A COGNITIVE MAPPING APPROACH IN REAL-TIME HAPTIC RENDERING INTERACTION FOR IMPROVED SPATIAL LEARNING ABILITY AMONG AUTISTIC PEOPLE

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT

Haptics is the utmost emergent science of technology that studies sensorimotor and haptic feedback through the interaction of a human with the virtual environment. Meanwhile, in the past decade, the use of haptic technology in autism has increased in terms of various disciplines that can assist in improving their learning skills. Nevertheless, the use of haptic technology in terms of spatial learning is still not fully utilized, and this weakens autistic people in the process of learning about their surroundings. Spatial knowledge is the ability of autistic people to navigate independently to a desired location and interact with the object's surroundings. Even though there has been recent achievement in haptic-based virtual environments (HBVE), the designing process of HBVE for spatial learning of autistic people has become more challenging. This is due to the lack of haptic-based virtual environment frameworks (HBVE-Framework) to provide better guidelines for designers during the course of the entire design process. This means that the proposed framework through this research becomes a fundamental principle in the development of a haptic-based virtual environment. The main objective of this research is to develop and present a HBVEF-framework to design a HBVE for autistic people to improve their spatial awareness and to significantly improve their interaction abilities through haptic rendering. This research also aims to present a reliable autonomous algorithm that minimizes the issues with localization and navigation skills among autistic people in a HBVE to improve their wayfinding and spatial knowledge. Moreover, this research also aims to examine the use of haptics modalities in autistic people to have the sense of touch and feel the surface of three-dimensional objects as an interaction tactic. This research begins by identifying the most appropriate components related to autistic people and the HBVE through literature review and the existing HBVEF-Framework. The identified components were then organized into a model-view-controller (MVC) pattern which was adapted from the modern GUI development platform to describe the structure of the HBVE-Framework. The constructed framework was evaluated by expert reviews from the perspective of different scholars and re-designed based on the expert reviews. Furthermore, a HBVE application was developed to demonstrate the logical view of the proposed framework. As part of user usability, a heuristic evaluation based on case study was conducted on the application to identify the usability problems and improve the usability of the application. Meanwhile, experimental evaluation of the application was conducted in four different groups to measure the efficiency and performance of the application; experimental evaluation based on navigation algorithms, experimental evaluation based on haptic sensory sensitivity, experimental evaluation based on real-time haptic rendering interaction and experimental evaluation based on the performance of autistic people with using the application in spatial learning and cognitive mapping. The outcomes of this conducted experiment proved with certainty that it could be mainstream in the process of developing a HBVE application related to autism.

Keywords: Haptic, Spatial Learning, Cognitive Mapping, Autistic people, Real-Time Rendering Interaction

PENDEKATAN PEMETAAN KOGNITIF DALAM INTERAKSI HAPTIK MASA NYATA UNTUK MENINGKATKAN KEUPAYAAN PEMBELAJARAN RUANG DALAM KALANGAN ORANG AUTISTIK

ABSTRAK

Haptics adalah sains teknologi yang paling maju yang dapat mengkaji maklum balas sensorimotor dan haptik melalui interaksi manusia dengan persekitaran maya. Sementara itu, dalam dekad yang lalu, penggunaan teknologi haptik terhadap autisme telah meningkat dari segi pelbagai disiplin yang dapat membantu dalam meningkatkan kemahiran pembelajaran mereka. Walau bagaimanapun, penggunaan teknologi haptik dari segi pembelajaran spatial masih belum digunakan sepenuhnya, dan ini melemahkan autisme dalam proses pembelajaran persekitaran mereka. Pengetahuan ruang adalah keupayaan kanak-kanak autisme untuk menavigasi secara bebas ke lokasi yang dikehendaki dan berinteraksi dengan objek-objek sekitarnya. Walaupun terdapat pencapaian yang tinggi dalam persekitaran maya berasaskan haptik (HBVE), tetapi proses perancangan HBVE untuk pembelajaran ruang bagi kanak-kanak autistik menjadi lebih mencabar. Ini kerana tidak ada kerangka persekitaran maya berasaskan haptik (HBVE-Framework) untuk menyediakan garis panduan yang lebih baik untuk pereka semasa proses perancangan keseluruhan. Ini bermakna rangka kerja yang dicadangkan melalui penyelidikan ini menjadi asas utama dalam pembangunan persekitaran maya berasaskan haptik. Objektif utama penyelidikan ini adalah untuk membangunkan dan mempersembahkan HBVE-Framework untuk merekabentuk HBVE untuk kanak-kanak dengan autisme untuk meningkatkan kesedaran ruang mereka dan dengan ketara dapat meningkatkan kebolehan interaksi dengan haptic rendering. Penyelidikan ini juga bertujuan untuk membentangkan algoritma navigasi yang dipercayai boleh meminimumkan masalah dengan penyetempatan dan kemahiran navigasi di kalangan kanak-kanak autistik dalam HBVE untuk meningkatkan pengetahuan jalan dan pengetahuan ruang mereka. Selain itu kajian ini juga bertujuan untuk mengkaji penggunaan modaliti haptik pada kanak-kanak dengan autisme untuk mempunyai kesentuhan dan dapat merasakan permukaan objek tiga dimensi sebagai taktik interaksi. Kajian ini bermula dengan mengenal pasti komponen-komponen yang paling sesuai berkaitan dengan kanak-kanak autistik dan HBVE menerusi kajian yang dilakukan terhadap kajian literatur dan HBVE-Framework. Komponen-komponen yang telah dikenal pasti kemudian dianjurkan dalam pola model-view-controller (MVC) yang disesuaikan melalui platform pembangunan GUI moden untuk menggambarkan struktur HBVE-Framework. Rangka kerja yang dibina dinilai berdasarkan ulasan pakar dari sudut pandang sarjana yang berlainan dan merangka semula rangka kerja berdasarkan ulasan pakar. Tambahan pula aplikasi HBVE yang dibangunkan untuk menunjukkan pandangan logik rangka kerja yang dicadangkan. Manakala, berkenaan dengan kebolehgunaan pengguna, penilaian heuristik dilakukan berdasarkan kajian kes pada aplikasi untuk mengenal pasti masalah kebolehgunaan untuk meningkatkan kebolehgunaan aplikasi itu. Sementara itu, penilaian eksperimen permohonan itu juga dijalankan dalam tiga kumpulan yang berbeza untuk mengukur kecekapan dan prestasi; penilaian eksperimen berdasarkan algoritma navigasi, penilaian eksperimen berdasarkan modaliti haptik, dan penilaian eksperimental berdasarkan prestasi anak autistik dengan dan tanpa menggunakan aplikasi dalam pembelajaran ruang. Akibat dari hasil eksperimen yang dijalankan, terbukti dengan pasti bahawa ia boleh menjadi arus utama dalam proses membangun aplikasi HBVE yang berkaitan dengan autisme.

