulus to an image in the working memory (Kornkasem & Black, 2015). Literature often mentioned that improving mental rotation ability is difficult and may require long intervention periods. Therefore, lowering cognitive load during training is important and an easier introduction can be helpful in affective as well as cognitive aspects of learning.

Immersive 3-D technologies receive criticisms about increasing cognitive load due to the richness of visual data. Few studies were conducted on three-dimensional mental rotation training environments and revealed that they do not create a higher cognitive load than their two-dimensional counterparts. Lee et al. (2016) reported that the cognitive load of 3-D AR-based training is significantly lower than that of 2-D mental rotation training. According to the authors, gesture-based interaction reduces working memory load and improves the internal computation of spatial transformations in mental rotation. Reit (2020) stated that demonstrations that can be experienced with physical movements reduce cognitive load. The authors argued that AR technology could allow users to explore a spatial problem rather than just visualize it, thus allowing more cognitive resources to be devoted to solving the problem. Hoe et al. (2019) determined that AR training created a lower cognitive load than the 2-D environment thanks to motion-based interaction. In their study on

astronomy learning, Sun et al. (2019) argued that especially for low spatial ability learners, the VR environment was more effective in reducing the cognitive load and improving learner performance. Zander et al. (2016) stated that a tablet-based 3-D application and a paper-based tool expose students to similar levels of cognitive load. However, the 3-D environment in this study is not immersive. While expecting AR application to induce lower cognitive load than 2-D training, Elford et al. (2022) found these two conditions were equal in terms of cognitive load and argued that the advantage brought by three-dimensional representations was counterbalanced by the gamification elements in the intervention that might have increased cognitive load.

When taking a 3-D mental rotation test with novel technology, participants may become overwhelmed if they are not given sufficient time and practice to familiarize themselves with the environment. Additionally, depth cues should be used properly for mediating cognitive load in stereoscopic representations (Price and Lee, 2010). On the other hand, 3-D presentation of mental rotation stimuli provides test-takers with additional visual information to make judgments. Neubauer et al. (2010) interpreted that 3-D presentation of stimuli ‘releases’ information processing load for all individuals, but more strongly for females.

2.9.2 Cognitive Fit Theory

Different representations containing the same information can present that information in fundamentally different ways. Each task requires different types of representation. Since humans have limited information processing capacity, problem-solving can be more effective by reducing unnecessary complexity. The mental representation in cognition is a joint formulation of problem representation and problem-solving tasks. In their theory based on information processing theory, Vessey (1991) suggested that for enhanced performance, there should be a cognitive fit between the information provided by the representation and the information required by the task at hand. When problem-solving aids (tools, techniques, and problem representations) facilitate the necessary task strategies, the complexity is

reduced and increased efficiency and effectiveness in problem-solving can be achieved. For spatial tasks, they prioritize graphs over tables as they will present spatially related information and lead to faster and more accurate problem-solving.

Although Vessey viewed the ways of representations within the scope of graphs vs. tables, they maintained that cognitive fit is not restricted to this duality. In any classification, information characteristics of a particular task should be identified and appropriate problem representations should be sought. Visual representations can take various forms in terms of fidelity. Dimensionality is one aspect that can dramatically change the nature of problem representation. Van der Land et al. (2013) indicated that 3-D virtual environments facilitated more effective learning than 2-D information displays. Particularly, they note that a 3-D environment can facilitate processing visual information through realism, immersion, and interactivity of the visual cues. For solving spatial problems, 3-D immersive environments can result in a better match of problem representation and task.

2.9.3 Situated Cognition

In their well-established theory, Brown et al. (1989) argued that “knowledge is situated, being in part a product of the activity, context and the culture in which it is developed and used”. Knowledge is not separable from the activity in which it is developed or deployed. Situations should be created in which people engage in authentic activity (i.e., meaningful and purposeful) whereby they use tools for learning in a way that is true to the real world.

2.9.4 Theories of Visual Imagery

During the perception of an object, the brain creates internal representations of objects and events using the visual information captured from the surroundings (Ganis, 2013). This internalization process is employed in creating better (or more complete) mental models and improving spatial ability (Kornkasem and Black,

2015). Visual mental imagery enables humans to store visual representations of these properties in long-term memory and retrieve and manipulate these representations when they are not physically present (Kosslyn et al., 2006). People can reorganize existing visual information for extracting new information which makes visual imagery very important for several domains.

There are two fundamental groups of theories of visual imagery. *Depictive theories* argue that visual images are encoded in a specific way to mentally represent the shape and spatial relations within visual objects or events. On the other hand, *non-depictive (propositional) theories* do not distinguish visual representations from other representations employed in thinking processes and deny the role of visual aspects of imagery in information processing. *Propositional* and *depictive* representations can be ideal for the brain to use in different situations.

2.10 Summary

The literature indicates that there were some attempts to improve spatial ability, specifically mental rotation ability with the use of 3-D environments. These environments highly vary in terms of the way of interaction and representational capabilities. Along with CAD software and games that are desktop-based, there are a few mobile applications and AR/VR modules using HMDs. Most of the studies targeting mental rotation ability using three-dimensional content addressed engineering students. However, this type of spatial ability is also critical for academic success in other disciplines. Therefore, it is important that both accurate identifications of students' spatial abilities can be done and that these abilities can be enhanced with short and targeted training sessions.

Mental rotation ability is commonly measured using pen and paper tests containing two-dimensional drawings that represent three-dimensional objects. On the other hand, using 3-D stimuli with a similar appearance to physical objects may influence mental rotation performance. A few prior works transferred mental rotation ability

tasks or tests into a three-dimensional environment before. However, these were done only for comparison purposes. To our knowledge, there is not a study that employed a complete mental rotation test to measure mental rotation ability in a three-dimensional environment to investigate the effectiveness of a 3-D spatial ability training module.

The literature review guided the researcher to design a Mixed Reality-based mental rotation ability training module and develop it with the help of expert software developers. Furthermore, the study aimed to demonstrate the effectiveness of this training with both two-dimensional desktop-based and three-dimensional Mixed Reality-based tests.

CHAPTER 3

METHODOLOGY

In this chapter, the research methodology and the research questions are presented. Information about the study design, usability and pilot studies, the procedure, the instruments employed in this study, and data analysis are provided. Comprehensive accounts of the design and development processes of the test and training modules are presented. Considerations about reliability, validity, and ethics are presented.

This study aims to measure and improve the mental rotation ability of undergraduate students in three dimensions using Mixed Reality technology. For this purpose, we transferred the “Purdue Spatial Visualization Test: Rotations” (PSVT:R) into a three-dimensional environment and administered it to undergraduate students using MR technology for measuring their mental rotation ability. Additionally, we developed an MR-based mental rotation training tool based on previous studies. We investigated the effect of the dimensionality of the mental rotation stimuli on performance. Taking into account the ability of students to learn spatial strategies, the MR-based training module was developed in which holographic figures designed for different levels of difficulty were used. This module aimed to increase success in challenging mental rotation tasks. Since it is the only research method for establishing cause-and-effect relationships, we employed the experimental method (Gay et al., 2009).

3.4 Research Questions

This study attempts to answer the following research questions:

- 1) What is the effect of the measurement environment on mental rotation performance?

- a) What is the effect of dimensionality of the test stimuli (2-D vs. 3-D) on mental rotation performance?
 - b) What is the effect of the dimensionality of the test stimuli (2-D vs. 3-D) on cognitive load?
 - c) Is gender difference observed in students' mental rotation performance in the test environments?
 - d) How does stimulus complexity affect mental rotation performance in the 3-D test environment?
- 2) Can mental rotation ability be improved with a Mixed Reality-based training application with 3-D content?
- a) Does the 3-D mental rotation training lead to a difference between male and female mental rotation ability improvement?
 - b) Does mental rotation ability improvement remain the same for different levels of stimulus complexity?
 - c) Is there a relationship between the feeling of presence and mental rotation ability improvement in the 3-D training environment?
 - d) Is there a relationship between cognitive load and mental rotation ability improvement in the 3-D training environment?
- 3) How are the students' mental rotation experiences in the three-dimensional training environment?

3.5 Study Design

This study investigates the research questions using a mixed-method research methodology. In the quantitative part, it examines whether there is a performance difference between the two-dimensional traditional mental rotation test and the three-dimensional test transferred to the Mixed Reality environment. In addition, the study

investigates the effectiveness of a 3-D mental rotation training program in terms of individual differences and stimulus complexity. In the qualitative part, user experience in the new training environment was explored. The quantitative research questions were answered using a pretest-intervention-posttest experimental design. The qualitative research question was answered using semi-structured interviews and researcher observations. The research design is elaborated on in the next section.

3.5.1 Mixed Method Design

The mixed method research design procedure entails the use of both quantitative and qualitative methods to achieve a clearer understanding of the research questions than either method by itself (Cresswell, 2015). The embedded design is a type of mixed method design in which there is a dominant method and a secondary method for answering the research question (Doyle & Brady, 2009). Since we emphasize the quantitative part and describe the qualitative part as a supportive method, the embedded approach to mixed method research design was adopted in this study.

Among the reasons for undertaking a mixed method approach are answering different research questions that call for different methods and explaining data generated in a study using different approaches (Doyle & Brady, 2009). This study addresses three main research questions and requires collection of both qualitative and quantitative data for answering them. Therefore, mixed method research design is used in the present study. For Research Questions 1 (*What is the effect of the measurement environment on mental rotation performance?*) and 2 (*Can mental rotation ability be improved with a Mixed Reality-based training application with 3-D content?*), we collected quantitative data using standardized tests, scales and questionnaires before, during and after the intervention. For Research Question 3 (*How are the students' mental rotation experiences in the three-dimensional training environment?*), qualitative data was obtained in the form of semi-structured interviews and observation notes. Qualitative data collection followed the

quantitative data collection. The research design employed helps understand how and why, is (or is not) the mental rotation training in the present study effective.

3.5.2 Variables of the Study

The independent variables of this study are the dimensionality of the stimulus (2-D vs. 3-D), gender, stimulus complexity, and sense of presence when measuring mental rotation ability. The dimensionality variable has two experimental conditions: Traditional Two-Dimensional PSVT:R (2-D PC) and Three-Dimensional PSVT:R (3-D MR). The dependent variables are the mental rotation test (PSVT:R) scores applied as a pre-test and post-test, and cognitive load. The variables of this study are seen in Figure 3.1.

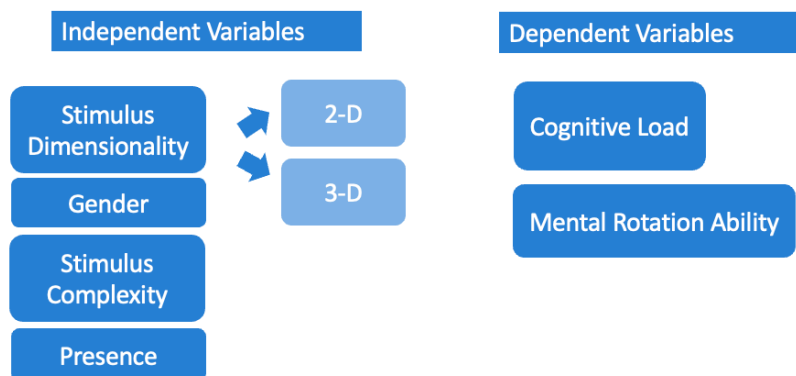


Figure 3.1: Variables of the Study

Since mental rotation is the type of spatial ability in which the greatest difference between genders is observed, it has been examined whether there is a difference between females' and males' improvement when they receive three-dimensional training for this ability. PSVT:R, which is used as a measurement tool, is unbiased for comparison between genders (Maeda & Yoon, 2016).

Considering the COVID-19 pandemic conditions, the participants were chosen among the students of Kastamonu University, which is the institution where the

researcher can easily access participants. The socio-economic status of the participants is not very high. As an indicator of the socio-economic status, only one in four participants' parent(s) has a bachelor's degree which is an indicator of the socio-economic status.

3.6 Participants

59 undergraduate students (12 in the pilot study) from a Turkish university participated in this study. This university was selected for its convenience as the researcher works at the institution. Students came from various departments of the university including Mathematics Education, Computer Engineering and Counselling. Socio-economic status of the students is not particularly high. More information about the sample demographics is provided in Table 4.1.

The convenience sampling method was employed in which the volunteers who had time available participated in the study. In one instance, a foreign student volunteer was excluded from the study as they had difficulty understanding the instructions. Since the study required five separate measurement and training sessions that require one-to-one interaction between the researcher and the participant, the number of participants was determined in this way.

Participants were mostly chosen from freshmen students with an average age of 19 since they take an Information Technology course that semester. The researcher spoke to them before the lessons to briefly introduce Mixed Reality technology and explain the study. Then volunteers joined the study by filling out an online form. 25 volunteers were included in the study for each testing condition (2-D online and 3-D Mixed-Reality PSVT:R) to make a total of 50 participants. 3 participants could not complete the participation due to health reasons and other responsibilities emerging during the course of the study. Their data was not included in the analysis. The final number of participants in the main study is 47. Students were randomly assigned to one of the testing conditions. Nevertheless, as there were more females

than males among the departments participating in this study, gender ratio between groups was retained.

3.7 Usability and Pilot Studies

Before the test and training module development were completed, a usability study was conducted with 5 participants. The researcher observed how they made sense of the new environment and adapted to it. Participants were probed to express their thoughts while they were using the module. With the permission of the participants, these sessions were video recorded. The researcher then watched these records to understand how they interacted with the headset and check if they performed the gestures easily in the way intended.

After the development was completed, a pilot study was conducted with 12 students to fine-tune the experimental procedures and instruments. This study involved completing the whole research procedure with the participants and obtaining feedback with the following interview. Specifically, technical issues regarding data collection were handled. The sequence and required average time for each step in the procedure were checked. Also, the participant familiarization process with the MR headset and the glitches in the interface design was elaborated. Accordingly, some revisions were made to the MR measurement tool and training module. For example, the rotation buttons were re-designed to be visually more realistic and easy to understand. In addition, taking into account the participant comments stating that taking the 30-item post-test immediately after the 3rd level of the training was exhausting, we decided to conduct the post-test a few days after the end of the training.

Expert judgments were received from specialists in the fields of Mathematics and Instructional Technology about the modules through face-to-face/online meetings and in written form. Depending on the physical distance between the expert and the researcher and expert availability, experts either used the MR headset in person,

watched the researcher using the application during an online meeting, or watched videos of the application in first-person view. In line with the comments, items were added to the demographic questionnaire, the scoring system in the training module was revised, the audio narrations were simplified, the rotation animation speeds were re-adjusted, the interface was cleared of some redundant elements, and changes were made in the design to use the three-dimensional environment more efficiently. The final version of the Mixed Reality-based application was developed according to the insights from the pilot study and expert opinion. Additionally, these two means were used to verify the validity and reliability of all instruments used in this study.

3.8 Procedure

The experiment was conducted in a technology lab at the university. Since the training tool is for individual use, the training levels and measurements were carried out in one-by-one sessions. Before coming to the sessions, the researcher asked participants to bring and wear their prescribed optical glasses or contact lenses (if any) so that they could use the application with corrected vision.

An experimental checklist was prepared for standardizing the procedure for the sample. Firstly, the researcher explained the aim of the study to the individual and gave them the consent form to sign and return for voluntary participation. Next, a demographic survey containing 15 items was administered to every volunteer. Before using the MR headset, students were instructed to inform the researcher in case they feel side effects such as motion sickness or dizziness so that the experiment can be interrupted. Also, participants were encouraged to express their need for rest. Since direct sunlight or bright environments may cause poor visibility, lighting was adjusted carefully for achieving an accurate representation of the 3-D content for all participants. The researcher then gave general instructions about the experiment and answered questions.

As the technology used is likely to be new for most of the participants, pre-training is necessary for minimizing effects related to novelty. Also, multiple sessions may help the novelty effect wear out. With this aim, a brief tutorial was completed in which participants learned how to navigate during HMD use and engaged in activities to familiarize themselves with the MR headset before taking the test. We demonstrated *click* and *airtap* hand gestures that are used to interact with the headset to the students. Airtap involves pointing the index finger to the ceiling and tapping it down quickly rising back again (Figure 3.2). We showed participants how to position their arms and elbows for airtap without feeling fatigued.

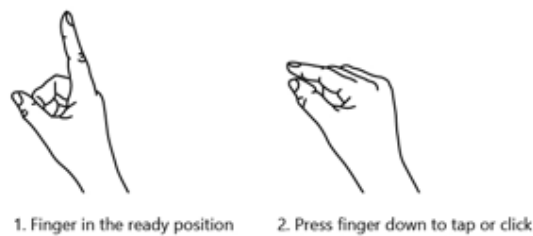


Figure 3.2: Airtap Gesture (<https://docs.microsoft.com/th-th/dynamics365/mixed-reality/guides/hl1>)

Before taking the test or training with the headset, tasks such as pressing holographic buttons closely and remotely, moving, resizing, and rotating objects, and navigating and calibrating the holographic operating system were carried out using the Microsoft Tips application. Eye calibration was performed before each session with the goggle, enabling the participant to have a more comfortable experience by accurately displaying holograms and tracking hand movements. Only when they are confident with the technology, students proceeded to the test. Figure 3.3 shows a participant taking the 3-D PSVT:R.

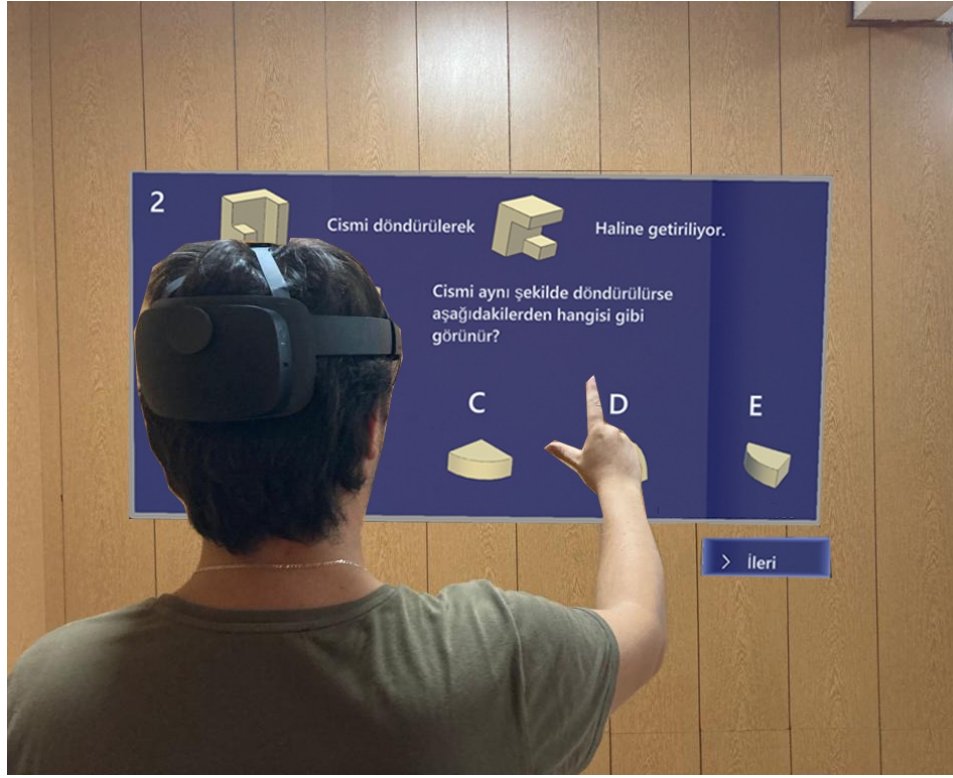


Figure 3.3: Taking 3-D PSVT:R on HoloLens 2

The flow of the study is shown in Figure 3.4. Each of the 47 undergraduate students took either the 2-D desktop-based mental rotation test or the 3-D MR-based mental rotation test. By wirelessly connecting the MR headset to a PC monitor, the researcher was able to observe the test process synchronously. She was present in all sessions for solving technical problems, providing instructions to participants, and taking thorough observation notes to understand the behaviors highlighted in the training experience.