Kata Kunci: Haptik, Pembelajaran Spatial, Kaedah Pemetaan Kognitif, Autistik, Interaksi

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LIST OF SYMBOLS AND ABBREVIATIONS

2D	:	Two-Dimensional
3D	:	Three-Dimensional
AASP	:	Adolescent/ Adult Sensory Profile
ACM	:	Association for Computing Machinery
AF	:	Application Factory
AHSON	:	Autonomous Haptic Spatial Orient-Navigate
API	:	Application Programming Interface
AS	:	Automatic Scaling
ASEBA: TRF	:	Achenbach System of Empirically Based Assessment Teacher Report Form
Aud	:	Audio Effects
BDR	:	Behavioral Data Repository
BVH	:	Bounding Volume Hierarchy
CAD	:	Computer-Aided Design
CPU	:	Central Processing Unit
CT	:	Computed Tomography Scan
CTRS–R: LV	:	Conners' Teacher Rating Scale–Revised: Long Version
DOF	:	Degree of Freedom
DSRM	:	Design Science Research Methodology
ECG	:	Electrocardiogram
EEG	:	Electroencephalogram
EMG	:	Electromyography
EMS	:	Electrical Muscle Stimulation
EtF	:	Electrotactile Feedback

FF	:	Force Feedback
GARS	:	Gilliam Autism Rating Scale-2
GADS	:	Gilliam Asperger Disorder Scale
GHz	:	Gigahertz
GoF	:	Grading of Force
GoM	:	Grading of Movement
GUI	:	Graphical User Interface
HBVE	:	Haptic-based virtual environment
HCI	:	Human Computer Interaction
HFA	:	High-Functioning Autism
HMDs	:	Head-Mounted Displays
Hz	:	Frequency
IAE	:	Intelligent Ambient Engine
IEEE	:	Institute of Electrical and Electronics Engineers
IMU	:	Inertial Measurement Units
INS	:	Instruction and Navigation Support
iOS	:	iPhone Operating System
IPO	:	Input, Process, Output
ISO/IEC	:	International Organization for Standardization/International Electrotechnical Commission
IVE	:	Immersive Virtual Environment
LCD	:	Low-Cost Display
LIDAR	:	Light Detection and Ranging
LK	:	Landmark Knowledge
MAD	:	Mean Absolute Deviation
MANCOVA	:	Multivariate Analysis of Covariance

MANOVA	:	Multivariate Analysis of Variance
MATLAB	:	MATrix LABoratory
MVC	:	Model-View-Controller
MVE	:	Motion and Visual Effects
NDD	:	Neurodevelopmental Disorders
NLR	:	Narrative Literature Review
NM	:	Navigation Map
ODDA	:	Object Detection and Object Avoidance
OM	:	Object Modelling
POV	:	Point of View
PPD-NOS	:	Pervasive Developmental Disorder-Not Otherwise Specified
RHI	:	Rubber hand illusion
RK	:	Route Knowledge
RQ	:	Research Question
SAGE	:	Scientific Advisory Group for Emergencies
SD	:	Standard Deviation
SDK	:	Software Development Kit
SHA	:	Software/ Hardware Application
SK	:	Survey Knowledge
SKT	:	Skin Temperature
SLAM	:	Simultaneous Localization and Mapping
SLR	:	Systematic Literature Review
SMD	:	Standardized Mean Difference
SPM	:	Sensory Processing Measure
SQuaRE	:	Systems and software Quality Requirements and Evaluation
SRQ	:	Sub-Research Question

SRS2	:	Social Responsiveness Scale-2
SSP	:	Short Sensory Profile
TF	:	Thermal Feedback
TSM	:	Tactile Sensitivity Measurement
UI	:	User Interface
UK	:	United Kingdom
USA	:	United State of America
UtF	:	Ultrasound Tactile Feedback
VE	:	Virtual environment
VHM	:	Virtual Hand Metaphor
VPM	:	Virtual Pointer Metaphor
VR	:	Virtual Reality
VRE	:	Virtual environment
VtF	:	Vibrotactile Feedback
WIM	:	World-In-Miniature
X3D	:	Extensible Three Dimensional

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

This chapter presents the background of research, describes research problems, and follows with the motivation for this research for the work developed in the hypothesis. The research objectives and research questions interrelated to this research were sought to be addressed. In addition to this, the importance and relevance of the research and the scope of this research have also been focused on understanding more about this research in terms of all aspects and content specifications. To understand the systematic and theoretical aspects of research, research methodology is used. Ultimately, the structure of this thesis is explained.

1.1 Background of Research

Autism Spectrum Disorders (ASD) is a neurodevelopmental disorder characterized by impairment and persistent challenges with certain abilities in social interaction, repetitive and restricted behaviours, interests or activities (atypical movement or atypical sensory behaviour (Suzuki et al., 2019)), and lack of spatial awareness (Mesibov et al., 2013; Smith, 2015). Individuals on the autism spectrum frequently have difficulties with attention, learning, and sensory processing (ASD)(Grace Megumi et al., 2012). Spectrum, in its most fundamental sense, describes the vast variety of possible manifestations of the condition (Tavassoli et al., 2014).

People with ASD can exhibit a wide range of cognitive characteristics, from those of a typically developing individual to those of a severely impaired one, as examples range from being extroverted to being completely non-verbal, and from being able to complete tasks on their own to requiring constant attention especially when finding their way to their desired object or location in an unfamiliar environment (Brunsdon & Happé, 2014; Joseph et al., 2002; Yingying et al., 2021). Autism Spectrum Disorder (ASD) is a lifelong developmental disorder that manifests in children before the age of three, and they will continue to show symptoms into adulthood. The prevalence of this disorder in males is four times higher than in females (Charman, 2011). In the meantime, spatial awareness is defined as your current position in any environment in relation to the surrounding objects or other people (Johns, 2003; Youngstrom & Strowbridge, 2012). Especially spatial awareness in autistic people is to allow them to explore their surroundings. As autistic people become more mobile, they are able to move and then walk to objects, and as a result, they are able to figure out how many steps it takes them to get to a specific location or object. When autistic people are able to move, they will gain an understanding of how their position in relation to objects changes as they move (Smith, 2015; Yingying et al., 2021).

Moreover, fewer researchers have reported that autistic people have difficulty differentiating between left and right and are confused about positional communication (Carpenter et al., 2002; Pellicano et al., 2013; Melanie Ring et al., 2018). In addition, it has been found that autistic people have difficulty with visuospatial understanding or visualising specific objects, such as their size, pattern, shape, and colour. Therefore, the ability of an individual to mentally interact with and manipulate an object that is surrounding them can be defined as "spatial visualisation" (Alvino, 2008; M. Zhang et al., 2020). These capabilities may be difficult to develop for autistic people, despite the fact that there are many activities that parents and carers can do to improve spatial awareness, particularly in a real-world environment (D. Li et al., 2019). This is due to a variety of factors, including their own safety concerns, atypical sensory behaviour, and a lack of a proper training platform (Ke & Im, 2013; D. Li et al., 2019; D. Moore et al., 2000; Schauder & Bennetto, 2016). This condition is still prevalent among autistic people, as expressed by the following witness statements:

“*I’ve often wondered how to explain the feeling of disconnect between myself, my body, and space. As well as the complete and utter lack of directional skills.*” by Gabbi in (Lowery, 2015)

“*Grandson has trouble with heavy school bag. Drops things, cannot find items in front of him. Walks in a way that nearly trips me. Total focus when drawing, watching tv or making models. Unaware of anything else when occupied. We suspected he had mild autism.*” by Vicki Edwards in (Lowery, 2015)

Specifically, Lowery (2015) wrote in his own online article that he, as an autistic person, had difficulty focusing on the big picture because of the poor spatial awareness skills he experienced. On the other hand, cognitive mapping is defined as the visual representation of a person's mental model for a particular process or concept (Bos et al., 2019; Matson et al., 2013; Schiller et al., 2015). This process made use of effective visual mapping as a strategic tool for organising, communicating, and remembering information. It will assist a person in organising complicated ideas and processes and recognising patterns and relationships (Behrens et al., 2018).

Smith (2015) discovered a link between spatial learning and cognitive mapping. The author's experiments provided conclusive evidence for this hypothesis. Based on the author reviews, there has study predicted the navigational task based on survey knowledge, which was tested with 27 high functioning adult autistics. Furthermore, the participants were tested with a memory task to remember the location of the object by constructing a cognitive map. There were a number of dependent measures involved, including the time taken to complete, and it was discovered that autistic people spend significantly less time (Sophie E Lind et al., 2013; Smith, 2015). Furthermore, when the NEPSY-II routes finding test is compared to the time spent in the virtual environment, autistic children take less time (Fornasari et al., 2013; Smith, 2015). These enable users to develop a cognitive map of their surroundings in order to remember where objects are located, and this will allow them to keep their spatial knowledge. Furthermore, based on the author's review, Smith (2015) stated that autistic participants performed better than control group participants on perceptual distance matching, indicated recall of routes on a map, and encoding of route information from a map. The author also showed that autistic participants were slower at learning spatial skills and less able to learn locations based on allocentric representations. They were also less likely to explore an environment sufficiently and more likely to revisit already explored locations.

In addition, Smith (2015) also stated that three issues must be resolved to enable spatial navigational behaviours in autism. First, perceptual, motor, and cognitive systems affect navigational behaviour. Navigational abilities can come from many different sources. Therefore, proficiency in one component process may not transfer to another, and weaker processes may affect performance. Such autistic skills in detail may assist map encoding, while imaginal viewpoint rotation impairments may affect route description. Understanding the issue will reduce the likelihood of researchers assuming that behaviours observed in one context or spatial scale will transpose to another. Another issue is that autism researchers must also understand the extent of navigation research. Because navigation is important for behaviour, it has been studied in a wide range of contexts and populations. Even though it is hard to consider everything at once, this breadth is essential. In the last issue, before making major claims regarding autistic navigation, autism studies had to overcome more general scientific challenges. The sample sizes in these studies are inconsistent. Autistic classes are compared to numerous control groups, which are likewise made up of people of various ages and abilities. Also extending this concept to a small group of autistic people. This means we must be careful when extrapolating behaviour. The main goal of autism research has been to come up with broad theories for the disorder. Because grand theories of autism have misinterpreted navigational skills, we must be more cautious and measured when defining a complicated and multifarious set of behaviours in a complex and diverse group of people. In addition, the sensory challenges that occur during navigation are essential components that need to be addressed since they have the potential to influence an individual's navigation decision (Birkett et al., 2022; Hilton et al., 2010).

Autistic people frequently display abnormal sensory behaviours across a variety of sensory modalities. These behaviours can include an indifference to pain, an adverse reaction to particular sounds or textures, an excessive need to smell or touch objects, and a visual fascination with lights or movement (Klintwall et al., 2011). Sensory abnormalities are a common symptom of autism that is observed in approximately 95 percent of people with the disorder, despite receiving less attention than social impairment (Tomchek & Dunn, 2007). But in recent years, the majority of researchers have begun to consider the abnormalities in sensory perception to be critical symptoms that require increased attention (Lang et al., 2012; Stevenson et al., 2014; Suzuki et al., 2019; Wodka et al., 2016). Even diagnostic assessment procedures for autistic people, such as the Autism Diagnostic Interview-Revised (ADI-R) (Rutter et al., 2003) and the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) (Association, 2013), have criteria for measuring "hyper- or hypo-reactivity to sensory input" or "unusual sensory interest," which is especially important to have a deep understanding of touch sensitivity conditions.

People with autism spectrum disorder can experience both hypersensitivity (over-responsiveness) and hyposensitivity (under-responsiveness) to a broad and diverse range of stimuli; however, the majority of autistic people have a combination of both types of sensitivity (Corbett et al., 2016; Puts et al., 2014; Zapata-Fonseca et al., 2018). Hypersensitivity in autistic people, in reference to particular sensory input such as touching a texture or object, can also be overwhelming. Therefore, autistic people may engage in sensory avoidance behaviours such as pulling away from physical touch or otherwise avoiding these activities (Tavassoli et al., 2014).

Hyposensitivity, on the other hand, refers to the difficulty that autistic people have in recognising sensations or getting feelings when they touch an object. Therefore, autistic people have a tendency to engage in sensory seeking in order to get more sensory input from an object or environment (Tavassoli et al., 2014). This indicates that a significant number of autistic people try to maintain a balance in their sensory system so that it does not interfere with their day-to-day activities, particularly those that involve dealing with spatial awareness, since these two aspects interact closely with one another (Puts et al., 2014; Tavassoli et al., 2014; Tomchek & Dunn, 2007). Thereby, introducing sensitivity therapies can improve and balance their level of sensitivity, which will dramatically improve their daily activities and improve their ability to learn spatial relationships (Baranek, 2002; Iarocci & McDonald, 2006). It means that researchers believed that introducing haptic technology into a virtual environment could help solve real-world problems such as their safety concerns, the issue of not having an adequate training platform for spatial learning and cognitive mapping, and the condition of atypical sensory behaviour, in which case the therapy could be one of the most effective sensitivity therapies for autistic people (Alhalabi et al., 2006; Carvalheiro et al., 2016; Tang, McMahan, et al., 2014; van Stralen et al., 2011; Vaucelle et al., 2009). This is due to the fact that the haptic device, which was designed to serve as an assistive wearable technology, is able to generate the sense of touch as haptic feedback to the individual while also allowing for control of virtual objects within a virtual environment (VE) (Battaglia et al., 2011; Robles-De-La-Torre, 2006; Sreelakshmi & Subash, 2017). Aside from haptic devices classified as wearable technology, there are other types of haptic technology generally categorised as graspable and touchable (Dennerlein & Yang, 2001; K. Salisbury et al., 2004a).

Furthermore, the current market offers a diverse range of haptic devices, such as the widely used PHANTHOM Desktop (Hamza-Lup et al., 2019; Oo et al., 2009); however, some researchers prefer the MYO Armband because it is significantly less expensive and easier to control from a distance (Javaid et al., 2021; S. R. Kurniawan & Pamungkas, 2018).

Meanwhile, haptic rendering is the process of decoding haptic information as haptic feedback during interaction and manipulation with virtual objects through haptic devices, and this interaction is presented based on real-time performance (M. C. Lin & Otaduy, 2008). This process allows the user, especially autistic people, to sense the virtual objects based on their physical attributes such as shape, texture, size, weight, hardness, force, pressure, stiffness, position, velocity, and viscosity (Bouyer et al., 2017; Díaz et al., 2006a; Leonard & Villeneuve, 2019). Additionally, a virtual environment can be defined as a platform that uses computer technology to create a simulated environment that can be explored in three dimensions with an immersive experience (Chertoff et al., 2010; Mine et al., 1997). This technology is capable of producing three different types of environments, which are known as non-immersive, semi-immersive, and fully-immersive simulations, respectively (Robertson et al., 1993; Sherman & Craig, 2018; Stansfield et al., 1995; Steinicke et al., 2006).