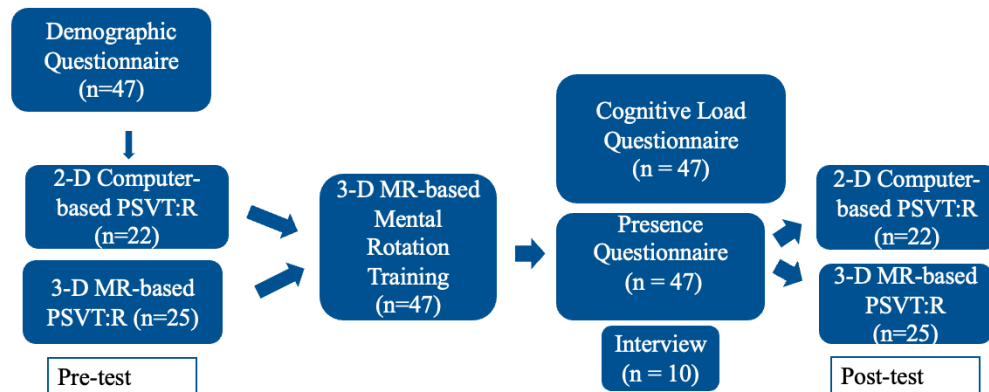


Figure 3.4 Flow of the study

For answering Research Question 1a, “What is the effect of the dimensionality of the stimuli used in mental rotation ability?” randomly selected half of the students took the computer-based 2-D version and the other half took the 3-D MR headset version. To control for gender, the same number of male and female participants were selected for the 2-D and 3-D groups. Test items in the two test versions are identical in all aspects (i.e., object, orientation) except for the testing environment.

Both versions of the test begin with two sample questions. For answering the two-dimensional computer-based test, participants used a mouse. In the three-dimensional condition, participants marked their answer choices using the '*airtap*' movement described earlier. The figures in the test items were displayed on a computer screen in the two-dimensional test. In the 3-D version, the test was displayed on a 53x105 panel 1.5 meters away from the user. The panel was fixed at this distance as participants could see the whole panel without moving their heads. The virtual objects in the test items were sufficiently large for perception and appeared to be ‘pinned’ on the air. It is possible to go closer or farther away from and walk around the holographic objects and view them from different angles in the 3-D test module. However, for this study, these actions were not allowed during the test as they could give an unfair advantage to the 3-D test-takers. For the same reason,

we did not enable rotating objects to try answers. With this design, we aimed to understand the effect of stimulus dimensionality on mental rotation performance.

Practice questions in the 3-D test involve written as well as audio instructions. Participants answer the questions using hand gestures recognized by the sensors capturing hand movements within a particular range of motion. The choice air-tapped by the participant turns orange to show that it is selected. Then, the participant air-taps on the Next button to proceed to the next question.

In both versions of the test, participants can answer questions directly by clicking on the objects that contain the choices of the question. Participants are re-directed once to the questions they skipped after the final question of the test. If they still do not wish to answer these questions, they may finish the test. It was found that the tasks presented to the individual within a reference frame can affect mental rotation performance by changing how they perform the rotations (Bilge & Taylor, 2017). Therefore, no frames were used for isolating separate test choices.

After the pre-test, a cognitive load scale Lee et al. (2016) was applied to the students. All participants used the three-dimensional mental rotation training system prepared in the Mixed Reality environment. Since there is only one MR tool available, the students received this training one by one. A technology lab with sufficient free space that enables students to navigate around the virtual shapes, was used for the training. While the time spent by the participants in the training varied between 30-74 minutes, 3 levels were completed in an average of 45 minutes. Each level was completed on a separate day.

Immediately after the completion of the three levels in the educational environment, a presence questionnaire (Witmer et al., 2005) was applied to the student to obtain their fresh opinions on the subject. Next, the cognitive load scale for the training was applied. Afterward, on a separate day, the participants took the post-test in the same environment followed by the cognitive load scale for testing. At the end of the application, a semi-structured retrospective interview was conducted with 10 participants. Interviewees were selected to be representative of the sample and reflect

the variability in terms of gender, pre-mental rotation ability, and other characteristics.

3.9 Apparatus

In this study, a Mixed Reality headset, Microsoft HoloLens 2 was employed for testing and training mental rotation ability (Figure 3.5). Microsoft HoloLens 2 employs the Windows 10 Holographic operating system. It supports six degrees of freedom that allow users to move their bodies as well as their heads. In addition to holographic imaging and spatial mapping, the device can recognize hand, head, and eye movements and voice commands. Wearing the headset, participants can view the 3-D display illuminated using laser light. The display has a 52-degree field of view. The test module was displayed on a 53x105 panel at 1.5 meters distance from the user. With the headset, it was ensured that all participants viewed the virtual objects from the same angle regardless of their height.



Figure 3.5: Microsoft HoloLens 2

3.10 Instruments

A demographic survey was administered to every volunteer for eliciting information about gender, age, department, socio-economic status, previous AR/VR experience,

gaming experience, and eye conditions. For forming this survey, the original demographic survey that Yoon (2011) used for collecting data about the people who take PSVT:R was modified according to the needs of the present study. The survey consists of 15 items and is given in Appendix B.

3.10.1 The Revised Purdue Spatial Visualization Test: Rotations

Purdue Spatial Visualization Test: Rotations (PSVT:R) is a mental rotation test that consists of 2-D isometric drawings (Guay, 1976). It is one of the most widely used mental rotation tests of which the evidence of reliability and validity are well-established across studies involving different demographics. When re-drawing the PSVT:R figures using the computer, Yoon (2011) detected some errors in the original paper-based drawing that may be potentially confusing for the people taking the test. Therefore, she revised the whole PSVT:R from which an example item can be seen in Figure 3.6. In this study, a revised version of the test was employed. Permission for employing this test on paper, online, or in the Mixed Reality environment was granted by Yoon via e-mail upon the request of the author. Turkish instructions of PSVT:R by Turgut and Uygan (2014) were employed during the study.

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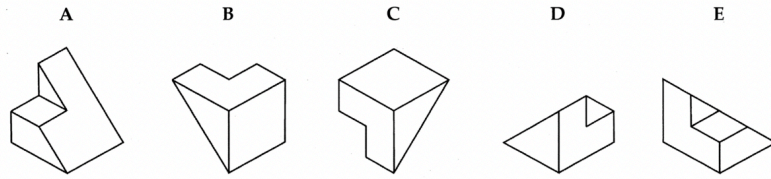
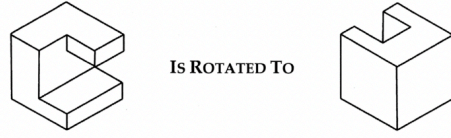


Figure 3.6: Item from Revised PSVT:R

In the computer-based 2-D test, images from the paper-based test were used. Practice questions have written instructions. Test items were displayed on a monitor and participants used a mouse to answer the questions. An example test item from the 2-D computer-based PSVT:R can be seen in Figure 3.7.

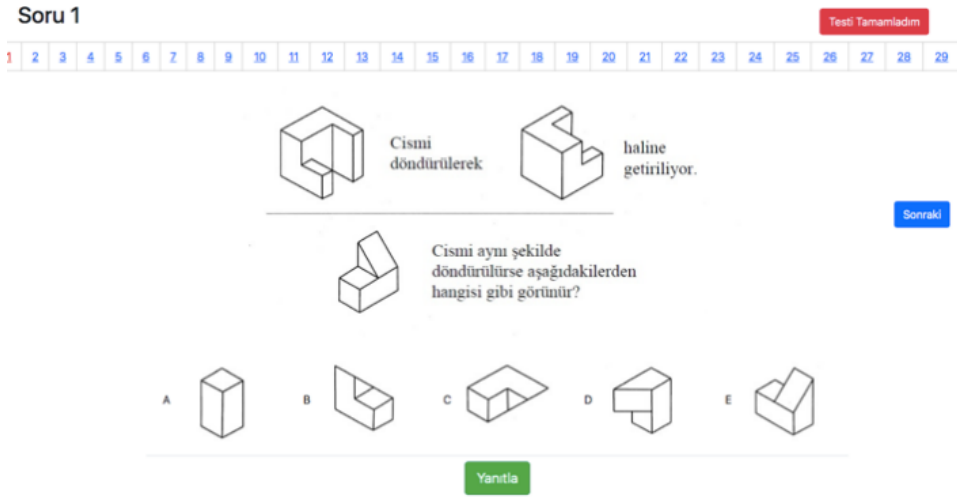


Figure 3.7: 2-D PSVT:R Item

The reason for designing the 3-D PSVT:R was to measure mental rotation ability in three dimensions through the use of an MR headset. Firstly, a total of 256 figures in the PSVT:R were drawn in 3-D using SketchUp. Example models are provided below (Figure 3.8). The 3-D test tool was not created from scratch, rather a valid and reliable test was moved into a different dimensionality. The whole test was converted to three-dimensional without any alteration in the content.



Figure 3.8: Examples of 3-D Models

In this study, PSVT:R, was transferred to a three-dimensional Mixed Reality environment and a measurement tool using Head Mounted Display (Microsoft HoloLens 2) was created. The transfer of three-dimensional content to the Mixed Reality environment was done using Unity, Mixed Reality Toolkit, and HoloLens Software Development Kit. All the items in PSVT:R were transferred to the MR environment in the form of holographic items based on the 2-D mental rotation test (Figure 3.9). In particular, care was taken that the models in the 3-D test were oriented in accordance with the original PSVT:R, sizing them to use the field of view most effectively and adjusting shading to minimize uncertainty. Shapes were made clearer by drawing edges in three-dimensional models. 3-D stimuli were attempted to resemble the 2-D drawings as closely as possible. The test module went through several design cycles with this aim. Every new version of the software was installed into the HoloLens through Windows Device Portal on a computer wirelessly connected to the Mixed Reality headset. The tool resulting from this process is named the *three-dimensional Purdue Spatial Visualisation Test: Rotations* (3-D PSVT:R). Test data was stored as text files that can be accessed through Windows Device Portal. Text files were then converted to spreadsheet files to be used for analysis.

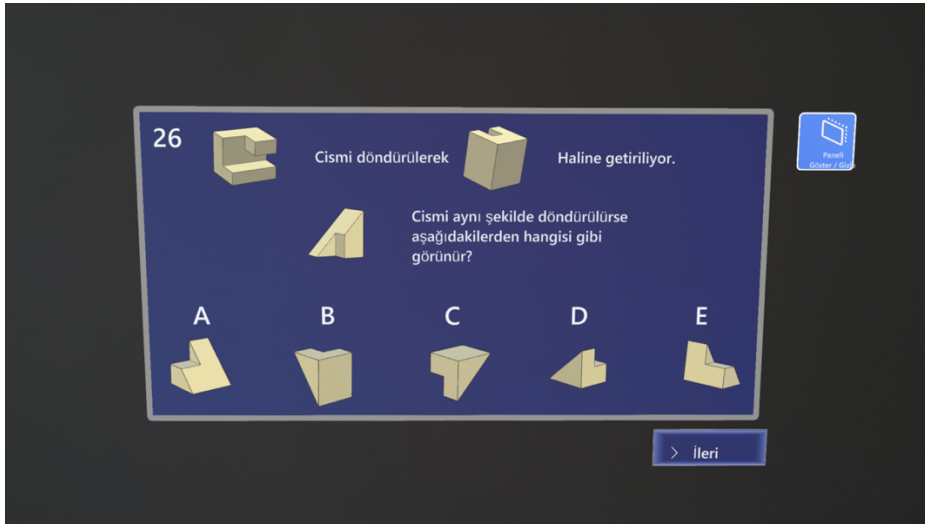


Figure 3.9: Sample Item from 3-D PSVT:R

Stimulus Complexity

There are two reasons for choosing the Purdue Spatial Visualization Test: Rotations (PSVT:R) in this study to transfer to and apply to university students in the Mixed Reality environment. Firstly, the test has more figural diversity than the Mental Rotation Test as it contains various object types consisting of inclined, cylindrical, and oblique surfaces. For the same reason, the test can be administered only to individuals aged 13 or older. The time limit suggested by Guay for this 30-item test is 20 minutes. Secondly, a comprehensive study of archival data showed that the Revised PSVT:R is unbiased for gender comparison (Maeda & Yoon, 2016). As the present study investigates the gender difference in mental rotation performance, this warrant was a suitable characteristic of the instrument.

The difficulty of the mental rotation task essentially influences the participant's performance. In the Shepard and Metzler-type tasks that were commonly used in previous research, the participant first reviews the two objects and then attempts to manipulate one of them until the two objects are aligned (Figure 3.10, left). When they appear to be aligned, they compare the objects and decide whether they are the same object or not (Bilge & Taylor, 2017). However, the Purdue Spatial Visualization Test: Rotations entails a more challenging process with each test item

containing eight distinct figures (Figure 3.10, right). Roughly, the two figures at the top are compared first, and the middle figure (target stimulus) is reviewed next. Following, the bottom figures are compared with the middle figure based on the relation between the two top figures. Additionally, returns and comparisons between the top, middle and bottom objects may be performed in between these processes.

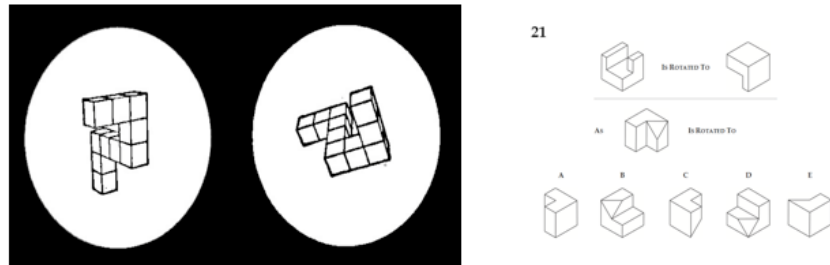


Figure 3.10: Shepard and Metzler type mental rotation task (on the left). An example item from the PSVT:R (on the right).

For the stimulus complexity variable, a complexity index was created based on the PSVT:R item categorization of Onyancha et al. (2009). Onyancha et al. (2009) categorized the PSVT:R items based on the figure and rotation types for determining the level of item difficulty. Indeed, the results showed that the rotation tasks consisting of Right Angle Only, Cylindrical, or Single Incline objects were completed with higher accuracy rates whereas items containing Oblique or Multiple Incline objects resulted in lower accuracy rates. As long as the extent of rotation is concerned, failures were more common in tasks involving 180-degree or multiple rotations than in tasks with 90-degree single rotations.

According to this index we created, the complexity score of the PSVT:R items can be between 2-6. Complexity values can be seen in Table 3.1. For example, item 1 contains a Single Inclined object and a Single Rotation of 90° which makes it one of the least complex items in the test with a 2-point complexity value.

Table 3.1 PSVT:R Item Complexity Index

	Object Type	Rotation Degree and Number	Complexity Point
1	1	1	2
2	1	1	2
3	2	1	3
4	1	1	2
5	1	2	3
6	1	2	3
7	1	1	2
8	2	4	6
9	1	3	4
10	1	2	3
11	1	3	4
12	1	2	3
13	1	3	4
14	2	3	5
15	2	1	3
16	1	3	4
17	1	4	5
18	1	3	4
19	2	2	4
20	1	3	4
21	2	2	4
22	2	2	4
23	1	4	5
24	1	2	3
25	2	4	6
26	1	4	5
27	2	4	6
28	2	4	6

30	2	4	6
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3.10.2 Presence Questionnaire

For measuring participants' feeling of presence, the Presence Questionnaire (Witmer et al., 2005) was used. Gökoğlu and Çakıroğlu (2019) adapted this questionnaire to the Turkish language. This scale consists of 29 items and includes sub-factors *Involvement*, *Adaptation/Immersion*, *Sensory Fidelity*, *Interaction*, and *Interface Quality*. Changes to the wording were made in 3 items to address the learning experience involved in the present study and approved by the adapting authors. Using this questionnaire, the relationship between presence scores and mental rotation scores after the mental rotation training was explored. The presence questionnaire can be found in Appendix D.

3.10.3 Cognitive Load Scale

Cognitive load in tests and the training environment was measured by the scale Lee et al. (2016) used. Since the scale in the aforementioned study was used for a mental rotation training system, it was deemed appropriate for the study. The first two items of this 4-item scale are about mental load (difficulty in using the application to learn the subject and the difficulty in learning the subject), and the last two items are about mental effort (the degree to which the use of the application is distracting and stressful). After it was translated into Turkish, its linguistic equivalence was checked by two language experts and necessary changes were made for a clearer presentation. The cognitive load scale can be found in Appendix C.

3.10.4 Interviews

Semi-structured interviews were conducted in this study with 10 participants to understand how they experienced the Mixed Reality-based training environment.

Students were probed to expand their thoughts when they touched on a notable point which is enabled by the semi-structured flow. The questions were directed to the students immediately after the end of the training so that they could recall their perceptions better. In individual interviews, participants expressed their mental rotation processes, strategies they used, and learning experiences within the immersive environment including the positive and negative aspects of their experience. They were also asked whether they experienced any side effects resulting from the use of the Mixed Reality headset. The interview duration was 5 – 10 minutes. With the participant's permission, each interview session was recorded. The interview questions can be found in Appendix E.

3.11 The MR-based Mental Rotation Training Application

In this study, a one-week training program was created to improve the mental rotation performance of undergraduate students. The training was done in a Mixed Reality environment since it can display three-dimensional objects in a precise manner and participants can interact rotate with and rotate these objects by performing hand gestures. Based on the related works on three-dimensional mental rotation, this application aims to facilitate the construction of the useful mental models required for mental transformations. Thus, it leverages an immersive HMD-based device that is expected to enhance participants' feeling of presence and lead to better cognitive engagement.

The creation of the training module in this study required a careful orchestration of many components including participant characteristics, content design, capabilities and limitations of the Mixed Reality environment, and options of evaluation. This case necessitated a more flexible approach to design as opposed to a linear process to follow. Therefore, rather than strictly following the steps of an instructional design model, we adopted the 'heuristic' approach to design by Zemke and Rossett (2002) which suggests treating instructional design models as general guidelines to follow.

Design Choices: Mixed Reality was used in the training module to take the real world as a reference point and to provide context to the axis arrows placed in the center of the objects while performing rotations on virtual objects.

There are several considerations for designing learning content to be presented on a holographic display which were taken into account in the design of this application. Firstly, bright colors were kept to a minimum as using those in large areas can cause eye fatigue for users (Microsoft, 2021). Menus with bright surfaces can cause hand occlusion which makes it difficult to make accurate judgments about the distance between the hand and the target surface. To conform with Microsoft's suggestions, HolographicBackplate was applied to the panels. Backplates with darker colors were employed in the design and bright colors were used sparingly and for shorter durations. Black borders were drawn on the training objects for eliminating jagged edges. Additionally, bold fonts were used to avoid jittering. There are two separate example screens below (Figure 3.11).

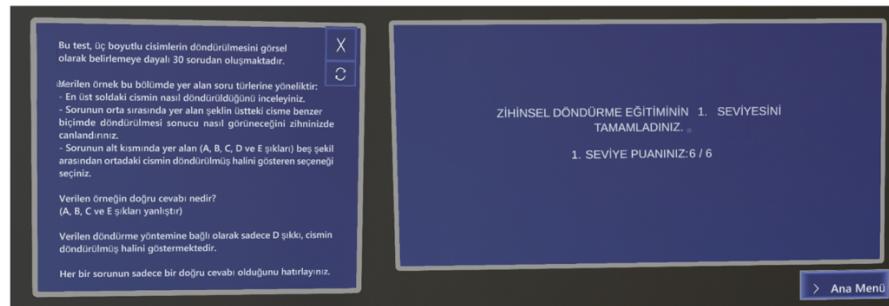


Figure 3.11: Color use in menu items. Test Instructions (left) Score Screen (right).

The training application is an interactive system that allows participants to manipulate 3-D figures to observe each distinct step in the mental rotation process with animations. The layout of the entire module is essentially the same except for the minor differences required by the nature of the task. This design resulted in a simple interface that does not hinder the participants' adaptation to the new learning environment. The storyboard of an example screen and its corresponding part in the final software can be seen in Figure 3.12.

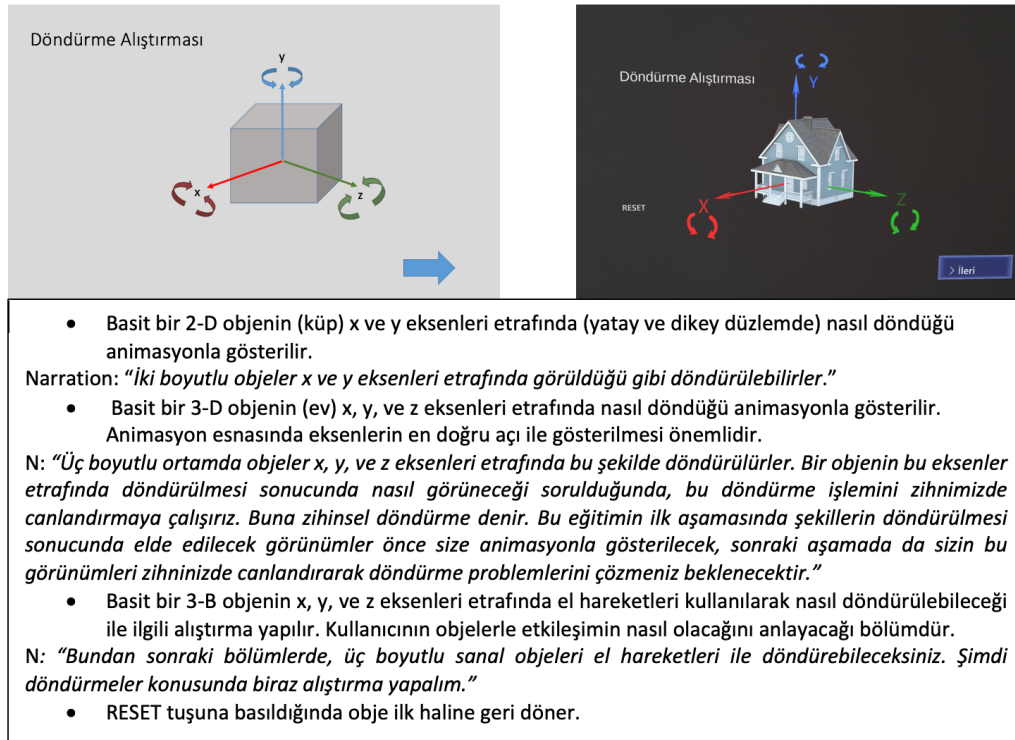


Figure 3.12: Storyboard and screen pairs example.