The use of a virtual environment not only gives autistic people the ability to create an interactive platform for them, but it also serves as a secure environment in which they can explore and exercise the skills they are hoping to acquire or improve (Ke & Im, 2013; Manju et al., 2017; Strickland, 1996; Strickland et al., 2007). It is possible that the combination of haptic and virtual environment technology will prove to be an effective therapeutic approach for any development that is related to the purpose of knowledge transfer or as an educational instrument (Dangxiao et al., 2019; Dong et al., 2017; Richard et al., 2021; Witmer et al., 1996; H. Wu et al., 2017; H. Zhao et al., 2017). Therefore, the purpose of this study is to investigate and grasp the knowledge and understanding of how the haptic-based virtual environment (HBVE) can be a suitable platform for improving autistic people's spatial learning and cognitive mapping skills.

1.2 Statement of Problem

A search in reputable search engines was conducted to identify relevant studies on understanding the haptic modality influence in autistic people and whether it provides tactile feedback as sensory feedback during interaction with a virtual environment. There were no review papers that specifically addressed interacting with virtual objects while using tactile senses simultaneously. These authors' research has only been partially focused on virtual object interaction with tactile sensory, but they have not specifically focused on a three-dimensional model (Cibrian et al., 2017; Paton et al., 2012; Söchting et al., 2015; Zapata-Fonseca et al., 2018). Hence, while haptic modalities have been widely used for autistic people to investigate various types of sensation, no proper study has been conducted for the interactions between virtual objects and tactile sensory feedback. Haptic-based virtual environments (HBVE) are widely utilised to assist autistic people learn fine motor abilities, STEM education, social communication and interaction, mental health therapy, sensory abnormalities, and other skills. These approaches improved autistic people's learning in most studies (Minogue & Jones, 2006; Pérusseau-Lambert, 2016; K. Salisbury et al., 2004b). However, the full potential of HBVE has yet to be realised in terms of improving spatial learning or cognitive mapping as a single or combined aspect.

Assistive navigation technologies may serve as guidance for autistic people navigating in virtual environments. Most assistive navigation technology addresses shortest-route difficulties. This is due to the fact that longer and more complex routes can make users lose their sense of direction. However, most users got lost, and the suggested route to the destination wasn't always suitable. Only one framework for HBVE for autistic people was found in the investigative process, and it focuses on spatial learning (Pérusseau-Lambert, 2016). This framework only considered shape perception from the perspective of spatial learning, not cognitive mapping. HBVE design also ignores autistic perspectives, spatial cognition, and haptic rendering.

1.3 Research Objectives

The purpose of this study is to build an effective real-time haptic rendering framework for autistic people to have awareness of their spatial environment via a cognitive mapping method. In order to reinforce this statement, there are a few objectives that are supportive:

i. To investigate elements related to autism, spatial learning and cognitive mapping skills, and haptic interaction that constitute a haptic-based spatial learning environment for autistic people to create their spatial awareness.
ii. To construct a new algorithm-design-framework based on haptic technology and spatial learning and cognitive mapping elements.
iii. To develop a simulation of a real-time haptic technology environment to demonstrate the logical view of the proposed algorithm-design-framework.
iv. To conduct an experimental study to analyze spatial awareness and cognitive mapping skills among autistic people in the proposed real-time haptic technology environment.

1.4 Research Questions

Based on the research objective, a number of research questions are highlighted, and they will be answered and organized in chapter form in this research. The research questions are indicated as "RQ".

- RQ1: What is the fundamental understanding of autistic people and their spatial learning and cognitive mapping?
- RQ2: What role does haptic technology play in the development of haptic-based virtual environments for learning purpose?
- RQ3: How would the autonomous assistive algorithm assist autistic people with wayfinding in HBVE?
- RQ4: How were the main and sub-components effectively identified and organised in the model structure and also usable to design the HBVE application?
- RQ5: How does a simulation of a haptic based virtual environment developed and tested?
- RQ6: Does the use of haptic technology improve spatial learning and cognitive mapping abilities via HBVE among autistic people?

1.5 The Importance and Relevance of Research

The proposed application in this dissertation is to use haptic-based virtual environment (HBVE) technology to improve spatial learning and cognitive mapping skills in autistic people. It means that, in addition to determining their level of spatial cognition skills, the developed application could improve their spatial cognition by assisting the individual in understanding and being aware of their location and surroundings, particularly when interacting with unfamiliar environments. Using a virtual environment platform is much more enjoyable and safer than practising in a real environment. The proposed haptic-based virtual environment framework (HBVE-Framework) in this research, in addition to the HBVE application, can serve as guidance for those researchers and designers involved in the process of designing or developing HBVE applications for autistic people in the concept of spatial cognition. The HBVE-Framework can highlight the main elements that are fundamental and required, as well as describe the logical structure from one element to another in the development of an HBVE. Furthermore, the HBVE-Framework is constructed with the AHSON algorithm as a navigation assistive element, which can resolve issues with localization and disorientation during navigation in a virtual environment. This proposed framework is constructed with haptic elements that can provide autistic people with haptic feedback so they can feel the sense of touch of virtual objects. The HBVE-Framework is generally based on two types of logical reviews: systematic literature reviews (SLR) and narrative literature reviews (NLR). The SLRs are reviewed based on the influence of haptic modalities used in HBVE for autistic people. Meanwhile, the NLRs are being reviewed based on autistic people's characteristics and abilities, spatial cognition elements, and haptic and virtual environment elements. Based on the results of these two types of logical reviews, researchers and designers can develop a wide range of HBVE applications for autistic people in the area of spatial cognition. Also, the information obtained from this entire study can be applied to other areas of skill development for autistic people.

1.6 Scope of Research

The research on the development of a haptic-based virtual environment framework (HVBE-Framework) deals with a number of distinct areas, including the skills that need to be focused on for autistic people, types of learning platform, the types of modalities, the haptic-based virtual environment framework, and the types of assistive navigation technology in virtual environments, in addition to a number of sub-domains that are contained within each of these four respective areas. Referring to Figure 1.1 will provide a clearer picture of the breadth of this thesis's scope. This research focused on spatial learning and cognitive mapping as learning skills among the many other skills that autistic people have. Furthermore, the haptic modality is chosen as the primary focus for this research. The type of assistive navigation technology that is emphasized is an autonomous algorithm based on wearable technology. The learning platform is a virtual environment, and the primary emphasis is placed on a non-immersive based virtual reality system.