Different symbolizations are used for denoting the canonical axes in different fields. Since our participants were the most familiar with the format in which y is the vertical axis, we used this format in our training module (Figure 3.13).

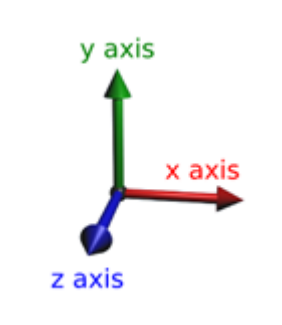


Figure 3.13 The denotation of the canonical axes used in the present study

Training Content: Mental rotation training usually involves everyday objects or nonsense geometric objects (Kornkasem & Black, 2011). Employing solely everyday objects in the training is relatively easy and more appropriate for younger age groups. Therefore, the 3-D model of an everyday object (i.e. house) was used

only at the introduction part. Nonsense figures can be used in two ways in mental rotation training: existing test items can be supported with feedback or new nonsense figures can be designed. To aim for more than near transfer (Smith et al., 2009), we designed training objects corresponding to each target stimulus in the PSVT:R using Sketchup. Some examples of the original items and corresponding training items are given in Figure 3.14.

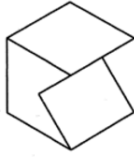
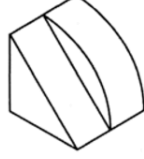
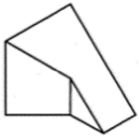
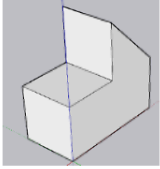
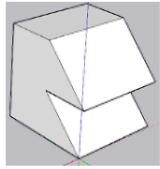
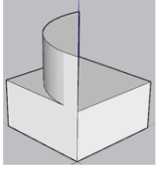
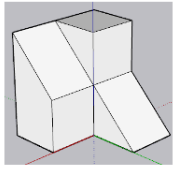
PSVT:R Item				
Training Object				

Figure 3.14 Design of Training Content

Similar to the test, our training objects entailed diverse figure types including inclined, cylindrical and oblique surfaces. Their initial position in the training module was also considered based on the desired level of challenge. For instance, in the first level of training, the initial position of the training object reveals more visual information than in the following levels. Each mental rotation task was constructed using labels such as “*Level 1 Single Incline*” and “*Level 3 Multiple Incline*” to form a concise training. Expert judgment was obtained for the appropriateness of the training objects for the module.

The MR-based training module developed in this study consists of three levels with increasing difficulty. Passive and interactive animations were used to improve students' mental rotation ability. Three-dimensional objects structurally similar to the stimuli in the PSVT:R test were designed and used in the rotation training. The training module content was created to reflect the morphological diversity in the test.

Interactive animations were used to help students construct the mental models required for mental transformations (Figure 3.15).

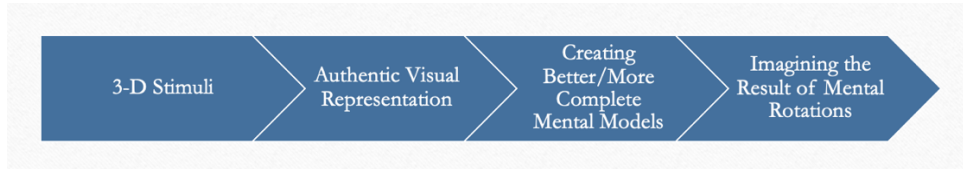


Figure 3.15: Improvement with 3-D Mental Rotation Training

The training application is presented on a “screen” with a wide field of view and it exceeds the representational capacity of traditional screens by allowing free navigation around holograms. Rotations on virtual objects are performed using hand gestures in Microsoft HoloLens 2 environment. This method of interaction both gives a “hands-on” feeling with motor manipulation and shows the actions of rotation at precise angles.

The developed training module has the following structure (Figure 3.16).

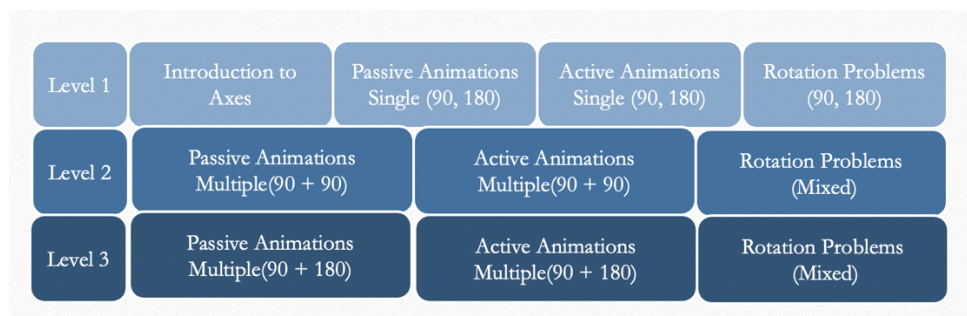


Figure 3.16: Content Flow of the Mental Rotation Training

Introduction: The MR-based 3-D mental rotation training system started from the basics by introducing the concepts of two-dimensional and three-dimensional. The 2-D coordinate system (x, y) was illustrated and the z -axis was added with an animation to represent the 3-D coordinate system. The canonical axes (x, y, z) are introduced and the factor of depth was emphasized. This introduction aimed to help in activating students’ prior knowledge in the related domain. Next, students were informed about the mental rotation process itself (i.e. how people visualize the rotations in their minds) and rotations around the canonical axes are exemplified via

passive animations. A familiar object (three-dimensional house) model is used in the animations in this section.

The rotation system to be used in the following sections was introduced to participants on the Rotation Practice screen (Figure 3.17). On this screen, participants were asked to mentally visualize the rotation that would take place before actually pushing the rotation buttons with hand gestures and to make a comparison between the image in their minds and the virtual object that is before them after pressing the buttons. If the participant says that the rotation they visualized in their mind did not match what happened when they pressed the button, some explanations made in the previous screens were reminded. At the end of the introduction, an outline of the training module is presented and participants are informed of what they are expected to do.



Figure 3.17: Rotation Practice Screen

All the objects in the training were positioned at a 45-degree angle to show two lateral surfaces (right and left) just like the stimuli used in most mental rotation tests. Although the participants were able to see all surfaces by moving around the objects throughout the training, this sideways positioning allowed the participants to have maximum visual information about the objects at first glance. Although the training

module is displayed at a distance of 1.5 meters from the student when the application first starts, since the panel is not used in the training module, this distance varies while the students approach and move away from the virtual objects. Participants see the holographic objects as if they are integrated into the real world. Zoom in/out feature was not included in the design since wandering around seemed a more natural way of interaction in the context of mental rotation.

Rotation Training: The next part of the material proceeds in 3 levels. Each level contains 10 different three-dimensional objects. Levels are different in terms of the difficulty of the shape to be rotated, the number of 3-D manipulations to be made, and the rotation angles of these manipulations. In a rotation task, the level increases as the number of inclined planes, the number of axes to be used in rotation, and the angle value increase. Some shapes do not contain an inclined plane, contain a single inclined plane, multiple inclined planes, and cylindrical and oblique surfaces. There are three different types of content at each level:

Passive animation: In passive animation sequences, the animation depicts the rotation of a holographic shape around the x , y , and z axes (Figure 3.18). At this stage, no extra user action is expected except for watching the animation. This type of content, which is usually in the first parts of a level; aims to familiarize the user with the environment and make them observe the processes of rotation in the environment, accompanied by audio narration. Passive animations can help participants in forming mental representations of rotations.

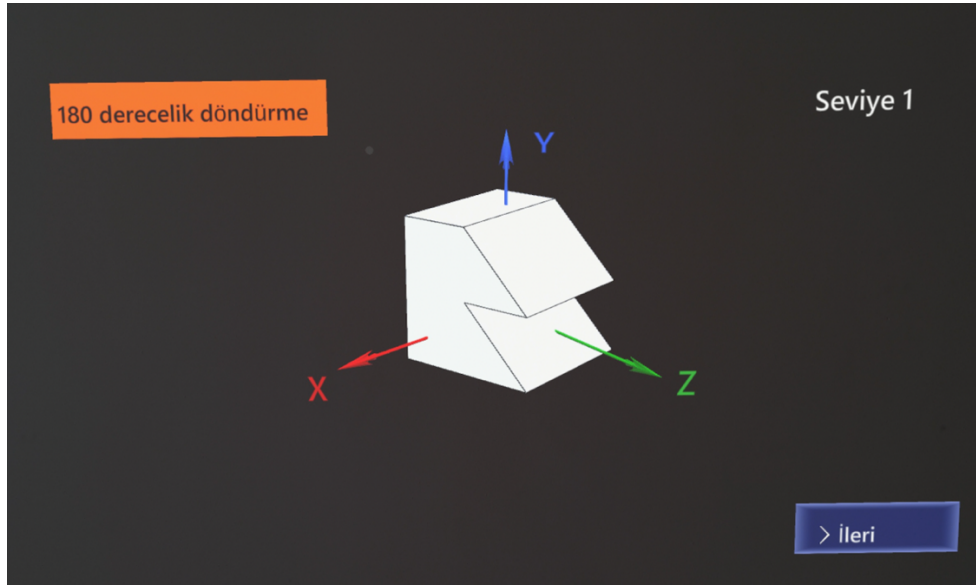


Figure 3.18: Passive Animation Example

In the training content, there are passive animations including 90 or 180 rotations around one axis and 90+90 and 90+180 degree rotations around different axes. After many trials, animation was set at a speed that is fast enough not to be boring to watch and slow enough for participants to understand. While rotating around one axis, the other axis arrows are removed from the animation to focus attention on that particular axis. For example, while the object is rotated around the z-axis, the x and y axes are masked till the end of the rotation and appear again after the object is reset to its original orientation.

Interactive animation: In interactive animation sequences, students rotate the holographic figure around the *x*, *y*, and *z* axes clockwise and counter-clockwise using the gestures defined in the headset. Each axis is symbolized by a color that it is commonly associated with (Figure 3.19). Two curvy arrows (representing clockwise and counter-clockwise) for each axis were located according to the plane they refer to. The three-dimensional environment allowed placing these buttons so that they are intuitive.

Interactive animations aim for the student to experiment with rotating the objects. In the training content, there are interactive animations with 90 and 180 rotations

around a single axis and 90+90 and 90+180 degree rotations around different axes. Participants can reset the object to bring it back to its original orientation. They decide how much time they will spend with this type of content.

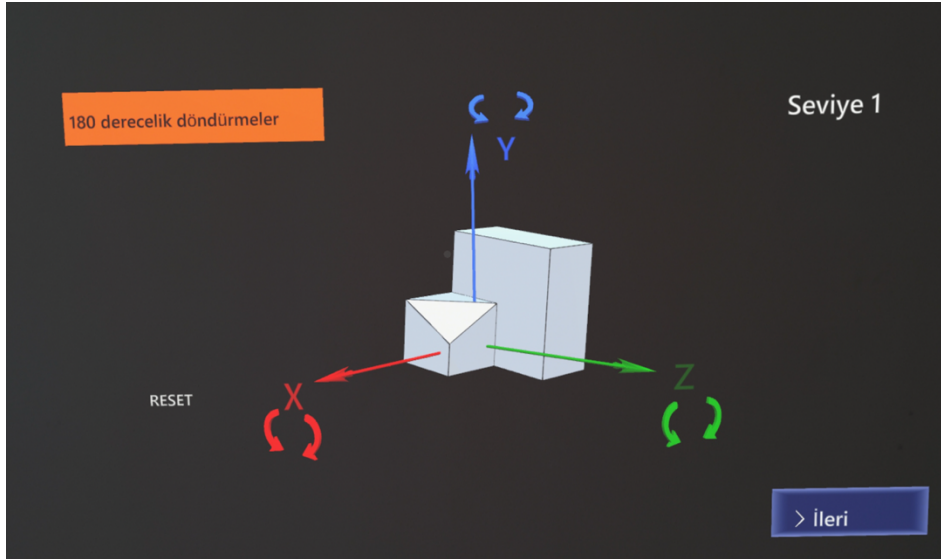


Figure 3.19: Interactive Animation Example

Rotation Problems: There are two types of rotation problems in this training module. In *specified* rotation problems, the participant is expected to reach the target orientation by making a certain number of moves and rotations with a certain angular value. (i.e., a single 90-degree rotation). This rotation hint is presented in the top left corner of the visual field. But the axis or axes to be rotated around is discovered by the participant.

In the more complex *not specified* rotation problems, the participant is asked to match the left figure to the right, and no hint is provided. Therefore, the learning support provided in the *specified* rotation problems gradually fades to create a new challenge. In questions without clues, the number of moves required to match the two objects is not known and the shape returns to its original position after a certain number of moves; thus, encouraging the participant to solve the problem in the shortest way possible and reducing the factor of chance. In each of the stages, students are given feedback that includes animation and sound. To minimize the trial

and error approach, students are given 3 to 5 attempts depending on the difficulty of the rotation problem.

If students do the right moves, the two objects match, and the left object turns green like the right object (Figure 3.20). If they cannot match the objects after using all the moves, participants can see the solution to the rotation problem in the form of animation by clicking the *See the Answer* button. The fewer attempts the student can solve the rotation problem with, the more points they gain. Thus, it is aimed to increase the motivation of the student to solve the rotation problem in the most efficient way. The limited number of moves and attempts allowed the user to reason *before* pressing the buttons and to proceed step by step in problems involving more than one rotation. This approach is important for triggering participants to visualize the rotations which can facilitate mental model construction. A scoring table was created in which problems were assigned points depending on their complexity. Participants were presented with their scores in the training module problems at the end of each training session.

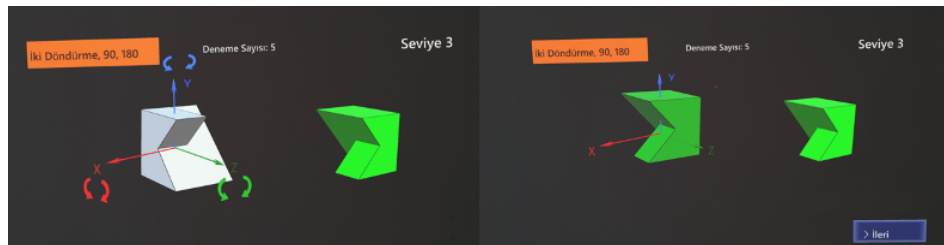


Figure 3.20 Rotation Problem Example

At each level, students are provided both with narrated passive animations and interactive animations that allow students to manipulate the 3-D virtual objects to solve mental rotation tasks. The interactive animations could be started, paused, and replayed by the user. Progressing from the first level to the third level, participants go through simple shapes and single rotations to complex tasks involving more complex shapes and rotation rules. To reduce cognitive load, we aimed to design a training module that is intuitive and simple to use. Color was not used except for the

axes, their corresponding buttons, and object matches. Interaction with the system is achieved by hand gestures.

3.12 Data Analysis Procedure

The independent variable of the first research question is the dimensionality of the mental rotation testing environment. The two experimental conditions entail the desktop-based 2-D PSVT:R and the 3-D MR-based PSVT:R. The dependent variable is the students' mental rotation scores defined by the accuracy rates of the answers given in the tests. The effect of the environment dimensionality on mental rotation ability was analyzed using the Mann-Whitney U test (RQ1a). The effect of dimensionality on cognitive load was analyzed using the Mann-Whitney U test (RQ1b).

The analysis of gender difference in mental rotation was conducted separately with Mann-Whitney U tests for the two testing environments (RQ1c). The relationship between the level of question difficulty and mental rotation performance was addressed with one-way ANOVA (RQ1d). The stimulus complexity value, which is the independent variable, varies between 2-6. The dependent variable is the number of people who answered the test item correctly.

The main concern of Research Question 2 is whether the MR-based training program improves mental rotation ability. The independent variables of the Research Question 2 (performance difference) and its sub-questions are a) gender, b) stimulus complexity, c) feeling of presence and d) cognitive load. The dependent variable is the difference between pre-test and post-test mental rotation scores. Wilcoxon signed-rank tests were conducted to look for a significant difference between the pre- and post-mental rotation ability scores measured in both two-dimensional and three-dimensional PSVT:R (RQ2). Gender difference in the improvement in mental rotation scores as a result of the training was addressed with an independent-samples t-test (RQ2a). A one-way ANOVA was used to reveal whether mental rotation

performance is affected by stimulus complexity (RQ2b). The stimulus complexity value is the independent variable. The dependent variable is the difference between the number of people who answered the test item correctly in the post-test and the number of people who answered correctly in the pre-test. Pearson correlation test was carried out to look for a correlation between the feeling of presence in the MR environment and mental rotation performance (RQ2c). Also, the same test was used for cognitive load and mental rotation performance correlation. (RQ2d).

Before conducting the statistical tests, assumptions of normal distribution and homogeneity of variance were checked. Where the assumption of normality is violated, non-parametric tests were used. Homogeneity of variance was checked with Levene's test which is an inferential statistic used to assess the equality of variance in different samples.

Research question 3 was analyzed by qualitative analysis. The interviews were audio recorded, transcribed and the themes were extracted by coding. In the Results section, the themes will be explained and triangulated by the observation notes obtained during the research.

3.13 Reliability

The reliability of a study essentially involves consistent measurement obtained with the instruments employed. In this study, students' mental rotation performance was measured with PSVT:R as a pre-test and post-test. The version of the test revised by Yoon (2011) was used because its validity and reliability were proven. As she suggested, no alterations were made in the test forms (i.e. design, order, content) for avoiding reliability issues.

The internal consistency coefficient of the test shows a good level of reliability (Cronbach's $\alpha=.862$). The Cronbach's alpha values of the test calculated in this study were .895 and .750 for the two-dimensional pre-test and post-test, while they were .749 and .739 for the three-dimensional pre-test and post-test. These values are

higher than .70, which is accepted as the threshold value by Cohen (1988). This indicates that PSVT:R can be employed in this study for measuring mental rotation ability.

The Cronbach Alpha (α) reliability coefficient calculated for the Turkish Adaptation of the Presence Questionnaire is .844. The internal consistency coefficient of the presence scale calculated in this study is .840.

3.14 Validity

The validity of a study refers to the compliance of the results and the initial research question. Internal validity depends on the results of a study allowing only one explanation. That is, the only variable that causes *systematic variation* in the dependent variable should be the independent variable we chose. In experimental studies, ‘the third variable’ problem is always a potential threat and considering possible confounding variables reduces the risk for internal validity-related issues. Although students were randomly assigned to different treatments, groups were equivalent in terms of potential extraneous variables (i.e. gender, age, GPA). All participants completed the study process with only one researcher and were treated equally to standardize the procedure. Environmental conditions (e.g. lighting, noise) were controlled against eliminating any systematic variation.

External validity is concerned with the applicability of the results of a study to different participants, settings, or times. Since this experiment was conducted in a controlled laboratory setting, it can be easily replicated by other researchers. The sample size was determined via power analysis to allow fair generalizability from the sample to the population. However, using merely undergraduate students may limit the generalizability of the results to the general public. Nevertheless, findings on cognitive processing are potentially more generalizable than findings involving social and cultural aspects (Field and Hole, 2002).

3.15 Ethical Considerations

As in any type of research study, ethical concerns apply to experimental studies. Active phases of this study (e.g. data collection and running the experiment) started after obtaining the approval of the METU Ethics Committee. Aligning with the guidelines specified by the committee, I took care that participants of this study would not be subjected to any physical or psychological harm. Participants were informed about the nature of the study and their rights (e.g. withdrawal at any point in the study). Informed consent forms were signed by volunteers before the experiment. Confidentiality about their data was ensured. For maintaining anonymity, student names were given a corresponding number to their names, and identification information was removed when transferring to SPSS for analysis. The collected data was not used for any purpose other than the present research. Participants were given monetary compensation for participation.