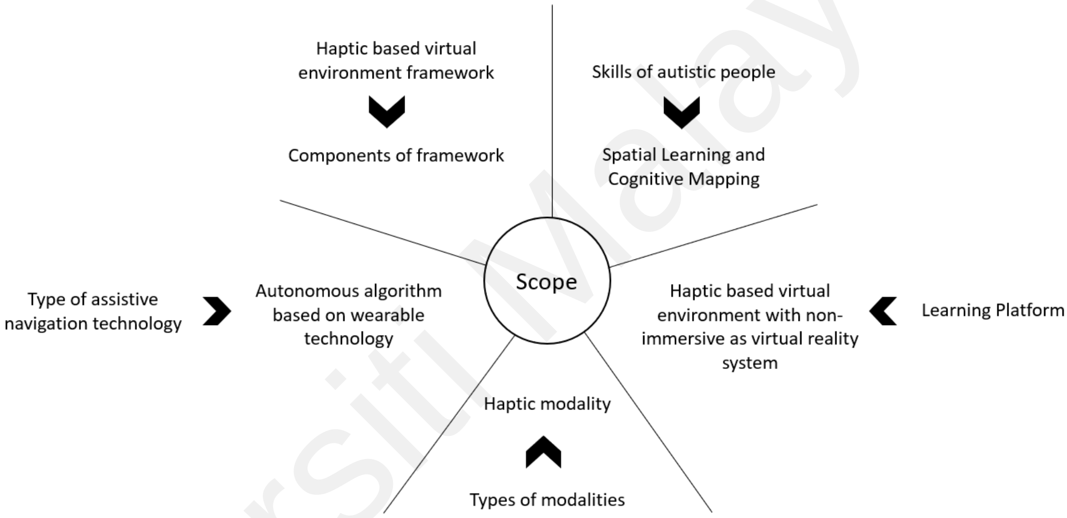


Figure 1.1: Scope of the Research

The sole purpose of the HBVE-framework that has been introduced is to provide support for the design and development of haptic-based virtual environment applications with the goal of assisting autistic people in improving their capabilities in the areas of spatial learning and cognitive mapping. This study focuses on autistic people who are considered to have mild autism and who exhibit the symptoms, skills, and behaviours depicted in Figure 1.2. For the context of this study, autistic people ranging in age from nine to twenty-seven years old will be recruited from Malaysia for the purpose of conducting an experimental evaluation of a simulation that has been developed based on the framework that has been proposed for use in this study. The components of the framework that are related to autistic people contain specific details pertaining to cognitive mapping and spatial learning. Even though the specific details of these components can be adapted to other kinds of learning skills or activities that are related to autistic people for the purpose of improving those individuals' abilities, this research will only focus on those aspects of the subject that fall within the scope of this research. The phases of requirements analysis, design, implementation, verification, and maintenance, which are based on the waterfall software development model, will be adapted so that a proper HBVE application can be developed based on the proposed framework (Faroque et al., 2018). This will allow for the successful development of the HBVE application. The design phase in the haptic-based virtual environment is the primary focus of this particular framework proposal, which, as the break line indicates, is the area of focus. However, this framework does not cover the remaining phases because they are outside its scope. During this phase, we will address the aspects that are associated with the design of the framework, particularly the process of determining which components are important and how they should be arranged within the framework.

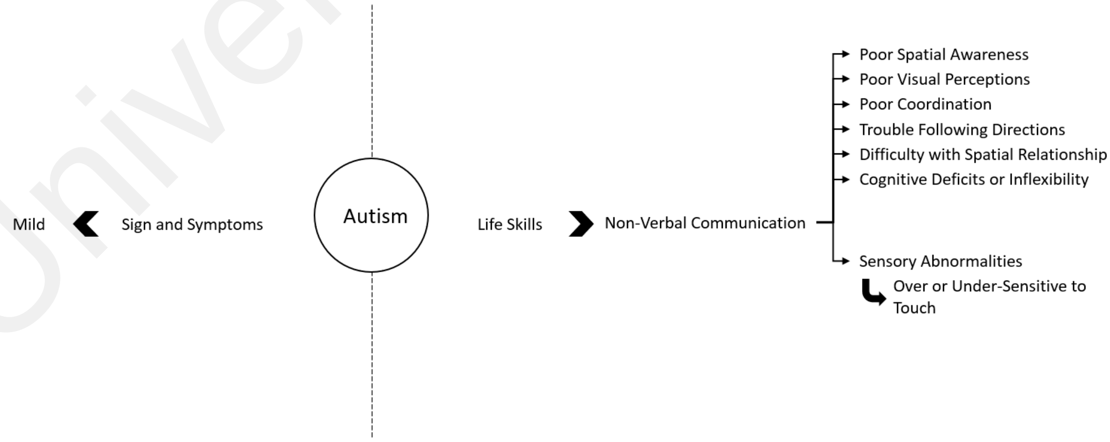


Figure 1.2: Signs and symptoms, life skills, and norms that are the subject of this research

1.7 Research Methodology

Design Science Research Methodology (DSRM) (Peffers et al., 2007) is utilised in this research activity. The Design Science Research Methodology (DSRM) is widely used in the category of algorithms and human/computer interaction artefacts, as seen in Figure 1.3. A fundamental technique is used to analyse and exhibit artefacts in order to overcome a specific research difficulty in the domain of DSRM. Since DSRM may be utilised as a methodological approach to achieve results that are both theoretical and practical in nature depending on the research challenge, it is becoming increasingly popular.

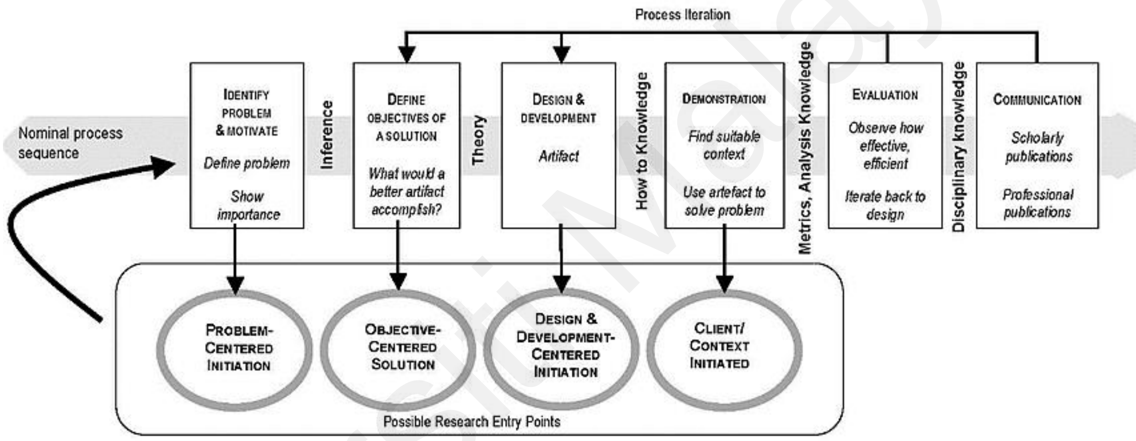


Figure 1.3: Design Science Research Methodology Process Model (Peffers et al., 2007)

For the purpose of gaining knowledge and understanding of the domain problems, this research will go through the following processes: identifying the problem, defining the objective of a solution, designing and developing an artefact, demonstration (using the artefact to solve problems), conducting evaluation (to determine the efficiency and effectiveness), and finally communicating the results and findings with the domain community. The research activities that were conducted in this study in accordance with the DSRM approach are depicted in the following Figure 1.4.

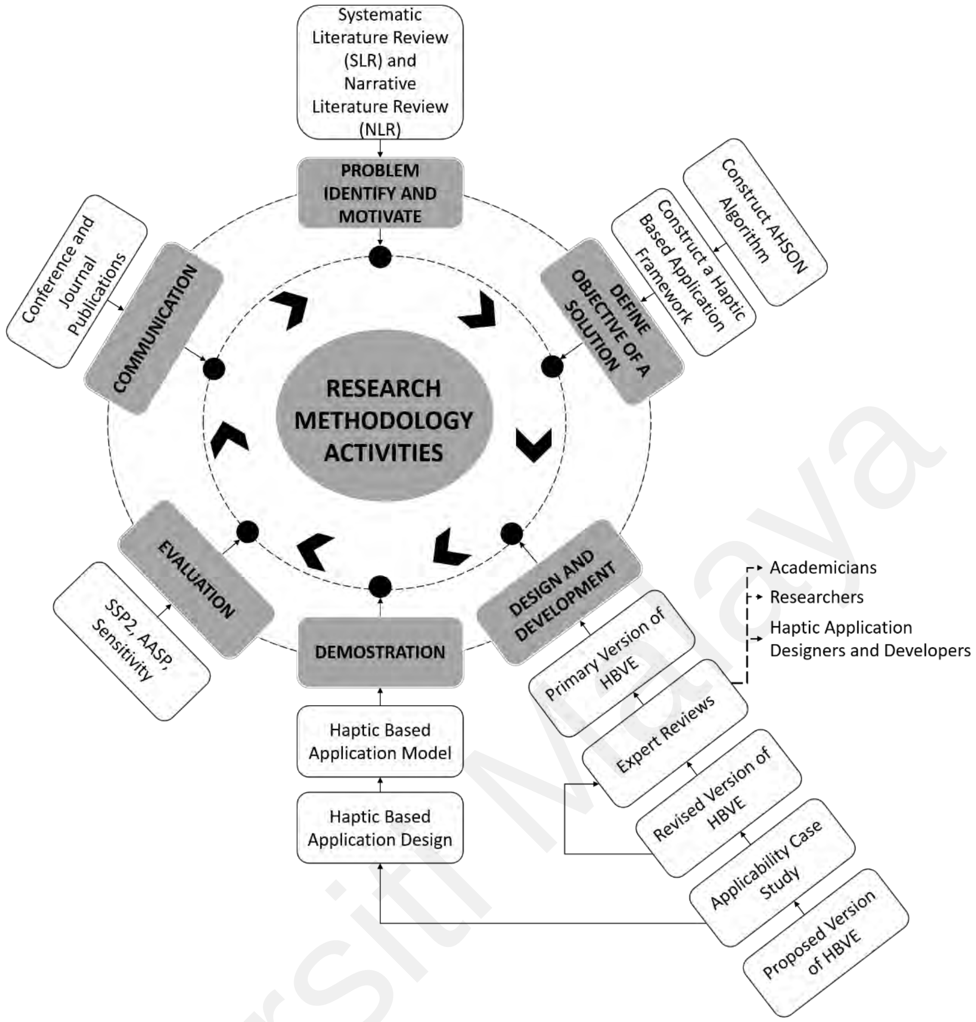


Figure 1.4: Haptic Based Application Framework for Autistic people

1.7.1 Problem Identification and Motivation

The main objective of this activity is to recognize the problem that have been encountered through a review of the literature or through external factors. Despite this, the scope of this research was limited to a review of the literature in order to identify the domain problem. In this research, the types of literature reviews used are systematic review (SLR) and narrative review (NLR). The differences between the two types of literature reviews are explained in greater detail in the following chapters 2, 3, 4, and 5. In order to recognise the influence of haptic modality on sensory sensitivity, the SLRs are employed in conjunction with other techniques. Meanwhile, the NLRs are used to recognise and discuss current knowledge in the fields of haptic technology, spatial cognition through haptic environment on autistic people, and the behaviour of autistic people from a contextual perspective. The components of the exciting HBVE-Framework were also covered in detail during this activity.

1.7.2 Define the Objectives of a Solution

This activity began with the recognition of research gaps, which was followed by the fulfill of the research gaps. Through the identification of potential solutions, it is hoped that this effort will help to specify how the research gap should be addressed. The objectives of the algorithm and framework, as well as their supportive elements in the design and development of a virtual environment for autistic people, are demonstrated in Chapters 4 and 5.

1.7.3 Design and Development

This activity aims to solve the problem by designing and developing an artefact based on the preceding activity's objectives. The information obtained from the literature review was reviewed and utilized in the design and development of the algorithm and HBVE-Framework. The proposed framework was subjected to expert evaluation and application evaluation, which resulted in component modifications as a result of the findings. The expert review of the proposed framework was carried out by three different groups of people: academicians, researchers, designer and developers of haptic applications. In addition, the proposed framework's applicability was evaluated by asking haptic designers and developers to select appropriate components (checklist) to design a HBVE utilizing the proposed framework. An applicability case study was conducted with this group of experts to learn about their thoughts and suggestions regarding designing haptic applications using the proposed framework. Last but not least, in response to all of the expert group's recommendations, considerable changes were made to the proposed framework. The details of this section are demonstrated in Chapter 5.

1.7.4 Demonstration

Specifically, the objective of this action is to demonstrate that the proposed artefact from the previous activity is capable of solving the identified problem(s). Therefore, it was necessary to construct a HBVE simulation as a proof of concept and to conduct usability evaluation in order to recognize and resolve usability problems in the HBVE before reaching autistic people. The design of the HBVE from the previous activity is used to develop a HBVE simulation. In order to conduct usability evaluation, a set of modified heuristic evaluations were used to study the usability of this application. The details of the development of the HBVE simulation and its usability evaluation were demonstrated in chapter 6.

1.7.5 Evaluation

This activity describes the evaluation that was carried out in order to address the research problem on the basis of the solutions that were developed. Therefore, in this section, an evaluation of the effectiveness of HBVE in spatial learning and cognitive mapping among autistic people was conducted using simulations. Different types of experimental evaluation of the simulation were conducted, including spatial orientation and navigation and spatial visualization and rotation, in order to measure the performance of spatial learning and cognitive mapping skills among autistic people. The outcome of this evaluation will determine the use of this proposed framework as a guideline to design various HBVE for autistic people to learn and improve their spatial learning and cognitive mapping skills in the real world. The details of the evaluation of the simulation are demonstrated in chapter 6.

1.7.6 Communication

As stated by Peffers et al. (2007), communication is an important aspect of research, and this is defined by the publication of papers in conferences and journals, where the construction of the artefact (algorithm and framework) is one of the aspects of the research process.

1.8 Organization of the Thesis

This dissertation is divided into seven (7) chapters, which are as follows:

1.8.1 Introduction

This chapter began by defining the domain of this dissertation. It enclosed the overall research area by defining and identifying the statement of problem, research objectives, research questions, the importance and relevance of research, the scope of research, the methodology used, as well as the organization of the thesis.

1.8.2 Theoretical perspective of spatial cognition and haptic for autistic people

This chapter began with an understanding of autistic people, followed by discussions of spatial learning, cognitive mapping, haptic technology, and modalities of interaction.

1.8.3 Exploring the real-time haptic rendering technologies and interaction components

As part of this chapter, we will discover about the perception of the present HBVE-Framework, the elements of HBVE and spatial cognition, as well as all of the related theoretical elements.