CHAPTER 4

RESULTS

Presented in this chapter are the results of the experimental study conducted for investigating the measurement and improvement of mental rotation ability. For the analysis based on quantitative data, the results are reported concerning the related research questions. Then, the qualitative results are presented with respect to the themes extracted with thematic analysis.

For a clear understanding of the results, Table 4.1 provides an overview of the sample about gender, department, and other variables related to this study.

Table 4.1 Sample demographics (n = 47)

Demographic	Category	Percent	Number
Gender	Male	36.2	17
	Female	63.8	30
Department	Mathematics Education	36.2	17
	Computer Engineering	25.5	12
	Counselling	8.5	4
	Social Sciences Education	8.5	4
	Mathematics	8.5	4
	Other	12.8	6
Playing digital games	Yes	61.7	29
	No	38.3	18
Gaming experience	0-1 Years	55.3	26
	2-5 Years	12.8	6
	More Than 5 Years	31.9	15
Gaming Frequency	Everyday	6.4	3
	Every Week	23.4	11
	Once A Month	14.9	7
	Once In 6 Months	19.1	9

	Less Than Once A Year	14.9	7
	Never	21.3	10
AR/VR Experience	No Experience	80.85	38
	Tried Before	19.15	9
Parent Higher Education	Yes	25.5	12
	No	74.5	35

As is shown in Table 4.1, the sample consisted of 63.8% females and 36.2% males. This ratio reflects the high female proportion observed in some departments of the university at which the study was conducted. Most of the participants were enrolled in the departments of Mathematics Education (36.2%) and Computer Engineering (25.5%). This is probably due to the fact that students from these departments realized the importance of mental rotation ability for their academic success more readily during their initial talk with the researcher. The departments of Counselling, Social Sciences Education and Mathematics yielded an equal number of participants (8.5%). The remaining 12.8% of the sample was from several different departments.

The participants were asked if they play digital games of any sort. More than half of the participants submitted to playing digital games (61.7%) on any platform or device. Specifically, while all of the male participants said that they play digital games at different frequencies, 37% of the female participants expressed that they engaged in such activity. However, more than half of the participants had 0-1 years of gaming experience (55.3). Everyday gamers were rare (6.4%) but apart from that, the sample had similar proportions of gamers for each gaming frequency: “Every week” (23.4%), “Once a Month” (14.9%), “Once in 6 Months” (19.1%) and “Less Than Once a Year” (14.9%). Approximately one-fifth of the participants said that they never play digital games.

Few participants said that they used Augmented Reality or Virtual Reality goggles before. The AR/VR experience percentage was similar in males and females with 18% and 20%, respectively. Finally, as an indicator of socio-economic status, the participants were asked if one or two of their parents has a bachelor's degree. Only 25% said that they have a parent who pursued higher education.

4.1 Research Question 1

4.1.1 Research question 1a

What is the effect of the dimensionality of the test stimuli (2-D vs. 3-D) on mental rotation performance?

Information about the descriptive statistics of the 2-D and 3-D Test Groups is given in Table 4.2. The participants in the 2-D test group ($M=15.95$, $SD=5.51$) and the 3-D test group ($M=15.24$, $SD=3.83$) showed equal performance in mental rotation ability. As can be seen, the range of the scores are fairly wide for both groups and variability is high.

Table 4.2 Descriptive Statistics of 2-D and 3-D Test Groups

	n	M	SD	Skewness	Kurtosis	Min	Max
2-D Test	22	15.95	5.51	1.03	.11	10	29
3-D Test	25	15.24	3.83	.90	.69	9	25

Since the data did not show normal distribution, the non-parametric Mann-Whitney U test was used to explore whether there is a difference between two-dimensional and three-dimensional PSVT:R. Table 4.3 shows the mean ranks for the two test groups and the test statistics.

Table 4.3 Difference between 2-D and 3-D Mental Rotation Scores

	2-D Test (n=22)	3-D Test (n=25)			
	Mean Rank	Mean Rank	z value	U value	p value
Mental Rotation Ability	23.84	24.14	-.075	271.50	.94

There is no significant difference between the three-dimensional rotation test scores (Mdn= 14.00) and the two-dimensional rotation test scores (Mdn= 14.00). ($U=271.50$, $z= -.075$, $p= .94$, $r= -.11$). In other words, the mental rotation ability of the 2-D test group and the 3-D test group were equal.

4.1.2 Research Question 1b

What is the effect of the dimensionality of the test stimuli (2-D vs. 3-D) on cognitive load?

The cognitive load scale consists of two factors: mental load and mental effort. Mental load is imposed by the nature of the task or the environment whereas mental effort involves the cognitive resources that are allocated by the learner for understanding the task.

Information about the descriptive statistics of the mental load of 2-D and 3-D Test Groups is given in Table 4.4. The participants in the 3-D test group ($M=7.12$, $SD= 3.07$) had lower mental load than the 2-D test group ($M=9.45$, $SD=3.60$).

Table 4.4 Mental Load in 2-D and 3-D Test Groups

	n	M	SD	Skewness	Kurtosis	Min	Max
2-D	22	9.45	3.60	-.27	-.83	2	14
3-D	25	7.12	3.07	.54	.47	2	14

Due to non-normal distribution, the Mann-Whitney U test was used to examine whether there was a difference in mental load between the two-dimensional and three-dimensional mental rotation tests. The mean ranks and test statistics are presented in Table 4.5. It was observed that the mental load (Mdn=9.50) in the two-dimensional test was higher than the three-dimensional test (Mdn=7.00) ($U=171.00$, $z= -2.23$, $p= .026$, $r= -.325$). In other words, the cognitive load imposed by the task

or the environment is higher in the 2-D computer-based environment than in the 3-D Mixed-Reality based environment.

Table 4.5 Mental Load Difference by Test Dimensionality

	2-D Test (n =22)	3-D Test (n = 25)			
Mental Load	Mean Rank	Mean Rank	z value	U value	p value
	28.73	19.84	-2.23*	171.00	.026*
* $p < .05$					

Information about the descriptive statistics of the mental effort of 2-D and 3-D Test Groups is given in Table 4.6. The participants in the 3-D test group ($M=4.80$, $SD = 3.59$) had lower mental effort than the 2-D test group ($M=7.09$, $SD=4.09$).

Table 4.6 Mental Effort in 2-D and 3-D Test Groups

	n	M	SD	Skewness	Kurtosis	Min	Max
2-D	22	7.09	4.09	.51	-.98	2	14
3-D	25	4.80	3.59	1.51	1.23	2	14

Since the data is not normally distributed, the Mann-Whitney U test was used to examine whether there was a difference in mental effort between the two-dimensional and three-dimensional mental rotation tests (Table 4.7).

Table 4.7 Mental Effort Difference by Test Dimensionality

	2-D Test (n =22)	3-D Test (n = 25)			
Mental Effort	Mean Rank	Mean Rank	z value	U value	p value
	28.68	19.88	-2.219*	172.00	.027*
* $p < .05$					

It was observed that mental effort ($Mdn=6.00$) in the two-dimensional test was higher than in the three-dimensional test ($Mdn=3.00$) ($U=172.00$, $z=-2.21$, $p=.027$, $r=-.323$). This means that the cognitive load that the learner allocates to understanding the task is higher in the 2-D computer-based environment than in the 3-D Mixed-Reality based environment. In general, the cognitive load in the three-dimensional test is lower than in the two-dimensional test.

Although it was not within the initial scope of this thesis, additional statistical analysis of the cognitive load levels from pre-test to post-test revealed a significant decrease in the case of 3-D mental rotation test. Meanwhile, the cognitive load levels in the 2-D test did not significantly from the beginning to the end of the training intervention.

4.1.3 Research Question 1c

Is gender difference observed in mental rotation performance in the test environments?

Information about the mental rotation performance of males and females is given in Table 4.8. Females ($M=14.30$, $SD=3.85$) had lower mental rotation scores than the males ($M=17.82$, $SD=5.19$).

Table 4.8 Mental Rotation Scores by Gender (Pre-test)

	n	M	SD	Skewness	Kurtosis	Min	Max
Females	30	14.30	3.85	.04	-1.20	10	29
Males	17	17.82	5.19	2.15	6.69	9	26

Due to non-normal distribution, the non-parametric Mann-Whitney U test was used to examine whether there was a difference between males' and females' mental rotation ability before training (Table 4.9).

Table 4.9 Difference Between Male and Female Test Scores

	Females (n = 30)	Males (n = 17)			
Mental Rotation Ability	Mean Rank	Mean Rank	<i>z</i> value	<i>U</i> value	<i>p</i> value
	20.42	30.32	-2.393*	147.50	.017*
* <i>p</i> < .05					

Male test scores (Mdn=18.00) were found to be higher than female (Mdn=14.00) test scores ($U=147.50$, $z= -2.39$, $p= .017$, $r= -.348$). Mean scores for the two measurements of mental rotation ability are presented in Figure 4.1.

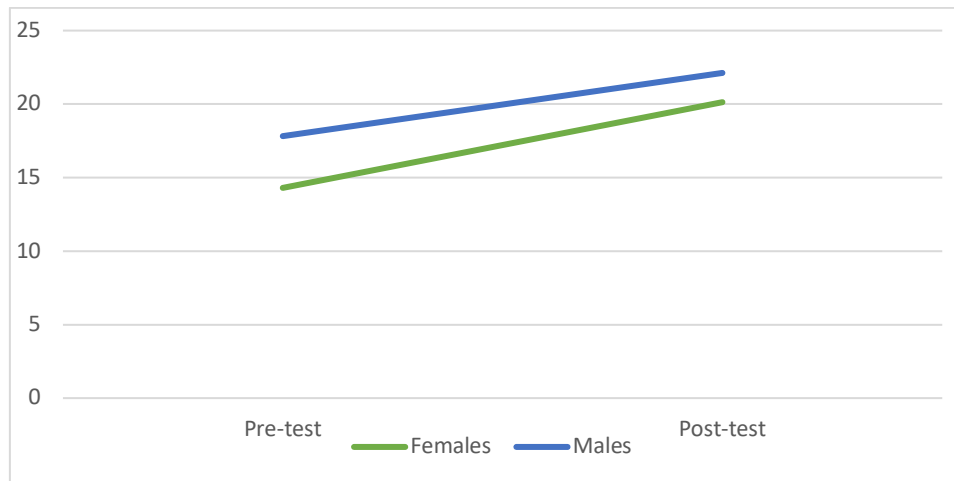


Figure 4.1: Mental Rotation Ability Scores by Gender

The gender difference was examined separately for the two-dimensional and three-dimensional groups with Mann-Whitney U tests (Table 4.10).

Table 4.10 Gender Difference by Test Versions

	Females	Males			
Mental Rotation Ability	Mean Rank	Mean Rank	<i>z</i> value	<i>U</i> value	<i>p</i> value

2-D Test	9.15	14.89	-2.045*	28.00	.04*
3-DTest	11.76	15.63	1.235	47.00	.23

* $p < .05$

Males' mental rotation ability (Mdn = 18) was higher than that of females (Mdn = 13.00) in the two-dimensional test ($U = 28.00$, $z = -2.04$, $p = .04$, $r = -.434$). In the three-dimensional test, there was no difference between the mental rotation ability of females (Mdn = 14.00) and males (Mdn = 16.50) ($U = 47.00$, $z = -1.23$, $p > .05$). Pre-test scores by test dimensionality are presented in Figure 4.2 for both genders.

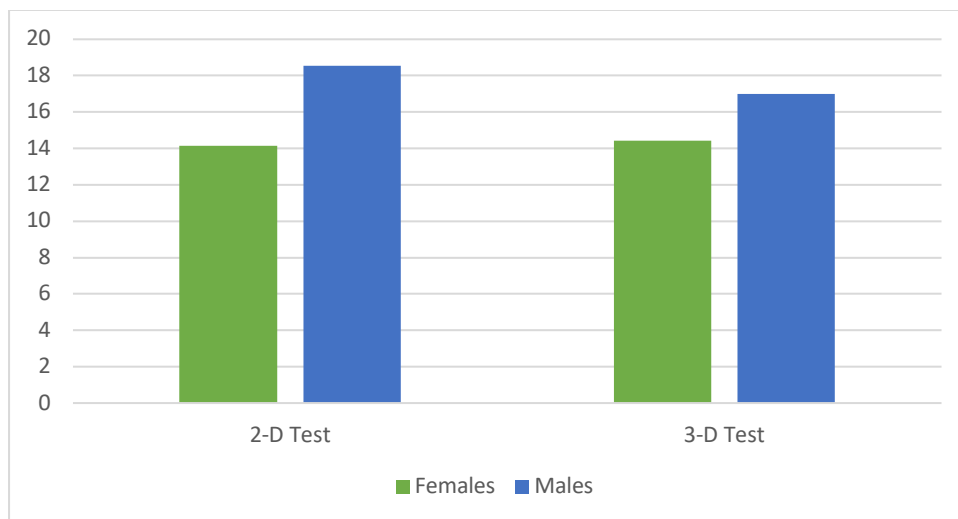


Figure 4.2: Mental Rotation Ability Scores/Test Dimensionality by Gender

After the training, the difference between the mental rotation ability of males and females was examined with an independent sample t-test using the post-test scores (Table 4.11).

Table 4.11 Gender Difference After Training

	n	Mean	SD	<i>t</i>	<i>p</i>
Females	30	20.28	3.30	1.81	.077
Males	17	22.12	4.20		

Although females' post-test scores ($M = 20.28$, $SD = 3.30$) are still lower than that of males ($M = 22.12$, $SD = 4.20$), there is no statistically significant difference, $t(45) = 1.81$, $p = .077$. In other words, females' mental rotation ability is not anymore significantly different from males' mental rotation ability after the Mixed Reality-based mental rotation training.

4.1.4 Research Question 1d

How does stimulus complexity affect mental rotation performance in the 3-D test environment?

In this question, success on test items was investigated in relation to the complexity of the PSVT:R test items. The independent variable is stimulus complexity and the dependent variable is the number of correct answers on the particular stimulus (i.e. test item). For quantifying the independent variable, a complexity index was created employing the PSVT:R item categorization of Onyancha et al. (2009) in which the items are categorized based on the figure and rotation types. According to this index, the complexity score of the PSVT:R items can be between 2-6. Therefore, a one-way ANOVA was conducted for comparing the means of the number of correct answers for 5 different levels of stimulus complexity. Descriptive information on the correct answers for the 5 complexity groups is given in Table 4.12.

Table 4.12 Success Rate by Item Complexity

Item Complexity Score	n	M	SD	Min	Max
2	4	37.00	1.82	35	39
3	7	26.86	6.41	19	39
4	9	23.78	3.30	19	29
5	5	21.00	4.63	14	27
6	5	15.80	9.14	5	27

Prior to conducting one-way ANOVA, assumptions of normality and homogeneity of variance were checked. Skewness (-.14) and Kurtosis (.60) values are between -1.96 and 1.96 which indicates normal distribution (Field, 2009). The results of the Kolmogorov-Smirnov ($p = .18$) and Shapiro-Wilk ($p = .16$) tests were not significant. Levene's statistic was not significant ($p = .16$) which showed that all complexity groups had equal variances. These checks confirmed the normal distribution of the number of correctly answered items in the pre-test.

The variation of success in the mental rotation test according to the difficulty level (stimulus complexity) of the test items was examined with one-way ANOVA. There is a significant difference between the number of correct answers by items with different complexity scores. The ANOVA result is significant ($F(4, 25) = 9.05$, $p = .00$). Means and standard deviations are given in the ANOVA table (Table 4.13).

Table 4.13 Success Rate in Test Items by Stimulus Complexity

Source	SS	df	MS	F	η^2
Stimulus Complexity	1108.25	4	277.06	9.05	.59*
Error	765.213	25	30.60		
Total	1873.46	29			

* $p < .01$

The relationship between stimulus complexity and the level of success in the test item is strong. Partial η^2 shows that 59% of the variance in achievement level in the test item is due to stimulus complexity. According to the follow-up tests, the achievement level for test items with a stimulus complexity of 2 points ($M = 37.00$, $SD = 1.82$) was higher than for test items with a stimulus complexity of 6 points ($M = 15.80$, $SD = 9.14$). As the difficulty level of the questions increases, the level of success decreases (Figure 4.3).

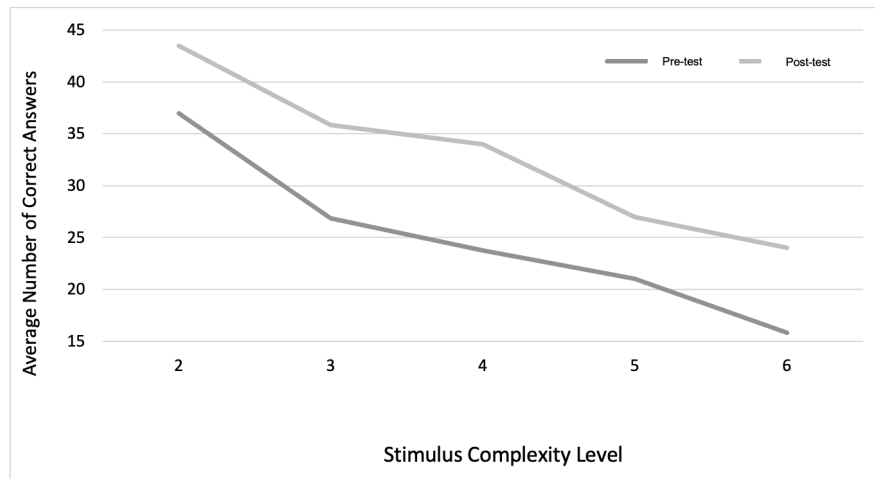


Figure 4.3: Stimulus Complexity and Success Rate

4.2 Research Question 2

Can mental rotation ability be improved with Mixed Reality applications using three-dimensional objects?

For answering this question, the participants' mental rotation ability test scores before and after the one-week targeted Mixed Reality-based mental rotation training were compared. The aim of this question was to identify if the training was effective in improving students' mental rotation ability. Information about the descriptive statistics is given in Table 4.14.

Table 4.14 Descriptive Statistics of Pre-test and Post-test Scores

	n	M	SD	Skewness	Kurtosis	Min	Max
Pretest	47	15.57	4.657	1.08	.66	9	29
Posttest	47	20.85	3.695	.43	-.37	15	30

Due to non-normal distribution, Wilcoxon signed-rank test was used to determine whether there was a difference between the mental rotation ability of the participants before and after the training (Table 4.15).

Table 4.15 Mental Rotation Ability Before and After Training

	Pre-test	SD	Post-test	SD	Improvement	z value	p value
Mental Rotation Ability	15.57	4.657	20.85	3.695	5.28	-5.724*	.000

The participants' mental rotation ability after the training (Mdn = 21.00) was significantly higher than before the training (Mdn = 14.00) ($z = -5.724$, $p < .01$, $r = .59$). The mean score of mental rotation ability was 15.57 before the training; which increased by 5.28 points to 20.85 after the training.

Separate Wilcoxon signed-rank tests were used to determine whether there was a difference between the mental rotation ability of the participants in the 2-D and 3-D test groups before and after the training (Table 4.16).

Table 4.16 Mental Rotation Ability Before and After Training by Test Group

Mental Rotation Ability	Pre-test	SD	Post-test	SD	Improvement	<i>z</i> value	<i>p</i> value
2-D Test Group	15.95	5.51	21.27	3.70	5.3	-3.814	.000
3-D Test Group	15.28	3.83	20.48	3.72	5.2	-4.378	.000

The difference between the pre-test and post-test for the group that took the test in the 2D environment ($z = -3.814$, $p < .01$, $r = .57$) and for the group that took the test in the 3D environment ($z = -4.378$, $p < .01$, $r = .61$) are both significant. In other words, the mental rotation ability of participants is higher after the training than before the training measured in both 2-D and 3-D environments.

Table 4.17 Mental Rotation Ability Improvement by Dimensionality

	N	Mean	SD	<i>t</i>	<i>p</i>
2-D	22	5.32	3.70	-.60	.55
3-D	25	5.24	3.20		

According to the independent sample t-test performed to determine which test group showed more skill development, those who took the two-dimensional ($M = 5.3$) and three-dimensional ($M = 5.24$) tests showed equal skill development. The results are presented in Table 4.17.

4.2.1 Research Question 2a

Does the 3-D mental rotation training lead to a difference between male and female mental rotation ability improvement?

After the mental rotation training, whether there was a difference between male and female participants in terms of mental rotation ability development was examined with the independent sample t-test (Table 4.18). Although the improvement of female participants ($M = 5.83$, $SD = 3.53$) was higher than males ($M = 4.29$, $SD = 3.36$), this difference was not significant, $t(45) = -1.459$, $p = .152$. Mental rotation ability improved equally in male and female participants.