1.8.4 Autonomous spatial orient-navigate algorithm as a channel of framework

This chapter presents the construction of an autonomous wayfinding algorithm based on spatial information in the virtual environment, along with its implementation in the framework as one of its navigation components.

1.8.5 Structuring of haptic based virtual environment framework

It is explained in detail in this chapter how the HBVE-Framework for autistic people was constructed. An expert evaluation was conducted in order to examine and validate the framework, as well as to make the necessary changes to the framework in accordance with the experts' suggestions. Apart from this, this chapter also conducted an applicability case study to determine the effectiveness of a framework for producing designs for HBVE for autistic people.

1.8.6 Real-time haptic rendering interaction simulation development and evaluation

With the use of the spatial learning and cognitive mapping method, this chapter discusses and demonstrates the implementation of the HBVE simulation for autistic people. It also includes an evaluation of the usability of the HBVE to identify and solve the usability problem, as well as an experimental evaluation of the simulation with autistic people.

1.8.7 Conclusion

This chapter contains the dissertation's recommendations as well as its conclusion remarks.

CHAPTER 2: THEORETICAL PERSPECTIVE OF SPATIAL COGNITION AND HAPTIC FOR AUTISTIC PEOPLE

This chapter begins with a review of relevant literature based on autism and the basic social interaction skills of autistic people, followed by a review of relevant literature based on spatial learning and cognitive methods used to provide spatial knowledge and cognitive mapping awareness among autistic people. An overview of the influence of modalities on autism is provided, as well as information about haptic technology and its use in the virtual world. This chapter featured two different styles of literature reviews: narrative and systematic.

2.1 Perspective of Autism Spectrum Disorders (ASD)

Ousley and Cermak (2014) defined autism spectrum disorder (ASD) as a neurodevelopmental disorder that can manifest itself in a variety of ways, including anomalies in social interaction or communication (social skills, speech, and language), restricted interests and activities, and uneven cognitive capacities. According to D. L. Christensen et al. (2018) and Y. S. Kim et al. (2011), autism spectrum disorder (ASD) is the most prevalent developmental disorder since the prevalence is predicted to be 1.47 percent to 2.64 percent of the total population, with a male/female ratio of 5/1. This ratio was obtained in a pretty close manner during an experiment conducted with individuals in Malaysia, where the male/female ratio was 3/1 (Dolah et al., 2011). Individuals with ASD can display a wide range of signs and symptoms (Keown et al., 2013), and these signs and symptoms can be diagnosed using a variety of methods, including standard ASD evaluations, observations based on their behaviour or activities, and the knowledge of therapists and other professionals (Manning-Courtney et al., 2013). Autism spectrum disorder, high-functioning autism, atypical autism, autism spectrum disorder, and pervasive developmental disorder are some of the terminologies used to describe people who are on the autism spectrum. Because of the similar manner in which doctors and parents use these terms, they are frequently misunderstood. When it comes to children, it is always their individual requirements that are genuinely crucial. Focusing on these needs rather than on all of the current phrases is the most beneficial thing one can do to help them get the appropriate therapy they require (Siegel, 1997). In the early stages of autism, there were just a few indications and symptoms that could be recognized in every person with autism. The most prevalent indications and symptoms experienced by both children and adults include poor social skills, speech and language difficulties, restricted activities, and inconsistent cognitive capacities. However, the severity of their symptoms, the combinations of symptoms, and the patterns of behaviour vary (Rowland & Schweigert, 2009).

2.1.1 Adaptability in Social Contexts

In basic social interaction, autistic people have difficulties with things such as: unusual body language and facial expressions; preferring to be alone rather than engaging in social interaction; and resisting touch, which causes them to have difficulty understanding a person's innermost feelings, behaviours, and nonverbal cues like body language and voice tones that indicate resistance to being touched (Clabaugh et al., 2019; Lozic, 2014). They become anti-social as a result of this behaviour (Carpenter et al., 2002; Charman, 2011; Rowland & Schweigert, 2009).

2.1.2 Challenges with Speech and Language

A person's speech and language ability will usually manifest itself in the form of symptoms such as: delayed speech even at the age of 2, or in the worst-case scenario, the person does not speak at all or speaks with a strange tone of voice, and then resorts to repeating words or statements over and over without communicating the intention of doing so (Ikonomi, 2020; Sandaruwan). The rest of the time, they have significant challenges with daily speeches or difficulties with maintaining fluid communication, as well as a lack of understanding of simple remarks or questions (Mody & Belliveau, 2013; Rowland & Schweigert, 2009).

2.1.3 Restricted Action and Behaviour

In terms of restricted actions and behaviour, autistic people, especially children, always show limitations and cannot be changed in terms of their behaviour and preferences. The following characteristics are common: continual bodily motions involving hand flapping, rocking, and spinning around; close attachment to uncommon things such as rubber bands, keys, and light switches; fixation on certain subjects of interest, frequently involving figures or symbols (Kana et al., 2011; Moseley & Pulvermueller, 2018). They prefer the same orders and routines and experience emotional change when their routine or surroundings vary. Additionally, autistic people are generally taken aback by objects that have resolved, moving elements, or parts of objects (Kana et al., 2011; Moseley & Pulvermueller, 2018; Rowland & Schweigert, 2009).

2.1.4 Inconsistent Cognitive Capabilities

Each individual with autism has a unique level of intellect, which is generally characterised by unevenly developed cognitive skills (Heaton et al., 2008). At the same time, researchers have discovered that most autistic people have difficulty with tasks that require symbolic or abstract thinking rather than ones that require rapid memory or visual skills (Brunsdon & Happé, 2014; Joseph et al., 2002). These symptoms are the most important variables that contribute to difficulties in understanding spatial cognition and establishing awareness of one's spatial environment, and they will be discussed in further depth in the following sections (Edgin & Pennington, 2005).

2.2 Perspective of Spatial Learning and Cognitive Mapping

In a HBVE, spatial learning and cognitive mapping is a set of strategies that employ a variety of learning methods that could be applied to autistic people to improve their abilities in spatial learning and cognitive mapping skills. This section discusses the significance of spatial awareness and cognitive learning for those who have autism spectrum disorders.

2.2.1 Characterization of Spatial Learning

Spatial awareness is the ability to be aware of one's surroundings in a given situation, as well as the knowledge and ability to do so (Klippel et al., 2010). It is the knowledge of the objects in the environment that corresponds to the users, and it also includes a comprehension of the relationships between these objects when the object's position is altered or changed (D. Jung et al., 2019; Ross et al., 2001). To put it another way, "spatial awareness" is the ability to recognize the relationship between objects in the environment and to the user itself. Therefore, autistic people should begin practicing and developing cognitive skills at an early age. From the perspective of researchers (Bliss et al., 1997; Ferrari et al., 2009), the ability to maintain spatial awareness is not something that most individuals are born with; rather, it is something that can be learned and increased via the use of a certain approach or methodology. One's development will lead to them becoming sensible or aware of the positioning of objects in their environment, and they should be able to clearly understand their current location as well as the distance between objects in their environment. Spatial awareness can be defined as an individual's overall perception of his or her surroundings. Consequently, according to Charman (2003) and Mitchell and Ropar (2004), there are just a few signs and symptoms that can be recognized earlier in order to facilitate the edification of autistic people.