Table 4.18 Mental Rotation Ability Improvement by Gender

	N	Mean	SD	<i>t</i>	<i>p</i>
Females	30	5.83	3.53	-1.459	.152
Males	17	4.29	3.36		

In the *c* section of Research Question 1, males were found to have higher mental rotation ability than females. However, the results of the analysis shows that the Mixed Reality-based mental rotation training is equally effective for both genders.

4.2.2 Research Question 2b

Does mental rotation ability improvement remain the same for different levels of stimulus complexity?

In this question, improved success on test items was investigated in relation to the complexity of the PSVT:R test items. The independent variable is stimulus complexity and the dependent variable is the difference between the number of

correct answers from pre-test to post-test. Onyancha *et al.* (2009) categorization of PSVT:R items were employed for quantifying the independent variable. According to this index, the complexity score of the PSVT:R items can be between 2-6. Therefore, a one-way ANOVA was conducted for comparing the improvement for 5 different levels of stimulus complexity.

Descriptive information on the success rate improvement for the 5 complexity groups is given in Table 4.19.

Table 4.19 Improvement of Success Rate by Item Complexity

Item Complexity Score	n	M	SD	Min	Max
2	4	6.50	2.38	3	8
3	7	9.00	4.86	3	15
4	9	10.22	4.81	1	15
5	5	6.00	4.00	1	11
6	5	8.20	5.80	1	15

Prior to conducting one-way ANOVA, assumptions of normality and homogeneity of variance were checked. Skewness (-.13) and Kurtosis (-1.3) values are between -1.96 and 1.96 which indicates normal distribution (Field, 2009). The results of Kolmogorov-Smirnov ($p = .099$) and Shapiro-Wilk ($p = .052$) tests were not significant. Levene's statistic was not significant ($p = .13$) which showed that all complexity groups had equal variances. These checks confirmed the normal distribution of the improvement of accuracy from pre-test to post-test.

The variation of the level of improvement in the mental rotation test according to the difficulty level (stimulus complexity) of the test items was examined with one-way ANOVA. Means and standard deviations are given in the ANOVA table (Table 4.20).

Table 4.20 Mental Rotation Ability Improvement by Stimulus Complexity

Source	SS	df	MS	F
Stimulus complexity	75.844	4	18.96	.872
Error	543.35	25	21.73	
Total	619.20	29		

There is no significant difference between the development level of the students' mental rotation performance after the mental rotation training in the three-dimensional environment by items with different complexity scores. According to the ANOVA result, there is no significant relationship between stimulus complexity and the level of improvement in test item-specific achievement ($F(4, 25) = .872, p > .05$). Score improvement by item complexity is presented in Figure 4.4.

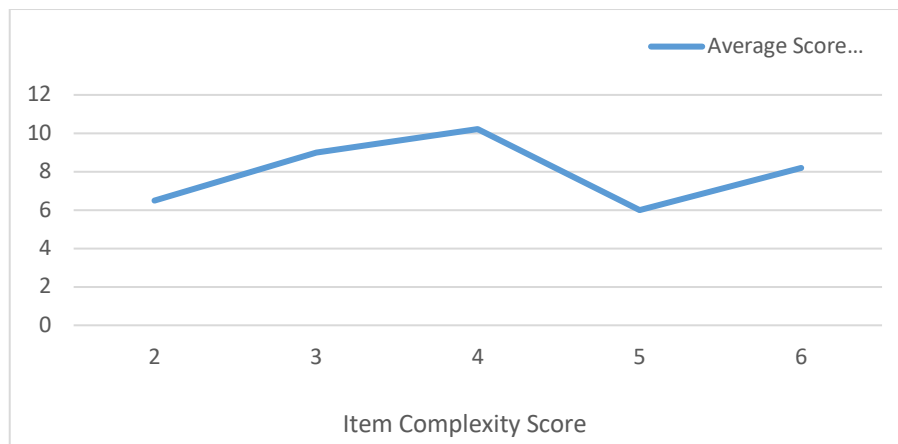


Figure 4.4: Mental Rotation Score Improvement by Item Complexity

This result shows that there has been an equal level of improvement for each difficulty level. This indicates that the training was effective for improving in tasks that contain multiple rotations with complex figures as well as single rotation and simpler figures.

4.2.3 Research Question 2c

Is there a relationship between feeling of presence and mental rotation ability improvement in the 3-D training environment?

This question aimed to identify if the degree of the sense of presence that the participants have in the Mixed Reality-based training environment affected the level of mental rotation ability improvement. The variables are the perceived Presence scores obtained using the Presence Questionnaire and the improvement of mental rotation ability which is calculated by subtracting the pretest score from the posttest score.

Pearson correlation test was used to determine whether there was a relationship between the level of sense of presence and the development of mental rotation ability (Table 4.21). No relationship was found between the sense of presence and the development of mental rotation ability ($r = .096$, $p > .05$).

Table 4.21 Relationship between Mental Rotation Ability Improvement and Sense of Presence

	Sense of Presence (M = 122)	
	<i>r</i>	<i>p</i>
Mental Rotation Ability Improvement (M = 5.28)	.096	.520

The result shows that the level of mental rotation ability improvement after the training is not related with the degree of presence perceived by the participants in the Mixed Reality-based training environment.

4.2.4 Research Question 2d

Is there a relationship between cognitive load and mental rotation ability improvement in the 3-D training environment?

This question aimed to identify if the degree of cognitive load that the participants' experience in the Mixed Reality-based training environment affected the level of mental rotation ability improvement. The variables are the cognitive load scores obtained using the Cognitive Load Scale and the improvement of mental rotation ability which is calculated by subtracting the pretest score from the post-test score.

Pearson correlation test was used to examine whether there is a relationship between the cognitive load in the three-dimensional environment and the development of mental rotation ability (Table 4.22). When the sub-dimensions of cognitive load for the pre-test and post-tests were examined, there was a significant relationship only between the mental load in the pre-test and the development of mental rotation ability ($r = .327, p < .05$). No relationship was found between mental effort in pre-test and the development of mental rotation ability ($r = .241, p > .05$); mental load in post-test and the development of mental rotation ability ($r = -.089, p > .05$); and mental effort in post-test and the development of mental rotation ability ($r = .110, p > .05$).

Table 4.22 Relationship between Mental Rotation Ability Improvement and Cognitive Load

	Mental Load				Mental Effort				Overall Cognitive Load			
	<i>Pre-test</i>		<i>Post-test</i>		<i>Pre-test</i>		<i>Post-test</i>		<i>Pre-test</i>		<i>Post-test</i>	
Mental Rotation Ability Improvement	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
	.33*	.02	.24	.10	-.09	.55	.11	.46	.10	.50	.18	.22

Overall, the result shows that the level of mental rotation ability improvement after the training is not related to the degree of cognitive load perceived by the participants in the Mixed Reality-based training environment. From the sub-dimensions of cognitive load measured after the pre-test and post-test, only mental load in the pre-test and mental rotation ability improvement has a weak correlation.

4.3 Research Question 3

How are the mental rotation experiences in the three-dimensional training environment?

To provide a frame for understanding the quotes better, Table 4.23 provides an overview of the sub-sample (n=10) that was interviewed in this study.

Table 4.23 Demographic Information of the Interviewed Subsample

Demographic Characteristic	Percentage	Number
Female	70%	7
Male	30%	3
Physical Sciences Departments	50%	5
Social Sciences Departments	50%	5
Non-gamer/Rare Gamer	40%	4
Occasional Gamer	40%	4
Frequent Gamer	20%	2
Previous AR/VR Experience	40%	4
No Previous AR/VR Experience	60%	6

Research Question 3 entails the qualitative part of this study. It aimed to understand participants' experiences during the Mixed Reality-based mental rotation training. For gathering the qualitative data, the researcher conducted semi-structured interviews following the completion of the training with some of the participants. The researcher herself conducted the interview. She was also present in all training sessions and took observation notes that can consolidate the results of the qualitative analysis.

The qualitative part of this study was carried out with thematic analysis. Thematic analysis is “a method for identifying, analyzing and reporting patterns (themes) within the data” (Braun and Clarke, 2006). From the interview transcriptions, 4 themes, 10 categories, and 27 codes were generated to describe the learning

experience that took place in this study. The themes and categories extracted by the researcher are listed in Table 4.24.

Table 4.24 Themes and Categories

Theme	Category
Mixed Reality Tool for Spatial Training	Representation
	Interaction
	Support
Cognitive Aspects	Metacognitive Strategy
	Mental Rotation Strategy
	Implications
Affective Aspects	Intrinsic Motivation
	Self-Efficacy
Technical Aspects	Side Effects
	Glitches

As can be seen in Table 4.22, the Mixed Reality-based training experience yielded four broad themes: *Mixed Reality Tool for Spatial Training*, *Cognitive Aspects*, *Affective Aspects* and *Technical Aspects*. Within the theme of *Mixed Reality Tool for Spatial Training*, participants highlighted the representational and interactional capabilities of this technology and the support mechanisms offered within the training system. The theme of *Cognitive Aspects* encompasses the metacognitive strategies enabled by the training, mental rotation strategies used by the participants and the implications of the training experience on participants' daily lives. The theme of *Affective Aspects* touched upon the aspects of motivation and confidence invoked by the experience. Finally, the theme of *Technical Aspects* entail the side effects and glitches experienced by the participants.

4.3.1 Mixed Reality Tool for Spatial Training

This is the most frequent theme in the analysis which is related to the perceptions of the participants about completing spatial ability training in the Mixed Reality

environment. It entails three categories and ten codes listed in Table 4.25. Participants intensely commented on the representational and instructional capabilities of this tool and how it supported them through practicing mental rotation.

Table 4.25 Categories of the *Mixed Reality Tool for Spatial Training* Theme

Category	Code	Frequency
Representation	Visualization/Imagining	10
	3-D/ All-angles View	10
	Navigation/Exploration	10
	Authenticity	8
	Animations/Visual Simulation	6
Interaction	Learning by Exploration	9
	Using Gestures	7
Support	Guidance	6
	Module Content	5
	Repeatability	3

4.3.1.1 Representation

The representation category is about the way of presenting information that the Mixed Reality-based training offers. Mental representations can be influenced by how information is presented. Consequently, the 3-D holographic display appeared to influence the mental processes of participants.

Visualizing/Imagining: A mental rotation task calls for transforming objects in the mind and using spatial training tools aim for cultivating such processes. All of the interviewees often emphasized the visualization processes that are essential for performing a mental rotation. The interviews showed that actions such as "*imagining*", "*experimenting with the eyes*", "*drawing the rotation in my head*" and "*visualizing*" are facilitated by the three-dimensional environment. Instead of pressing random buttons to find the solution to rotation problems, participants

experimented with hand movements and engaged in strategic planning by thinking aloud.

“When rotating the objects [in the application], I imagine what the next position will be. Then I press the button, the thing I imagined is right before my eyes.” (Participant #37)

“I rotated the objects in my head while also using my hands to perform the rotation.” (Participant #6)

3-D/ All-angles View: Different representational devices support exploration of content to some degree. In the Presence Questionnaire, participants were asked “*How well could you examine objects from multiple viewpoints?*” and a very high average score was obtained (4.75/5.00). This meant that generally, participants could examine the objects in detail. All interviewees appreciated the 3-D representation of the training material. They thought it was interesting and helpful for understanding the content.

“The fact that we can see the object smoothly from all sides allows us to visualize it in a three-dimensional way and helps us to focus on solving the problem easily.” (Participant #18)

This feature also strengthened participants’ sense of being in control.

“In the 3-D environment, the feeling that I really see that object helped me think more easily. It helped me to make clearer decisions, made me feel empowered, and made learning easier.” (Participant #33)

Navigation/Exploration: The participants described the training in the immersive 3-D environment as “*learning by experimenting/exploring*”. Participants who have difficulties in solving rotation problems in a three-dimensional environment may need more visual information about objects. The participants used the opportunity to look at the holograms from every angle by wandering around them. This behavior, which is used automatically when needed, increased in the third level of the training, where rotation problems are more complex. In addition, when solving challenging

problems, the students approached the holographic objects and examined the upper surfaces by going on their tiptoes and lower surfaces by bending over. These features added flexibility to the training and made the students feel like they were really in that environment. Although the real world continues to be seen with the integrated virtual objects when wearing the MR goggle, for some students this experience was enough to forget about the outside world.

“When I was in doubt, I wandered around the object to fill the gaps in my mind. That really helped.” (Participant #10)

Authenticity: An authentic training experience would call for an environment in which the participants make sense of the training objects as if they do in the physical environment. In the Presence Questionnaire, participants were asked *“How involved were you in the virtual environment experience?”* and a high average score was obtained (4.61/5.00) while 5.00 meant that they were involved in the experience. Enabled by 3-D representation, the training content seemed very realistic to most participants. Although they could still partly see the physical world, they appeared quite immersed in the training environment. One of them even said that she was confused for a short while when she removed the headset after the training session.

“You step into a virtual world and every move you make is real. You can actually touch, hear and see. And for example, when you rotate the shape, the shape you rotate in your mind is right in front of you.” (Participant #53)

“Wearing the headset, you get isolated from the world. There are only the things before you, virtually. You can directly control them. You get used to the ‘screen’... I was a bit bewildered when I took the headset off. Going back to the real world...” (Participant #41)

Animations: Animations were found helpful by most interviewees. The headset was said to *“show everything”*. The animations provided a visual simulation of the to-be-performed rotations. The participants found the animations useful and stated that the replay feature helped them understand better. Many students simulated the action of

rotation with hand movements simultaneously, even while watching the passive animation without any instruction to use their hands.

“It was smart that the objects were rotating, we understand better when it is rotated, say, 90 or 180 degrees.” (Participant #33)

4.3.1.2 Interaction

This category encompasses the interactional affordances of the Mixed Reality-based training system: enabling wandering behavior and gesture-based input method.

Learning by Exploration: Many interviewees commented that the fact that they could interact with the training content was both interesting and effective. One participant said that the training module “*triggered*” them to action. Rotating the objects within the Mixed Reality environment acted as a verification of the rotations they mentally performed.

“...Then I tried things out and started to get the idea: It will happen this way, not that way...” (Participant #10)

Using Gestures: Gesture-based interaction was used in the Mixed Reality-based training. In the Presence Questionnaire, participants were asked “*How well could you move or manipulate objects in the virtual environment?*” and a high average score was obtained (4.65/5.00). Generally, participants thought that they could interact with the objects comprehensively. Participants interacted with the training environment with the *airtap* gesture, which allows pressing virtual buttons from a distance by tapping the index finger and the thumb while looking at a hologram. Participants were glad to interact with their hands alone, without the need for another tool. Being able to select, rotate and manipulate holograms is a feature that students find useful for their mental rotation ability. Although no real *touch* action takes place, participants often describe their interactions with holograms with this word.

“Rotating the objects using my hands felt so real.” (Participant #6)

“When I use my fingers, it's like I'm rotating that shape that way. It's like I'm really there, not virtual.” (Participant #41)

4.3.1.3 Support

This category comprises of the supporting features of the training that participants viewed as particularly beneficial for understanding.

Guidance: The design of the training application is fairly simple with some additional features that participants could use if needed. Some interviewees found audio instructions helpful for monitoring their current progress within the module and comprehending the task at hand. One student noted that the sound effects matched the user's actions well to create a realistic experience. Hints provided in the *specified* rotation problems were found useful for understanding the topic.

Module Content: Animated examples that show the user how a rotation is performed were found helpful by many interviewees. The introduction part that provides information about the mental rotation process itself and how people visualize the rotations in their minds were considered effective. Specifically, the introduction of the canonical axes whereby a 2-D coordinate system transforms into a 3-D coordinate system was found a better approach than directly saying “*Come on, rotate this!*”.

“It was easier for us to understand because we practiced a lot with the examples.” (Participant #21)

Repeatability: This code was extracted from three participants' interviews. It is expected since they started the training with highly different levels of spatial ability. Therefore, some of them may not have needed to watch the animated rotations repeatedly. However, the ones that use this feature appreciated it.

“I took care to comprehend the idea of the rotations in the training. For this, many times I did the same thing over and over again.” (Participant #21)

“It was engraved in my mind after watching several times.” (Participant #6)

4.3.2 Cognitive Aspects

This theme is related to the perceptions of the participants about how training in the Mixed Reality environment changed or supported their cognitive processes during mental rotation. It entails three categories and seven codes listed in Table 4.26.

Table 4.26 Categories of the *Cognitive Aspects* Theme

Category	Code	Frequency
Metacognitive Strategy	Thinking by Axes	10
	Awareness of Prior Learning Gaps	6
Mental Rotation Strategy	Piecemeal Strategy	9
	Holistic Strategy	1
	Strategy Change	2
Implications	Adaptation to the Physical World	7
	Comparison with Traditional Learning Experiences	5

Participants frequently touched upon the thinking processes promoted by the training tool and how it facilitated learning. Their accounts of the training experience revealed that they often engaged in self-monitoring practices.

4.3.2.1 Metacognitive Strategy

This category revolved around the episodes in which the student thought about their own thinking processes. Students were aware that the training changed their way of thinking which makes rotating easier. They also evaluated their understanding and

expressed their opinions on why mental rotation might be more difficult for them before.

Thinking by Axes: Thinking about the axis of rotation is a natural starting point for some of the participants. According to all interviewees, a useful feature of the training is that the 3-D axis arrows integrated at the center of the holograms in the animations trained them to think in an axis-oriented manner. Observations and interviews showed that the majority of the participants did not have a complete understanding of the x , y , and z axes before the training. It has been frequently stated that especially the x and z axes were confused with each other. As a result of the introduction of the axes and their use in animations, the students expressed that they visualize them in their minds even when the objects do not have axis arrows placed in the center.

“I learned about rotations in the x and z axis, so now it comes easier when I'm picturing something rotating in my head.” (Participant #33)

“But now, after doing it with the goggle, when I look at an object, I can imagine it as if the axes are running through it and see what would happen if I rotated it”. (Participant #10)

Awareness of Prior Learning Gaps/Misconceptions: Many interviewees observed that they had misconceptions about rotating 3-D objects in their minds before completing the training.

“[Before the training] I was not able to imagine it completely, I was just trying to reason out which surface of the object would be visible from this side.” (Participant #6)

“[In the pretest], I was doing without thinking about the planes. This time [in the training], when I solve the problems, I was imagining that the object was rotating in the x , y , or z axes. This time I've done it in the planes. This time I really tilted and raised the figures in my head.” (Participant #37)

“It's easy when there are only x and y, in two dimensions. But when the third dimension came about, when z came about, I couldn't distinguish between x and z in the first test. The training taught me that the object rotates this way [showing with hand gestures] in z.” (Participant #33)

4.3.2.2 Mental Rotation Strategies

Participants made use of the representational capability of the headset that enables viewing virtual objects from all possible angles, including top and bottom views. Interviewees were asked about the strategies they used while solving rotation problems. Observations and participants' verbal expressions provided further hints. Among the strategies devised by Just and Carpenter (1985), *mental rotation around the standard and task-defined axes* were employed. Additionally, the *perspective change* strategy, which involves mentally changing the position of the self was employed by some of the participants: *“I was thinking about from where I am looking at the object.”* The training module may have facilitated imagining how one object would look if they looked from different angles by enabling moving around the virtual training objects. *The comparison of orientation-free descriptions* was also evident in participants' verbalizations of their strategy: *“Firstly, I visualized what happens if I move some sharp points of cube-like parts of the object.”* *The comparison of orientation-free descriptions* corresponds to the *piecemeal* strategy in the other common categorization of mental rotation strategies.

Piecemeal Strategy: Individuals who use the piecemeal (analytical) strategy analyze the object first and refer to a part of the object for rotation (Sorby, 2009). Several remarks were made about using *piecemeal* strategies.

“I looked at one part of the object and decided the rotation angle.”
(Participant #41)

“I move the objects starting from its edges. I keep one of the edges in my mind, I find where it [the application] takes that edge to, how much and to what degree it is rotated.” (Participant #37)

Holistic Strategy: In holistic strategy, the object is handled as a whole while the rotation task is being performed in the mind. Remarks to using *holistic* strategies cannot be distinguished as easily as *piecemeal* strategies in students’ accounts of how they approached the problem. In only one instance, the use of a holistic mental rotation strategy was detected.

“This is how I did it in our first test, I was holding and placing object parts, and sometimes I made mistakes. But with the headset, I learned to do it using the x-axis, y-axis, and z-axis. I also tried this in the test. Focusing on one part of the object creates problems after question 10.” (Participant #10)

This may result from the little use participants made of thinking about the target stimuli as a whole while rotating it or they may have taken this approach for granted and did not comment on its use without further prompting.

Strategy Change: Mental rotation strategies that one individual uses can change both over time and from task to task. In two instances participants noted a shift from one strategy to the other.

“At first I looked at the whole object. Then I realized that I can understand by looking at one part of the object.” (Participant #18)

4.3.2.3 Implications

This category involves the broader perspective that the interviewees took while evaluating how a Mixed Reality-based spatial ability training system can affect their perceptions about the physical world and modify their views about traditional learning practices.

Adaptation to the Physical World: Most of the interviewees observed the effect of the training with real-life objects and actions:

“...after a while, I feel my mind opening up. In real life, I feel as if I can see inside objects as well.” (Participant #20)

“Now I can visualize things in my head. While walking on the road after the last training session, I thought to myself, “I wonder what if this house rotates upside down or if it rotates horizontally”. Now I can picture them in my head. Before I could visualize them in bits and pieces, I had to draw pictures. But now I can picture it much more easily in my head.” (Participant #22)

“I started visualizing more easily in my mind, which I normally wouldn't be able to do. Because theoretically... we couldn't rotate it from the outside as it always came across on paper, or because a teacher could not rotate the object as it was...but we were able to do it with the headset.” (Participant #37)

This code goes back to the *Authenticity* of the training environment as because the training experience feels real, its effects can extend beyond the training sessions. The realization that spatial ability is situated within the physical world appears to allow them to connect the training and perform mental rotation with everyday objects.

Comparison with Traditional Learning Experiences: The technology used in this study was new to all participants. Half of the interviewees compared the Mixed Reality-based spatial ability training experience to the more traditional educational practices and all preferred it over those practices.

“We had similar topics in high school. We were expected to rotate on paper. But I think it would be great if a program like this could be done in every school then. We could have done it learning by ourselves.” (Participant #21)

Because it is different from traditional learning environments, participants compared Mixed Reality with those technologies. They especially recognized that it could promote self-directed learning.

4.3.3 Affective Aspects

This category gathers together the motivational characteristics and the confidence facilitated by awareness of progress in the training experience. It entails two categories and six codes shown in Table 4.27. Although it was a challenging topic, students mostly had positive feelings about the training.

Table 4.27 Categories of the *Affective Aspects* Theme

Category	Code	Frequency
Intrinsic Motivation	Fun	7
	Satisfying	6
	Intriguing	2
	Pleasantly Challenging	2
Self-Efficacy	Awareness of Progress	10
	Levels Getting Easier	7

4.3.3.1 Intrinsic Motivation

Fun: Many interviewees said that they enjoyed using the application, and doing things in 3-D. This was also evident in the training sessions in which the researcher observed that some participants approached the application as if it is a game. One participant even said that she had a dream about “*rotating things with the headset*” previously.

“It was fun, rotating those shapes, doing things. It was very exciting to wonder if your decision was right or wrong. I was very happy doing all of it.” (Participant #20)

Satisfying: Most of the interviewees said that they were lucky to participate in the training. They found it satisfying that they could see the training objects just the way they can see things in the physical world.

“At first you are trying to get to know the axes. When you rotate it, it becomes easier to understand which way it rotates, because you understood it well before. I think it's something everyone should experience. I am so glad that I did.” (Participant #53)

Intriguing: In the Presence Questionnaire, participants were asked “*Were there moments during the virtual environment experience when you felt completely focused on the task or environment?*” and a fairly high average score was obtained (4.65/5.00). This indicates that generally, they concentrated on the learning content and the environment. Most participants were curious about the objects, which is supported by the application as it led them to explore the environment. They would wander around the holograms, and look at them from different angles to see the otherwise invisible surfaces. They also kneeled or raised on tiptoes to see the top and bottom surfaces. Some also mentioned this in the interviews:

“For some objects, you can't see inside when it rotates backward. I've looked a few times to see if there are any holes inside or on the back and if there are any different shapes. Out of curiosity, I also looked around so I could explore it.” (Participant #22)

Pleasantly Challenging: Although it varies from participant to participant, it was not rare to see signs of challenge during observations. Many exclamations such as loud “*Oh!*” sounds were made when a participant comes across a rotation problem that they think is difficult. The step-by-step rotation approach was used for neutralizing this initial confusion. Additionally, even though the application has a forgiving scoring mechanism that reduces points for false attempts as opposed to clearing out completely, it still managed to push participants to think before they act.

“Getting it right the first time makes one happy. It’s human nature. I tried to do it on the first try, too. I thought about it first, then I did it. I did the hard ones even better.” (Participant #18)

“When I used one of my tries, I was actually sure about what I would do, but I didn’t want to make another mistake. So I thought a little more.” (Participant #37)

4.3.3.2 Self-Efficacy

In this category, references to beliefs on the potential increase of performance are gathered. The increased confidence reflected by the participants’ expressions stemmed from thinking that the Mixed Reality-based training made mental rotation easier for them.

Awareness of Progress: Most of the participants believed that after the three-dimensional mental rotation training, their competencies in mental rotation ability have increased. The majority of them think that they can solve rotation problems not only in a three-dimensional environment, but also on paper; they can solve the mental rotation test more easily, and their abilities have improved.

“I had just seen the z-axis on two-dimensional paper at school. Now, if I was to take a similar test, it [the application] is very useful, I think I have improved myself in this subject. I was able to rotate objects myself before watching the animations, especially towards the final stages.” (Participant #10)

“I couldn’t rotate objects in this way in the first test, I couldn’t think I such detail... I think now I can rotate better because I practiced.” (Participant #22)

Levels Getting Easier: Although the application was designed in three levels getting progressively difficult, most participants did not find it getting more complex at each

level. Many of them thought it was getting easier to make decisions towards the end of the training due to the practice they got.

“You think it is a bit challenging at level 1, but in 2 and 3, because it gives us an example...it shows you the direction.” (Participant #37)

“I'd better do the test I did on the first day right now because the training improved me. At first, you are trying to get to know the axes. When you rotate it, it becomes easier to understand which way it turns, since this already sank in later on.” (Participant #41)

4.3.4 Technical Aspects

This theme comprises of the references that the participants made about the technical issues related with using the Mixed-Reality based training. It entails two categories and four codes presented in Table 4.28. While mention to these codes is infrequent, they were included in the analysis to be interpreted together with the researchers' observations from the training sessions.

Table 4.28 Categories of the *Technical Aspects* Theme

Category	Code	Frequency
Side Effects	Eye Strain	3
	Headache	2
Glitches	Getting used to Hand Gestures	2
	Response Time	1

4.3.4.1 Side Effects

For avoiding possible side effects of using the goggle during the training, a multi-session training with short sessions (approximately 15 minutes each) was designed. On the other hand, in order not to limit their experimentation with the holographic objects, the participants were allowed to spend as much time as they wanted in each

level of the training. Participants spent 30-74 minutes in the training and 3 sessions were completed in an average of 45 minutes which was our original estimation. It should be noted that solving mental rotation problems is inherently challenging and can induce a high cognitive load on some of the low spatial ability participants which may also be a reason for side effects such as headaches. One student illustrated this point by saying *"I am learning but it exhausts my brain"*.

Eye Strain: The common reason for using such colors is to attract attention to the content. In the Mixed Reality-based environment, 3-D representation promptly immerses users in the learning content. In the design of the application, bright colors were avoided as much as possible. Backplates with darker colors were employed. On the other hand, lighter colors were used in some parts to achieve the contrast level needed for clarity. 2 interviewees mentioned situations such as *"mild eye strain, similar to the one that occurs when I use my phone for a long time"* and *"it made my eyes strain, maybe because I wear optical glasses... For a short time, not much..."*.

Headache: The variability in the session duration results from the fact that the participants' pre-mental rotation ability scores were highly variable. Many high spatial ability participants completed the training module in shorter sessions. On the other hand, a few low-ability participants had single sessions exceeding 40 minutes. As a result, 2 participants mentioned *"mild headache"*.

"The headset is kind of heavy... when I first took it on, and that session was a bit longer... I thought "I have a headache" when I took it off." (Participant #37)

However, despite of the continuous checks that the researcher made, no simulator discomfort was observed or expressed by the participants to the degree that could cause delaying the session or termination of participation.

4.3.4.2 Glitches

Getting Used to Hand Gestures: In this study, gestures to be used for interacting with the Mixed Reality headset were demonstrated beforehand by the researcher. Then, participants were taken through the Microsoft Tips application which helped them to familiarize themselves with the environment and the gestures before using the application. The instructor further helped the students during this familiarization process. Nevertheless, for a few participants, it was harder to get used to hand gestures. In this respect, 2 participants said that they sometimes had difficulty performing the gestures correctly. This may be partly because they may have found it difficult to “unlearn” the gesture-like touches they often do on the screens of their smartphones.

“It sometimes does not get my hand movements.” (Participant #33)

“It took me some time to get the finger movements right.” (Participant #41)

Response Time: One participant from the Computer Engineering program commented that it would be better if the interactions were a little faster. This code did not emerge more than once in the interviews; however, the researcher observed in the in-session talks with the participants that there is a 1 or 2 seconds delay between the “transitions” from one episode to another which made some participants unsure that they used gestures correctly to start the action. This may result from skipping the ‘release’ movement required for the hand gesture to be completed and recognized by the sensors integrated in the headset. On the other hand, this delay was not present when a participant is interacting with content that is in the same episode. Therefore, it was not noticeable for most participants. Another indicator of the degree to which a delay was a part of their experience, the score of the related item in the Presence Questionnaire can be examined. Item 19 which asks “*How much delay did you experience between your actions and expected outcomes?*” received the lowest average score (3.65/5.00). 5 meaning “no delay at all”, however, the value is still quite acceptable and well above the medium value.

4.4 Summary

In this chapter, the qualitative and the quantitative results of this study are presented. The quantitative results of this study indicate that there is no significant effect of stimulus dimensionality on mental rotation ability performance. However, the two test conditions were different in terms of cognitive load. For both sub-dimensions, mental load and mental effort, the cognitive load was higher in the two-dimensional test than in the three-dimensional test. Although it was a newer technology for a test medium, Mixed Reality environment was used fairly easily by the students. As expected, the level of success in the test items decreased as the difficulty level of the questions increased.

The participants' mental rotation ability after the Mixed Reality-based training was significantly higher than before the training. The qualitative analysis revealed that the participants perceived the Mixed Reality-based training as a fun and authentic experience that cultivated visualization processes and exploration by enabling all-angle view, navigation, and hand gestures. Before the training, males outperformed females in the two-dimensional test but not in the three-dimensional test. After the training, the gender difference is reduced to a statistically non-significant amount. No significant difference was found between the development level of the students' mental rotation performance after the mental rotation training in the three-dimensional environment by items with different complexity scores. There has been an equal level of improvement for each difficulty level. The module encouraged participants to think by axes and affected their thought processes after the training. All interviewees were aware of their progress. The level of improvement in mental rotation ability is not related to the sense of perception or cognitive load in the Mixed Reality-based training experience. Overall, the sense of presence in the training environment was very high and side effects such as mild headache and eyestrain were to a minimum degree and did not hinder participation.

CHAPTER 5

DISCUSSION

Mental rotation ability, a type of spatial ability, involves visualizing the results of manipulating two or three-dimensional objects in the mind. Not only it facilitates many everyday activities but also is important for academic and professional success in several domains. In the 2-D tests that are heavily used for measuring mental rotation ability, there are transformations from 2-D to 3-D (and *vice versa*) seen as redundant for measuring an ability that entails thinking in 3-D (Strasser et al., 2010) which may induce a heavier and extraneous cognitive load on the individual (Lee et al., 2016). In tests carried out in three-dimensional environments, it is possible to eliminate the dimension transformations that are not essential for the mental rotation process.

Many training interventions have been implemented to improve mental rotation ability most of which entailed 2-D representations in the learning content, which may not completely support understanding the mental rotation processes of 3-D objects. 3-D mental rotation training can overcome some of the limitations of two-dimensional training systems. With the growing demand for the use of three-dimensional learning environments, it is possible to examine this type of spatial ability with more authentic stimuli; and purposefully and promptly remediate it with training in these environments.

This study aimed to measure and improve mental rotation ability and explore the learning experience in a Mixed Reality-based spatial training environment. Therefore, a mixed method research design was employed for answering the research questions of this study. Participants' mental rotation ability was measured with computer or Mixed Reality headset-based tests to understand their baseline ability levels. We also designed and developed a one-week Mixed Reality-based training for improving mental rotation ability. Participants completed three targeted sessions

using the headset and their mental rotation ability was measured again. After the intervention, semi-structured interviews were conducted. The results revealed that the Mixed Reality-based test did not differ from the 2-D computer-based test in terms of accuracy but it induced a lower cognitive load than its 2-D counterpart. The Mixed Reality-based training was found effective in improving mental rotation ability. The interviews indicated that the Mixed Reality-based training experience was easily adopted and appreciated for its representational and interactional capabilities for most of the participants. Side effects were at a minimum. Therefore, it can be said that Mixed Reality can be a suitable medium for testing and training mental rotation ability and is acceptable by undergraduate students.

With its way of representation and interaction, Mixed Reality can help ‘situate’ spatial problems (i.e. mental rotation problems) within the user’s environment. Therefore, it can off-load part of the mental rotation task onto this environment and enable users to automatically utilize it for solving problems (Brown et al., 1989). Placing virtual geometrical objects in front of the participants and allowing them to observe them from every possible angle, mental rotation problems were situated in the physical world in this study. The solution to complex spatial problems was “embedded in ongoing activity”, which is moving around the holograms, standing up on tiptoes to see the top surfaces of the training objects, kneeling to see the bottom surfaces, and going closer to and stepping away from the holograms for zooming in and out. The Mixed Reality environment authentically presents the task and influences how the user perceives the activity (mental rotation problems). More complete perception, then, facilitates users’ actions that contribute to learning.

3-D mental rotation problems require people to visualize the consequences of the rotations performed on objects and in a way, think in three dimensions. Therefore, the Mixed Reality-based mental rotation training module is intended to achieve more effective mental rotation problem-solving by facilitating better mental representations by providing 3-D holographic representation. Holographic representations and all-angle views in the Mixed Reality environment can contribute to spatial problem-solving. Thus, one explanation to the effectiveness of the module

could be that it achieved a cognitive fit (Vessey, 1991) with the mental rotation problems by displaying the information in a highly visual and authentic way.

5.1 Effectiveness of Mixed Reality-based Training

The effectiveness of the Mixed Reality-based training application designed and developed in this study was explored with the following research question:

Can mental rotation ability be improved with a Mixed Reality application using three-dimensional objects?

In this study, we designed and developed an immersive spatial ability training module. Mixed Reality-based training, consisting of three short sessions with an average duration of 45 minutes, improved the mental rotation ability of undergraduate students with an effect size of $d=.59$. Although the needs of the individual may differ, this type of spatial ability can be raised above a certain level in a short period. It is important to note that the improvement could have been larger if the training duration was longer. In the future, immersive spatial training with more sessions can be designed. However, the sessions should be still shorter than 40 minutes because students may experience side effects due to the elongated use of a headset.

Most of the existing AR-based mental rotation training systems were still bound by traditional screens. (Ha and Fang, 2018; Hoe et al., 2019). To elude the use of AR markers, virtual manipulatives with attached sensor boards (Ha and Fang, 2018) or Leap Motion devices attached to HMD goggles were employed (Ariali, 2020). In the present study, the training application is presented on a “screen” with a wide field of view and it exceeds the representational capacity of traditional screens by allowing free navigation around holograms. Virtual object rotations are performed using hand gestures in Microsoft HoloLens 2 environment which gives a “hands-on” feeling with motor manipulation. Using Mixed Reality, the reference point for the rotations

is the physical world in the training module which provides context to the axis arrows placed in the center of the objects while performing rotations on virtual objects.

Some of the previous 3-D mental rotation training systems employed the existing PSVT:R test stimuli as training content without any modification other than the addition of color and rotation axes (Alqahtani et al., 2017). Ariali (2020) modified the standard MRT items to increase the difficulty for training. In the present study, three-dimensional objects structurally similar to the stimuli in the PSVT:R test were designed and used in the rotation training. Since it can encourage analytical strategy, color was not used for distinguishing object surfaces from each other. Passive and interactive animations were jointly used to improve students' mental rotation ability.

As mentioned extensively in the interviews, the use of passive and interactive holographic animations helped students to visualize the rotations in their minds. Furthermore, the qualitative analysis showed that the application facilitated “*thinking by axes*” which allowed them to reorganize the existing visual information for problem-solving. As Kosslyn et al. (2006) pointed out, this is how visual imagery functions, and hence, it is important for success in several domains.

The possibility of a multiple-angle view, which was discussed in Rafi and Samsudin (2009), was taken one step further in this study, and the participants were allowed to solve mental rotation problems by navigating around holographic objects to complete their mental models more naturally. In Molina-Carmona et al. (2018b), participants who completed Virtual Reality-based training showed an increase of 3.17 points in the PSVT:R test. While all participants in their study were engineering students with typically higher spatial ability ($M = 22.00$), the group in the present study had lower ($M = 15.57$) mental rotation ability at baseline. This may have caused a relatively higher score increase. Traditional two-dimensional methods and the three-dimensional immersive environment are equally effective for students with high spatial ability (Martin-Gutierrez et al., 2015). Such findings may indicate that for certain groups with high spatial ability, the facilitating effect of immersive environments is not essential. On the contrary, lower-ability groups may need more

the form of representation of the three-dimensional environment that assists the mental rotation processes.

Mixed Reality-based mental rotation training developed in this study can improve this spatial ability with a short-term intervention. In addition, the effectiveness of the training was demonstrated with the standard two-dimensional test, as well as the three-dimensional version of the mental rotation ability test taken in the same environment as the training. In this study, there was a higher improvement in the two-dimensional PSVT:R ($M = 5.32$) followed by the three-dimensional test ($M = 5.24$) which is not statistically different. Improvements in the three-dimensional test can be due to the elimination of “dimensionality crossing” and achieving a cognitive fit between information representation and spatial task when the effectiveness of a 3-D training environment is measured within a 3-D environment. Effectiveness in different dimensionalities should be re-examined with longer training and more participants.

5.1.1 Gender Difference in Mental Rotation Ability Before and After the Training

The difference between male and female participants’ mental rotation ability was investigated with the following question:

Is gender difference observed in mental rotation performance in the test environments?

According to pre-study analysis results, a gender difference was present in the mental rotation ability of the participants. As is the case with most prior studies, men outperformed women in the 2-D desktop-based PSVT:R. This finding also aligns with the result of the meta-analysis (Maeda & Yoon, 2013) with 40 studies conducted for investigating gender differences in the mental rotation test employed in this study, PSVT:R. On the other hand, a gender difference was not observed in the 3-D Mixed Reality-based mental rotation test. This finding is also supported by some

studies that employed 3-D tasks other than the PSVT:R for investigating gender difference. For example, Parsons et al. (2004) and Neubauer et al. (2010) reported no gender difference in mental rotation ability when the tasks are presented in 3-D.

Neubauer et al. (2010) commented that female disadvantage in 2-D mental rotation tests may not be due to the mental rotation process itself but to the necessity of extracting a three-dimensional image from a two-dimensional image. Similarly, Parsons et al. (2004: p.560) speculated that the confirmation of gender difference in paper-based MRT and the lack of gender difference in the virtual version of MRT may be due to the “differences in how males and females approach the two tasks or differences in the cognitive demands of the two tasks”. Although the former explanation still may be valid, in the present study the latter explanation has more basis since 3-D test was found to induce lower cognitive load than the 2-D test. With the Mixed Reality headset providing extra visual information about the stimuli, perceiving and comparing objects may have become easier for female participants. According to Rodan (2016), as a result of increasing interaction with new technologies, it is expected that gender differences will cease to be observed in mental rotation tasks in environments where these technologies are used.

Another important finding is that while there was a gender difference in mental rotation ability before the training, this difference disappeared after the training. Thus, as a result of the training given, the disadvantage of women against men in terms of mental rotation ability seems to have disappeared. This is contrary to Lin and Yeh’s (2019) suggestion that long-term training is required for closing the gender gap in spatial ability. Similar to Ha and Fang (2018), real three-dimensional stimuli and motion-based interaction helped increase mental rotation ability. Kornkasem and Black (2015) stated that training combining spatial cues and situated environments in cognitive processes is beneficial for individuals with low spatial ability. As it is often stated in the interviews, the design of the training module enabled individuals to become more self-confident about their spatial abilities.

Does the 3-D mental rotation training lead to a difference between male and female students' mental rotation ability improvement?

In this study, mental rotation ability developed equally in females and males as a result of the training. Whereas the expected male advantage was observed at the outset of the study, male participants were found to have increased mental rotation ability as much as female participants, who had relatively lower levels of ability. Therefore, the training was effective for both genders. In similar studies, Ha and Fang (2018) found that females benefited more than males from 3-D mental rotation training. Ha and Fang (2018) claim that 3-D touch-based training may help alleviate the prevalent gender difference in mental rotation ability reported in the literature. The contradicting result of this study may be due to different sample characteristics or the more immersive training environment. More studies are required for drawing conclusions on this matter.

5.2 Effect of Stimulus Dimensionality and Complexity

5.2.1 Effect of Stimulus Dimensionality

We investigated the effect of stimulus dimensionality on mental rotation accuracy with the following question:

What is the effect of the dimensionality of the test stimuli (2-D vs. 3-D) on mental rotation performance?

In this study, undergraduate students took the mental rotation test either on a computer or a Mixed Reality headset. Investigations on the three-dimensional measurement tool revealed that there was no difference in mental rotation performance between taking the PSVT:R in a two-dimensional computer or a three-dimensional Mixed Reality headset environment. A similar degree of test accuracy was measured in the two versions of the test. Price and Lee (2010) also did not find a difference in accuracy rates in spatial tasks presented on paper and 3-D projection.

On the other hand, et al. (2022) found that participants score higher in MRT using 3-D stimuli than in MRT using 2-D stimuli when they are both displayed on a headset. This difference may be related to the fact that although the time for familiarization with the headset was allocated and that they reported lower cognitive load than the 2-D group, the performance of the 3-D group may be hindered due to having to wear some accessories during the test. Lochhead et al. (2022) studied the effect of dimensionality on 2-D and 3-D mental rotation tests with a paired-sample design. Their procedure involved participants taking the two versions of Immersive MRT successively. As we thought that this type of design may result in a learning/practice effect, the 2-D and 3-D test scores in this study are obtained from different groups.

Connolly et al. (2010) used marker-based AR to understand its effect on paper-based mental rotation test performance. They noted that such visual aid especially benefits low spatial ability participants. Some participants in the 3-D test-takers noted that walking around the holographic objects would make the test easier; however, this was restricted in this particular study as we think this would give them an unfair advantage against the 2-D test-takers. As we were interested in the actual performances of individuals without unlikely boosts, the 3-D group was not allowed to look at test items from multiple angles. Nevertheless, the visual properties of the holographic display enabled them to perceive the virtual objects in three dimensions like tangible objects. This may also partly explain the lower cognitive load experienced in the 3-D test.

In subsequent studies, the three-dimensional test can be compared in two situations with and without navigation to understand what happens differently in terms of mental rotation performance if participants see 3-D virtual objects from all angles they desire. A similar comparison was made by Jeng and Liu (2016), who compared the computer-based versions of MRT, another mental rotation test, with and without interactive animation. Their results showed that especially females improved performance on the interactive test items.

5.2.2 Effect of Stimulus Complexity

The effect of the complexity of the test items on mental rotation accuracy was investigated with the following question:

How does stimulus complexity affect mental rotation performance in the 3-D test environment?

In the seminal work of Shepard and Metzler (1971), the mental rotation tasks were based on deciding whether the stimuli pair depicted the same object from different perspectives or completely different objects. Employing such tasks, the authors concluded that the response time in the mental rotation task increased linearly when the angular difference between the objects in the pair of stimuli increased. Known as the *Angular Disparity Effect*, this was the first examination of the effect of stimulus complexity on performance. The mental rotation tasks employed in the present study were more diverse in terms of object types, rotation phases and answer choices. Therefore, accuracy was chosen instead of response time as an indicator of performance to investigate how its affected by stimulus complexity.

The complexity index based on the PSVT item categorization of Onyancha et al. (2009) was based on the figure and rotation types in test items. In this study, when the mental rotation test items are classified according to the complexity index, it is seen that the level of item success decreases as the stimulus complexity increases. Accordingly, as the structural complexity of the shape used in the test item, the number of rotation moves required to reach the correct answer, and the rotation angle values increase, the probability of the participants answering that item correctly decreases. This was also the case with Chen and Yang (2014) who investigated the problem-solving processes of students during the online mental rotation test, PVRT (a shorter version of PSVT:R) using eye-tracking method. They concluded that accuracy performance was aligned closely with the rotation angle and the initial position of test items.

We investigated the improvement in mental rotation accuracy from the pre-test to the post-test in different levels of test item complexity with the following question:

Does mental rotation ability improvement remain the same for different levels of stimulus complexity?

No relationship was found between the complexity of the test items and the participants' rate of success specific to the items of that complexity value. Users increased their success in items with 2 to 6 complexity points at the same level. This finding is in parallel with Onyancha et al. (2009) that their Experimental group (with a pretest score of 60 percent or less) improved their scores in all question types such that there was no significant difference between them and the Intermediate group (with a test score between 60 to 80 percent) after Computer-Assisted Drawing-based training. Other studies also found that lower scorers in the pre-test improve more with 3-D training using various devices (Rizzo et al., 1998; Bell et al., 2018; Zhou et al., 2022).

At the end of the training in the present study, the participants were not only more competent in solving problems involving simpler shapes and rotation rules; but they also increased their competence in solving problems that involve multiple moves and complex shapes. This may result from changing mental rotation strategy as a result of the explicit training as well as adaptation to task difficulty by applying training experience through former test items (Kaufmann et al., 2008).

The type of all-around improvement in the present study is likely to be seen in groups that on average have 60 percent pre-test score like the one in this study. These are at the same time the group that need such training the most. Therefore, this result provides another evidence for the promising potential of immersive spatial training systems.

5.3 Cognitive Load in Measuring Mental Rotation Ability

5.3.1 Cognitive Load in Different Dimensionalities

The research question below investigated the effect of stimulus dimensionality on cognitive load:

What is the effect of the dimensionality of the test stimuli (2-D vs. 3-D) on cognitive load?

In this study, it was seen that the two-dimensional mental rotation test induced more cognitive load than the three-dimensional test in terms of both mental load and mental effort. Previously, it was found that three-dimensional virtual environments create less cognitive load in a spatial task than two-dimensional video (Dan & Reiner, 2017). In some studies, concerns have been expressed that immersive three-dimensional technologies such as Mixed Reality may create high cognitive load due to intense sensory cues used for fidelity. Specifically, Parsons et al. (2004) commented that spatial ability tests in 3-D environments are more visually complex than 2-D platforms which can make cognitive load higher in those. However, if these cues contain the necessary information to solve the problem and remove the uncertainty, they can alleviate the cognitive load.

Chen and Yang (2014) suggest that the cognitive load required for making sense of the material can be reduced if instructional design choices are made accordingly in presenting spatial tasks. In this study, before starting the test, orientation activities were carried out with the MR goggles, and care was taken to ensure that the training module is useful and easy to use. As a result, in a test environment where all participants are not accustomed to both the display device (Mixed Reality goggles) and the interaction type (gesture-based), the cognitive load of the users was lower than in the two-dimensional test environment entailing a computer screen and a mouse which they are familiar with. Similar to Dan and Reiner (2017), it was seen that the two-dimensional test induced more cognitive load than the three-

dimensional test in terms of both mental load and mental effort. This finding indicates that three-dimensional representation reduces the information processing load as was the case in Neubauer et al. (2010).

There may be several reasons for the lower cognitive load measured in the 3-D testing environment. Firstly, the hologram-like drawings in the 3-D test may have enabled easier perception of the mental rotation tasks than in the 2-D test presented on a traditional computer screen. Such representations might have been perceived as less confusing or stressful by the participants. Similarly, the 3-D test was shown on a Mixed Reality headset which may have allowed participants to focus better on the tasks with less distraction from the physical world. It is also possible that using gestures for selecting answer choices may have promoted the cognitive processes entailed in mental rotation.

The training module may also have mitigated the cognitive load inherent in mental rotation. Even in passive animation sequences where the rotation is to be watched only, the users accompanied the animations with hand gestures. In this way, they may have transferred some of their cognitive load to motor movements by providing coordination between their bodies and virtual objects (Jang et al., 2017). Similarly, wandering behavior may have transferred some of the cognitive load to the environment and allocated more cognitive resources to problem-solving.

Cognitive load can be considered in terms of redundant visual information as well. Lochhead et al. (2022) investigated the effect of the background used in IMRT by comparing a “clean” background that is simple and similar to previous mental rotation measurement environments and a “cluttered” background that contains a furnished virtual living room. The furniture in this case is not necessary for solving the mental rotation problems. However, background complexity did not influence MRT scores. In the present study, the 3-D test was displayed on a holographic panel outside of which participants could see the physical world. Although the panel can be switched off, experimenting with the background was not within the scope of this study. Nevertheless, it would be interesting to compare versions of PSVT:R with and

without a panel framing the test items to look further into the effect of the background. Probably immersive environments provide a setting that is not distractive by addressing the senses thoroughly.

5.3.2 Cognitive Load and Mental Rotation Ability Improvement

The relationship between cognitive load and mental rotation ability improvement in the Mixed Reality training module was investigated with the following research question:

Is there a relationship between cognitive load and mental rotation ability improvement in the 3-D training environment?

No significant relationship was found between mental rotation ability improvement with pre-test mental effort, post-test mental effort and post-test mental load. A significant relationship was found between the mental load in the pre-test and the development of mental rotation ability. Mental load refers to the load imposed by the cognitive task itself, as opposed to the mental effort that involves extraneous challenges during mental rotation. The significant relationship between the mental load in the pre-test and the development of mental rotation ability indicated that participants who improved more were the ones that struggled most during the mental rotation tasks before the training. If we assume that the most struggling students are the ones with the lowest levels of mental rotation ability, this interpretation also aligns with the studies reporting that low scorers in their pre-test benefit more from the 3-D VR-based mental rotation training (Bell et al. 2018; Zhou et al., 2022). However, we could not find another study that explicitly investigates the relationship between cognitive load and mental rotation ability improvement after an intervention. Therefore, more studies are needed for reaching a conclusion on this relationship.

3-D PSVT:R developed in this study does not disadvantage the participant in terms of cognitive load and measures three-dimensional thinking skills in a three-

dimensional environment. It can be integrated for similar training to be given in immersive three-dimensional environments and used instead of the two-dimensional version. This test can be used in departments such as Engineering where spatial ability is important for academic success. Additionally, the test module can be used as a mental rotation exercise by allowing participants to move around the shapes.

One final note on the cognitive load is about the change from the pre-test to the post-test. Although it was out of the scope of this thesis, additional statistical analysis of the cognitive load levels revealed a significant decrease in the case of 3-D mental rotation test from pre-test to post-test and not in the 2-D test. This may indicate that receiving the test in the training environment (i.e. Mixed Reality headset) could alleviate cognitive load of learners due to familiarity. However, a superior performance in mental rotation did not accompany the reduction in cognitive load. Overall, the relationship between performance and cognitive load is a worthwhile area for further investigation.

5.4 Sense of Presence and Effectiveness

The relationship between the sense of presence and mental rotation ability improvement in the Mixed Reality training module was investigated with the following research question:

Is there a relationship between feeling of presence and mental rotation ability improvement in the 3-D training environment?

There is no relationship between the sense of presence in the three-dimensional environment and the development of mental rotation ability. According to the Presence Questionnaire, the participants' sense of presence is high in the training environment (122 out of 145). Although presence may contribute to positive learning outcomes, about only one fourth of the reviewed studies reported such connection in Mikropoulos and Natsis' review (2011). Therefore, the relationship between

presence and learning is not clear and may be bound by the characteristics of the environment as well as the participants.

Foroughi et al. (2015) found a weak correlation between the sense of presence and mental rotation ability in three-dimensional environments. However, in this study, unlike that study, there was an experience involving multiple training sessions and audio narration. Moreover, training employed a set of stimuli different from the test. Comparisons with a more traditional setting can provide more information about the relationship between a sense of presence and mental rotation ability. Alternatively, comparisons in the context of mental rotation can be made for the more objective concept of immersion (Chang et al., 2018; Molina-Carmona et al., 2018a).

5.5 Mixed Reality-based Training Experience

The training experiences of the participants in the Mixed Reality-based environment were explored with the following research question:

How are the students' mental rotation experiences in the three-dimensional training environment?

The qualitative analysis indicated that the representational capabilities of the Mixed-Reality-based spatial training environment were highlighted and Visualization, All-angles View, Exploration, Authenticity, and Animations were found to be useful mechanisms and features that enhanced learning. The way of interaction using gestures led participants to freely explore the environment. While the application provided instructional support with audio instructions, hints, examples, and introductory material; repeatability was regarded as useful for getting more practice.

Since mental rotation and physical rotation share similar processes, performing physical rotation exercises can improve mental rotation ability (Gardony et al., 2014). Rotation actions performed by using hands-on virtual objects, which resemble manual rotation, may have contributed to the development of ability. In addition,

gesture-based interaction provided the participant with a sense of control, providing a more enjoyable and accepted experience (Lin & Yeh, 2019).

Regarding cognitive aspects, the application made participants aware of the misconceptions they had before the training and observe that these were corrected. Specifically, all interviews showed that the participants started to think by the axes and make more purposeful decisions while solving mental rotation problems. Interviewees' expressions mostly indicated the use of the piecemeal strategy, but also showed that their strategy may change depending on the task. For exploring mental rotation strategies better, the next studies may employ fewer rotation tasks and engage in more concentrated discussions with participants about their strategies. This was beyond the scope of this study.

The application was found fun, satisfying, intriguing, and challenging pleasantly. Most of the participants preferred this type of training rather than traditional approaches and expressed that the training led them to reflect on the physical world and perform mental rotations on real objects after the training sessions. All of the interviewees were aware of their progress and they felt that they were getting better at handling harder problems. No side effects were reported other than a few mentioning a "mild eye strain" and "mild headache". Some participants took time to get used to the hand gestures. Figure 5.1 summarizes the key characteristics of the Mixed Reality-based mental rotation training experience.

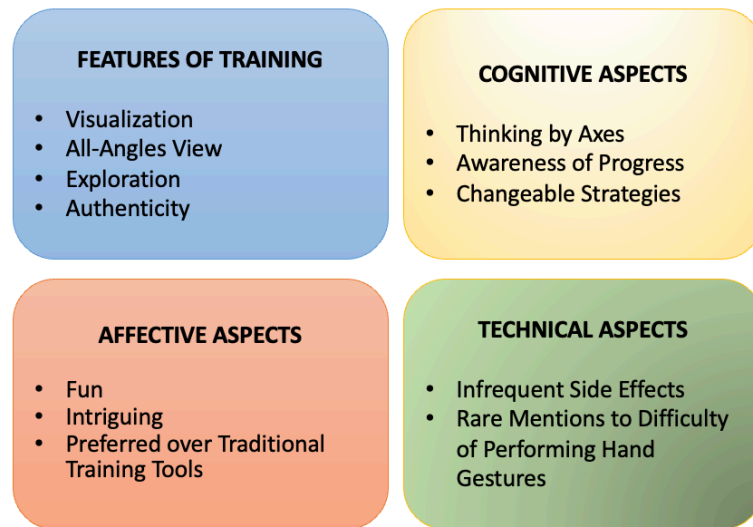


Figure 5.1 Summary of the Key Features of Training Experience

5.6 Limitations

While designing the study, we attempted to cover as many considerations as possible. However, there are some limitations. The primary limitation is the lack of a control group in terms of another training method. Comparing the effectiveness of the Mixed-Reality based training module with another tool could provide more information. However, as we focused on stimulus dimensionality, such a design would be hard to manage. Secondly, the hand movements used for rotation are not identical to real-life rotation gestures. In Microsoft HoloLens 2, it is possible to rotate holograms with one hand or with both hands, but this feature was not used in the present application as structured rotations are required around the x , y , and z axes, i.e., clockwise and counter-clockwise. For a more natural interface, full hand tracking should be achieved in Extended Reality systems.

Thirdly, we focused on accuracy in mental rotation performance, not on response time. Several mental rotation studies focused on response time alone or together with accuracy. However, in this study, almost all participants used all of the allocated time

for the test. This may be because the participants started to participate in this study with typically low spatial ability.

CHAPTER 6

CONCLUSION

This study aimed to measure and improve mental rotation ability in a three-dimensional environment. A spatial ability test was transferred into a 3-D environment and compared with the 2-D original test. A Mixed Reality-based spatial ability training module was designed and developed, its instructional effectiveness was examined and user experience within and about this new environment was explored. Therefore, the results can provide valuable insights to practitioners as well as teachers, researchers, educational software designers, and developers. The implications of the study are listed in Table 6.1 and explained in the following.

Table 6.1 The Implications of the Study

Implications on Education and Training
Offering built-in measurement in immersive spatial ability training
Effective spatial ability training with short sessions
Easily modifiable tool for different education levels
Preventing cognitive overload in three-dimensional environments
Promoting equal gender representation in spatial-ability related careers
Implications on Research
Documenting the effectiveness of 3-D training with 3-D as well as 2-D tests
Increasing the range of sensory input for effective spatial ability training
Offering design guidelines for Mixed Reality-based learning environments

6.1 Implications on Education and Training

6.1.1 Built-In Measurement In Immersive Spatial Ability Training

As educational practices using Mixed Reality technologies increase, the need for cultivating different cognitive processes is likely to arise. Increased exposure to 3-D visualizations will necessitate students to make sense of them to benefit from the representations of “complicated or imperceptible three-dimensional relationships and to generate more accurate mental representations of concepts and phenomena” (Stieff et al., 2005). Traditional measurement tools will not be sufficient to measure learning occurring in three-dimensional environments; therefore, measurements can be made in these environments. The 3-D test module developed in this study offers a new approach to immersive spatial training with built-in measurement. It can also be used as a mental rotation exercise simply by allowing participants to move around the holographic objects or making them rotatable for answering the questions.

This study shows that practitioners can benefit from immersive testing tools to enable valid measurement of cognitive abilities. It is important to know how they can support their students’ spatial abilities in three-dimensional environments as these become increasingly common. Specifically, teachers could consider utilizing the appealing aspects of such immersive tools for supporting the spatial problem-solving processes required in various domains. With lower-cost alternatives for state-of-the-art AR and VR displays instructors will find more opportunities to experiment with such applications.

6.1.2 Effective Spatial Ability Training with Short Sessions

With Extended Reality-based technology tools becoming more accessible, applications such as Three-Dimensional Mental Rotation Training, which can be effective with short sessions, might be more suitable for situations that require practical solutions. In our training, students interacted with the holographic content

to solve the mental rotation tasks, which engaged them in an interactive experience that involves both the virtual content and the physical surroundings. 3-D presentation of content and gesture-based interaction may be factors contributing to mental rotation ability improvement (Lee et al., 2016). Practice with holographic objects may have facilitated the construction of more complete mental models of the rotations. Specifically, this training allowed learners to wander around the holograms if they had difficulty comprehending the stimuli and enabled them to '*fill in the blanks*' in their mental representations. Furthermore, interviews indicated that the participants in this study were aware of the fact that their mental rotation performance increased in the course of the training program. This may be helpful for increasing learner motivation to engage with the training content.

The training module can be used for measuring first-year students' baseline spatial ability and as a supplementary tool for improvement in programs that require this ability for success. Students can use such training on their own and complete the training at their own pace. With a medium-high effect size calculated as close to 0.6, the technological expertise spent in the design and development stages will be able to pay off the financial and temporal resources.

In this study, the mental rotation training was designed to involve multiple but short sessions for avoiding possible side effects that may occur during the training. Each level of training lasted approximately 15 minutes while the total duration of training varied as in interactive animations participants were allowed to spend as much time as they wanted. The longest time one participant spent in a single session was 40 minutes which is likely to induce side effects such as headache when working with a headset. Thus, future Mixed Reality-based training should also keep the length of sessions below 40 minutes. Ideally, 10-15 minute multiple sessions may be appropriate for this environment.

6.1.3 Easily Modifiable Tool For Different Education Levels

The design and development of the Mixed Reality-based training module developed in this study took considerable time and effort. However, it can be modified to address different education levels with minimal content changes. Stimuli with different complexity can be included for different age groups. Rotation tasks can be made easier or more challenging by adding color to surfaces or different visual scaffolding mechanisms that are allowed in an immersive environment.

6.1.4 Alleviating Cognitive Overload In Three-Dimensional Environments

Extended Reality technologies can provide highly immersive experiences with advanced holographic content, surround sounds, and tactile interfaces. Especially in the game industry, this potential is utilized. On the other hand, designers and educators are concerned that a heavy cognitive load will occur as a result of the intense use of these features in three-dimensional environments. This study shows that with minimalistic and user-friendly designs, it is possible to prevent cognitive load from inhibiting learning in technology-based learning environments. High effectiveness and acceptable cognitive load levels will ensure that three-dimensional spatial ability testing and training modules are increasingly used for screening and training in academic and professional programs.

6.1.5 Promoting Equal Gender Representation In Spatial Ability-Related Careers

As in the previous studies, the fact that there is no gender difference in mental rotation ability in a three-dimensional environment can be interpreted as training in this environment may be more beneficial for women. In this study, with the mental rotation training that enables gesture-based interaction with real three-dimensional

stimuli, gender difference between women and men in mental rotation ability seems to disappear. Therefore, it has been revealed that the gender difference in this ability can be changed with interventions.

Gender differences in spatial ability can lead to gender differences in mathematics and science, and early performance on spatial tasks can predict future success in STEM domains (Reilly et al., 2017). Closing the gender gap with intensive training using Mixed Reality technology can positively affect women and individuals with low socioeconomic levels to pursue careers that require spatial abilities and their success in these professions. Therefore, it may contribute towards equal gender representation in the STEM domains. It should be noted, however, that early spatial training could be beneficial for preventing the gender gap from widening (Newcombe and Frick, 2010). Thus, the STEM curriculum may address rich visualizations of scientific concepts to integrate spatial tasks.

6.2 Implications on Research

6.2.1 Documenting The Effectiveness Of 3-D Training With 3-D As Well As 2-D Tests

In this study, a realistic and reliable measurement tool was obtained with the mental rotation test which was developed using three-dimensional models and administered in Mixed Reality goggles. In the scope of the literature review conducted in this study, no other studies were found in which a three-dimensional mental rotation ability test in an immersive environment is used to measure the effectiveness of a three-dimensional spatial ability training module. Three-dimensional training has been shown to increase success in the three-dimensional mental rotation test. Likewise, the training module improved the mental rotation ability as measured by the traditional two-dimensional test. Thus, a new study has been added to the studies showing that spatial ability can be developed with Mixed Reality tools and this was documented with two standardized tests administered in different dimensionalities.

The training application can be informative for instructional designers and researchers who will address spatial ability training in immersive environments.

6.2.2 Increasing The Range Of Sensory Input For Effective Spatial Ability Training

Mental rotation is still a challenging topic today. In this study, the participants mostly performed actions such as hand gestures and thinking aloud while solving rotation problems during training. The participants appreciated the realistic visuals, the audio instructions and the involvement of motoric manipulation with gesture-based interaction. The need to involve as many senses as possible in the mental rotation of the participants may be considered in future training. For example, rotation problems can be solved with input tools such as data gloves giving haptic feedback in the 3D environment.

6.2.3 Offering Design Guidelines For Mixed Reality-Based Learning Environments

Although considerable budgets are assigned to the educational use of Mixed Reality technology, well-designed targeted applications are still not common. User-friendly libraries and toolkits can smooth the learning curve in software development for Mixed Reality goggles and new applications can be created by instructional specialists. Software designers and developers can benefit from the comprehensive details this study provided on the practical considerations in creating Mixed Reality-based measurement tools and training modules.

Learning content design for holographic displays requires specific considerations. Based on Microsoft's (2021) suggestions, we list the general design recommendations for Mixed Reality-based training interventions derived from this study:

- The physical space should be designed beforehand to allow free navigation.
- The exterior lighting in the environment should be adjusted not to hinder vision.
- Where applicable, participants should be wearing the means of corrected vision before proceeding to work with the Mixed Reality headset.
- Depending on the device used, any calibrations should be completed before proceeding to the actual task to ensure accurate functioning and representation.
- Gestures should be practiced before proceeding to training tasks. They should not be complex or overwhelming to the degree that causes physical load.
- Bright colors should be used sparingly to prevent eye fatigue. For directing attention to the specifics of a task, they may be used in small areas.
- To avoid hand occlusion, menus with darker colors should be employed in the design.
- Where necessary, borders should be drawn on the training objects for eliminating jagged edges.
- Bold fonts should be used to avoid jittering.
- Sound effects should be used to enrich the experience with notifications of success and failure.
- Certain on-screen menu items can be designed in 2-D and arranged to appear on demand for avoiding clutter.
- Where possible, buttons should be designed to reflect the dimensionality (i.e. 3-D) of the spatial tasks. (i.e. locating 3-D curvy arrows for rotation buttons instead of textual buttons)
- Where possible, the first ‘scene’ of the task should be within the limits of the device’s field of view. For bigger objects, the zoom-in/out feature is necessary.
- For clear perception and easy manipulation of multiple objects within a single ‘scene’, a distance of 1.5 meters was found appropriate. This initial distance was employed to minimize unnecessary head and neck movements.

However, designs that involve large bodies (i.e. applications of architecture) would likely require different adjustments.

- Both text (on demand) and audio instructions should be provided. Audio instructions are especially helpful in hands-on tasks.
- Gamification elements might be integrated into the design to increase engagement with challenging tasks.

6.3 Suggestions for Future Spatial Ability Training Systems

While the interest in Metaverse is growing, we should be open to finding practical ways of carrying out various cognitive tasks in 3-D environments. New tests can be developed specifically for these environments besides the transfer of standard tests to the Mixed Reality environment as in this study.

Most of the 3-D mental rotation training research is conducted on undergraduate students. Future studies may focus on earlier grade levels to improve this ability earlier in students' educational experiences. Specifically, more studies on 3-D mental rotation training for preschool students could contribute to the field as it is recognized that mental rotation ability can be trained in the early years of education.

Specific design guidelines for immersive platforms should be elucidated through evidence-based studies. Perceptions in and about such environments should be investigated. Here are some suggestions for future immersive spatial ability training interventions:

Combination of authenticity and enhancement: While the benefit of 3-D mental rotation stems from the closeness to real-life physical rotation, AR/VR designers should look for smoother ways to represent the phases in rotation processes and allow for switching between these phases sometimes even more smoothly than physical rotation. Additionally, focusing on user acceptance and user-friendliness is important for such novel training environments (Chang et al., 2020).

Gesture and motion-based interaction for intuitive design: It has been noted in prior research that manual rotation and mental rotation share similar underlying processes (Wiedenbauer & Jansen-Osmann, 2008). According to Wexler et al. (1998), mental rotation is driven by the prediction of the visual consequences of an about-to-be-executed motor action. Using gesture-based interaction, 3-D training systems can provide a simulation of physical rotation to facilitate mental rotation. Thus, motion sensors are likely to be commonly employed for capturing gestures and body movements rather than several types of physical controllers to achieve a more intuitive and user-friendly design, especially in AR/VR environments.

Use of eye-tracking to measure cognitive load and establish typical behavior in mental rotation: Research that explores cognitive load and its relationship to the effectiveness of 3-D mental rotation training is scarce. To explore this question, future research might use different methods to obtain more diverse data on user behavior in spatial ability training in three-dimensional environments. For example, eye-tracking offers great opportunities for characterizing the cognitive processes involved in the mental rotation processes of different target groups. The parts of stimuli on which students focus most during mental rotation can help to understand the behaviors of low and high-ability students. For paper-based 2-D environments, this type of modeling was undertaken by Just and Carpenter (1985). Although an early remark was made about combining VR with an eye-tracking device by Parsons et al. (2004), there are still operational barriers to exploring eye movements in 3-D environments, such as the processing capabilities of common AR/VR devices and the difficulty of analyzing large amounts of data.

Employing adaptive systems: Wang et al. (2020) emphasized the need for systems that are responsive to individual student's strengths and weaknesses. To address different user needs, adaptive training offers content that is appropriate for different current ability levels. Adjusting difficulty according to learner needs can be an important focus for future systems.

6.4 Summary

In this study, a Mixed Reality-based spatial ability training module was designed and developed, and its instructional effectiveness was proven using both traditional 2-D and Mixed Reality-based versions of the “Purdue Spatial Visualizations Test: Rotation”. The mental rotation performance in 2-D and 3-D tests was not different while the 3-D immersive test environment induced lower cognitive load than the 2-D test environment. Interviews that explored the user experience within and about this new environment revealed that this immersive spatial ability training was appreciated for its representational and interactional capabilities. Participants were aware that the training changed how they approached mental rotation tasks and that it supported their progress. Gender difference in mental rotation ability was found only in the 2-D online test and not in the 3-D Mixed Reality-based test, and disappeared after the one-week training. Suggestions for future research include increasing the range of sensory input in spatial ability training, aiming for methods to achieve more realistic gesture-based rotation, searching for ways to achieve all-around eye-tracking of holographic content and focusing on adaptive systems. Design recommendations for immersive environments outlined important suggestions related to interface, environmental setup and interaction.

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APPENDICES

A. Consent Form

ZİHİNSEL DÖNDÜRME BECERİLERİNİN ÜÇ BOYUTLU ORTAMDA ÖLÇÜLMESİ VE GELİŞTİRİLMESİ:

Değerli Katılımcı,

Bu çalışma zihinsel döndürme becerilerini Artırılmış Gerçeklik ortamında geliştirilmesini hedef almaktadır. Bu amaçla, size 30 soruluk bir zihinsel döndürme testi uygulayacağız. Test bittiğinde size deneyiminiz ile ilgili sorular sorulacaktır. Test oturumunun yaklaşık 40 dakika sürmesi beklenmektedir. Daha sonra ise Artırılmış Gerçeklik ortamında gerçekleştirilecek olan üç oturumluk zihinsel döndürme becerisi eğitimi verilecektir. Bu eğitim sürecinin bir hafta içinde bitmesi planlanmıştır.

Çalışmanın herhangi bir noktasında sebep belirtmeksizin katılımınızı sonlandırabilirsiniz. Görüşmelerdeki herhangi bir soru size rahatsız hissettirirse soruya cevap vermek zorunda değilsiniz. Çalışmaya katılmadan vazgeçmenin size bir etkisi olmayacaktır. Bu çalışmada elde edilecek kayıtlar gizli tutulacaktır.

Eğer bu çalışma ile ilgili sorunuz varsa araştırmacı ile zeyneppiri@kastamonu.edu.tr adresinden iletişime geçebilirsiniz.

Bu araştırmaya katılmayı düşündüğünüz için teşekkür ederim.

Lütfen aşağıdaki soruları uygun kutucuğu işaretleyerek cevaplayınız.

	EVET	HAYIR
1. Araştırmacılardan yapılacak olan çalışma ile ilgili gerekli bilgileri aldım.	☐	☐
2. Yapılacak olan çalışmaya dair sorularım tatmin edici şekilde cevaplandı ve istediğimde başka soru sorabileceğimi biliyorum.	☐	☐
3. İstediğim takdirde sebep belirtmeksizin ve araştırmacı tarafından göreceğim muameleyi etkilemeksizin çalışmaya katılmaktan vazgeçebileceğimi veya herhangi bir soruyu cevaplamayı reddedebileceğimi biliyorum.	☐	☐
4. Araştırmacıya gizlilik ilkeleri doğrultusunda bilgi sağlamayı kabul ediyorum.	☐	☐
5. Yukarıda belirtilen şartlar altında bu çalışmaya katılmak istiyorum.	☐	☐
6. Toplanacak bilginin bu araştırmanın amaçları doğrultusunda kimliğimin belirlenemeyeceği şekilde anonimleştirilerek kullanılmasına izin veriyorum.	☐	☐

Katılımcı İmzası: _____ Katılımcı ID: _____ Tarih: _____

Katılımcı İsmi: _____

İletişim Bilgileri: _____

Araştırmacı İsmi: _____

Araştırmacı İmzası: _____

B. Demographic Survey

ID_____

Demografik Anket

Bu anket sizin hakkınızda temel demografik bilgileri edinmek amacıyla hazırlanmıştır. Verdiğiniz bilgiler yalnızca araştırma amacıyla kullanılacak ve gizli tutulacaktır. Katılımınız gönüllüdür ve takdir edilmektedir.

Lütfen aşağıdaki boşlukları veya ☒ kutucukları doldurunuz.

1. Cinsiyet: ☐ Kadın ☐ Erkek

2. Yaş: _____

3. Bölüm: _____

4. Sınıf: _____

Lütfen aşağıda uygun seçenekleri ☒ ile işaretleyiniz.

5. Hangi elinizi kullanıyorsunuz?

☐ Sol ☐ Sağ

6. Kendinizde olan göz rahatsızlıklarını işaretleyiniz:

☐ Miyop ☐ Hipermetrop ☐ Astigmat ☐ Renk Körlüğü ☐ Diğer:

7. Bilgisayar oyunları oynuyor musunuz?

☐ Evet ☐ Hayır

8. Kaç yıllık bilgisayar oyunları deneyiminiz var?

☐ 0-1 Yıl ☐ 2-5 Yıl ☐ 5 Yıldan Fazla

9. Bilgisayar oyunlarını hangi sıklıkta oynarsınız?

☐ Her Gün ☐ Her Hafta ☐ Ayda Bir ☐ 6 Ayda Bir

☐ Yılda Birden Az ☐ Hiçbir Zaman

10. Son 3 yıldır yoğun olarak oynadığınız oyunlar varsa, adlarını yazar mısınız?

.....

11. Sanal Gerçeklik/ Artırılmış Gerçeklik deneyim düzeyiniz nedir?

☐ Deneyimim Yok ☐ Daha Önce Denedim ☐ Çok Deneyimim Var ☐ Uzmanım

12. Bu testi (Purdue Zihinsel Canlandırma Testi) daha önce aldınız mı?

☐ Evet ☐ Hayır

13. Şimdiye kadar okulunuz veya başka bir kuruluş tarafından üstün yetenekli bir öğrenci olarak adlandırıldığınız oldu mu?

☐ Evet ☐ Hayır

14. Yukarıdaki soruya cevabınız 'Evet' ise, bu ne zaman oldu? Lütfen uygun olanların tümünü işaretleyiniz.

☐ Okulöncesi ☐ İlkokul
☐ Orta Okul ☐ Lise

15. Anneniz veya babanız üniversiteye devam etti mi (iki yıllık veya dört yıllık) ?

☐ Evet ☐ Hayır

☐ Bunların dışındaysa, lütfen belirtiniz: _____

C. Cognitive Load Scale

BİLİŞSEL YÜK ÖLÇEĞİ (2-B ÖN TEST)

1. Zihinsel döndürme testi için bu sistemi (bilgisayar) kullanmak zihinsel olarak zorlayıcıdır.

Kesinlikle Katılmıyorum 1 ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ **7 Kesinlikle Katılıyorum**

2. Zihinsel döndürme problemlerini çözmek zihinsel olarak zorlayıcıdır.

Kesinlikle Katılmıyorum 1 ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ **7 Kesinlikle Katılıyorum**

3. Bu test sistemini (bilgisayar) kullanmak kafamı karıştırıyor.

Kesinlikle Katılmıyorum 1 ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ **7 Kesinlikle Katılıyorum**

4. Bu test sistemini (bilgisayar) kullanmak streslidir.

Kesinlikle Katılmıyorum 1 ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ **7 Kesinlikle Katılıyorum**

D. Presence Questionnaire

Bulunuşluk Hissi Ölçeği (BHÖ)

Yaşamış olduğunuz sanal gerçeklik deneyimini aşağıdaki şekilde belirtildiği gibi 1'den 5'e kadar puanlayınız. İşaretleme yaparken ara seçeneklerin de geçerli olabileceğini unutmayınız. Soruları dikkatli bir şekilde okuyarak **sırasıyla** ve **birbirinden bağımsız olarak** cevaplayınız. Hiçbir soruyu boş bırakmayınız ve verdiğiniz cevabı değiştirmeyiniz.

DENEYİMLEDİĞİN ORTAM İLE İLGİLİ OLARAK;

1. Olayları ne kadar kontrol edebildin?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

2. Başlattığın (veya gerçekleştirdiğin) eylemlere ortam ne kadar tepki verdi?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

3. Ortam ile etkileşimin ne kadar doğal görünüyordu?

1	2	3	4	5
OLDUKÇA YAPAY		ORTA		TAMAMEN DOĞAL

4. Ortamın görsel yönleri seni ne kadar içine aldı?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

5. Ortamdaki sesler seni ne kadar içine aldı?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

6. Ortam içerisinde hareketin kontrol edildiği sistem ne kadar doğaldı?

1	2	3	4	5
OLDUKÇA YAPAY		ORTA		TAMAMEN DOĞAL

7. Ortamda hareket eden nesnelerin sende uyandırdığı his ne kadar inandırıcıydı?

1	2	3	4	5
HİÇ		ORTA		ÇOK İNANDIRICI

8. Sanal ortamdaki deneyimlerin, gerçek dünyadaki deneyimlerin ile ne kadar tutarlı görünüyordu?

1	2	3	4	5
TUTARSIZ		ORTA		ÇOK TUTARLI

9. Gerçekleştirdiğin eylemlere karşılık olarak bir sonraki adımda ne olacağını tahmin edebildin mi?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

10. Gözlüğü kullanarak ortamı ne kadar aktif bir şekilde inceleyebildin veya araştırabildin?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

11. Sesleri ne kadar tanıyabildin?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

12. Seslerin geldiği yeri ne kadar belirleyebildin?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

13. El hareketlerini kullanarak sanal ortamı ne kadar aktif olarak inceleyebildin veya araştırabildin?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

14. Sanal ortam içerisindeki etrafta gezinme hissi ne kadar inandırıcıydı?

1	2	3	4	5
HİÇ		ORTA		ÇOK İNANDIRICI

15. Nesneleri ne kadar yakından inceleyebildin?

1	2	3	4	5
HİÇ		ORTA		ÇOK YAKINDAN

16. Nesneleri farklı bakış açılarından ne kadar inceleyebildin?

1	2	3	4	5
HİÇ		ORTA		DETAYLI OLARAK

17. Sanal ortamdaki nesneleri ne kadar hareket ettirebildin veya yönlendirebildin?

1	2	3	4	5
HİÇ		ORTA		KAPSAMLI OLARAK

18. Sanal ortam deneyimine ne kadar dâhil oldun?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

19. Ortamdaki hareketlerin ile hareketlerinin beklenen sonuçları arasında ne kadar gecikme yaşadın?

1	2	3	4	5
HİÇ		ORTA		UZUN SÜRE

20. Sanal ortam deneyimine ne kadar çabuk uyum sağladın?

1	2	3	4	5
HİÇ		YAVAŞÇA		1 DAKİKADAN DAHA KISA

21. Yaşadığınız deneyim sonrasında sanal ortamda hareket etme ve etkileşime girme konusunda kendinizi ne kadar yeterli hissettin?

1	2	3	4	5
YETERSİZ		ORTA		ÇOK YETERLİ

22. Verilen görevleri veya gerekli etkinlikleri yerine getirirken, gözlüğün görüntü kalitesi seni ne kadar engelledi veya dikkatini dağıttı?

1	2	3	4	5
HİÇ		ORTA		ÇOK ENGELLEDİ

23. El hareketleri, verilen görevlerin veya diğer etkinliklerin yerine getirilmesini ne kadar engelledi?

1	2	3	4	5
HİÇ		ORTA		ÇOK ENGELLEDİ

24. Ortamdaki görev veya etkinlikleri yerine getirmek için kullanılan sistemlerden çok verilen görevlere veya etkinliklere ne kadar konsantre olabildin?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

25. Duyuların bu deneyimi ne kadar yoğun yaşadı?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

26. Nesneleri fiziksel etkileşim yoluyla tanımak (bir nesneye dokunmak, bir yüzeyin üzerinde yürümek veya bir duvar veya nesneye çarpmak) ne kadar kolay oldu?

1	2	3	4	5
ÇOK ZOR		ORTA		ÇOK KOLAY

27. Sanal ortam deneyimi sırasında ortama veya göreve tamamen odaklandığınızı hissettiğiniz anlar oldu mu?

1	2	3	4	5
HİÇ		ORTA		ÇOK

28. Sanal ortamla etkileşim kurmak için kullanılan el hareketlerine ne kadar kolay uyum sağladın?

1	2	3	4	5
HİÇ		ORTA		TAMAMEN

29. Sanal ortamda farklı duyularla sağlanan bilgiler (örneğin; görme, duyma, dokunma) tutarlı mıydı?

1	2	3	4	5
TUTARSIZ		ORTA		ÇOK TUTARLI

E. Interview Questions

- 1)** Can you summarize your mental rotation process in the measuring environment?
 - How did you solve the questions in the test?
- 2)** What are the positive aspects of the experience of using the Mixed Reality-based training environment?
- 3)** What are the negative aspects of the experience of using the Mixed Reality-based training environment?
- 4)** Do you think that the Mixed Reality-based training environment helped improve your mental rotation ability?
 - If yes, what features of the environment might have supported the development of this skill?
- 5)** Did using the Mixed Reality headset for training cause any side effects for you?

CURRICULUM VITAE (ONLY FOR DOCTORAL THESIS)

PERSONAL INFORMATION

Surname, Name: Piri, Zeynep
Nationality: Turkish (TC)

EDUCATION

Degree	Institution	Year of Graduation
MS	University of Bristol	2013
BS	DEU Computer Education and Instructional Technologies	2009
High School	Sinop Anadolu High School, Sinop	2005

WORK EXPERIENCE

Year	Place	Enrollment
2015-Present	Kastamonu University	Research Assistant
2009-2011	Ministry of Education	Teacher

FOREIGN LANGUAGES

English