2.2.1.1 Specific Signs and Symptoms Determine Spatial Awareness

In addition to spatial awareness, a clear understanding of the concepts of direction, distance, and position will be present in the minds of autistic people (Lowery, 2015). When a user moves towards something, even something as simple as an object, it will become closer to them. Similarly, a distant object will appear smaller in size because of the distance between them. The space around them, as well as the proximity of individuals in their immediate vicinity, is now extremely significant. Eventually, as they mature, all of their activities and movements become more regulated and confined when they are in close proximity to people due to the fact that they have personal space. Autism is associated with a lack of spatial awareness, which is also associated with visual impairment (Coulter, 2009; Dakin & Frith, 2005). They are clumsy by nature and are prone to colliding with others. In their interactions with people or objects, they would rather be close to them or far away from them, depending on their preference. The organization of presentations may also appear to be a challenging task. These individuals with autism have difficulty discriminating between left and right and are confused about positional communication (Greenspan & Wieder, 1997; Pearson et al., 2014; Strickland et al., 2007). They have difficulty envisioning or producing the specifics of the objects, such as their size, patterns, color, and overall appearance, among other things (Alvino, 2008; Potrzeba et al., 2015; Scott & Baron-Cohen, 1996; Strickland, 1996). Montello (1993) wrote in his article "Scale and Multiple Psychologies of Space" that cognitive mapping is one of the applicable learning methods to overcome spatial problems, and that this learning mode is practiced and implemented using a mental model of a person in order to minimize the symptoms of spatial problems.

2.2.2 Characterization of Cognitive Mapping

In the late 1940s, Professor Edward C.Tolman of the University of California, Berkeley, developed a method of cognitive mapping that was widely adopted (Tolman, 1948). There are many different definitions of cognitive mapping that are described by different fields of academics, but the majority of the definitions refer to the same concepts, terminology, and concerns in the majority of the definitions. In order to collect, code, store, recall, and decode any information from their spatial environment in terms of relative location, attributes, or objects, people use cognitive mapping, which can be defined as a process of mental demonstration. Tolman's (Tolman, 1948) experiment was performed on the brains of rats, and subsequent neuroscience research on spatial memory and cognitive map formation in rats developed with the use of single-cell recordings. With this method, researchers have found several different types of neurons, such as place cells, grid cells, boundary cells, and head direction cells, which are active in relation to the environment an animal is in (Grieves & Jeffery, 2017; Moser et al., 2008). These types of neurons form the neural basis of cognitive maps (Grieves & Jeffery, 2017; Y. D. Yang et al., 2017). It means that the animal's spatial orientation is formed and influenced by the interaction of all of these cells. It also helps by incorporating spatial knowledge into a cognitive map of any given environment.

In addition, studies have shown that the human brain also contains evidence of cells that are spatially adapted. Certain neurons in the human hippocampus respond to specific locations in the same way that place cells in the rat brain do (Ekstrom et al., 2003). In addition, research has found that hippocampal activity is related to the boundaries that exist in an environment (Bird et al., 2010). In the meantime, it has also been discovered that grid cell activity can be seen in a network that includes the human entorhinal cortex as well as the head direction cell in the thalamus and subiculum (Doeller et al., 2010; M. Kim & Maguire, 2019). Some neuroimaging research suggests that the neural representations of spatial knowledge in the human hippocampus, such as distance, can have an effect on the formation of a cognitive map (Deuker et al., 2016; Howard et al., 2014; Morgan et al., 2011). Moreover, there have been neuroimaging studies that have shown this to be present in autistic people, with the term "social brain" being used to describe it. This term can also refer to the neural substrates that are involved in the processing of social information (Ecker et al., 2015; Müller & Fishman, 2018). In addition, the functions of the hippocampal system focused primarily on the concept of cognitive mapping, which is related to memory and spatial reasoning in people with autism (Behrens et al., 2018; Constantinescu et al., 2016; Mythili & Shanavas, 2016; Puerto et al., 2019; Schiller et al., 2015; Theves et al., 2019). This refers to the process of constructing and forming mental models in autistic people through information recall and recognition of their spatial knowledge (Joseph et al., 2002).

Furthermore, in conjunction with this, there have also been a large number of studies conducted with behavioral measures in order to comprehend and investigate the formation of cognitive maps (Craig et al., 2017; Vieweg, 2012; Yoshida et al., 2010). There has been a recent study on behavioral measures that showed the use of computational modelling for characterizing the cognitive strategies that autistic people use during social interactions (Craig et al., 2017; Yoshida et al., 2010). This means that a person's cognitive mapping abilities allow them to navigate their surroundings even after they have been blinded. These two concepts of spatial knowledge and cognitive mapping skills are interconnected, and the procedures of navigation or wayfinding assist autistic people in navigating and finding their desired location or object (Johns, 2003; H. Zhang et al., 2014a).

2.2.3 The Basic Principle of Spatial Learning and Cognitive Mapping

The spatial learning method is relatively connected from the cognitive mapping technique (Johns, 2003; Qiu et al., 2020; Wen et al., 2011; H. Zhang et al., 2014a). The spatial relationships of landmarks are learned by an individual with autism who is able to explore a real environment without being aware of the relationships between the landmarks to one another, the distance between two locations or objects, and the lack of knowledge or identification of the route that must be followed in order to travel between the objects or locations (Lowery, 2015). By creating a virtual environment in which the physical landmarks are represented as data set items, these landmarks can be put in the virtual environment according to the basic relationship between the landmarks that has been established (attributes of objects and locations). Moreover, the individual who is exploring the virtual environment should be able to not only understand their spatial connections but also the relationships between different data sets (objects and locations)(Rosenman et al., 2007; Waller et al., 1998). A basic definition is that the virtual "urban" environment will educate the user about their spatial relationship with the objects and locations in their surroundings. According to the cognitive mapping method, an individual who is aware of and has learnt their spatial ability acquires, stores, and uses the knowledge gathered about the location and attributes of objects in a virtual environment. This procedure is based on the cognitive mapping method.

2.2.4 Define the "Scenario Environment" for Spatial Learning and Cognitive Mapping

It is critical to identify the best virtual situational or scenario environment to use as a knowledge transfer platform for spatial learning and cognitive mapping. This virtual-based scenario environment is typically focused on virtual objects and their relationships and behaviours with their surroundings (C. J. Chen, 2010). This means that the developed virtual environment represents specific real-environment concepts, which will help autistic people in the future when navigating or wayfinding in a similar scenario environment. To discover the suitable scenario for the development of the virtual environment as a platform for spatial learning and cognitive mapping knowledge transfer, the designer must first understand what types of situations or scenarios autistic people require spatial knowledge. Furthermore, it is unclear what types of elements, information, and environmental design are beneficial to autistic people in navigating and learning their surroundings. This is dependent on autistic people's need for spatial information, so it cannot possibly focus on those irrelevant elements. Therefore, as a designer, knowing which elements or information were the most relevant and important for the respective scenario for the specific group of autistic people could be useful in designing the virtual environment (Darken & Peterson, 2014).

According to studies, the majority of autistic people lack spatial knowledge in an "urban" environment (Amon et al., 2018; Dong et al., 2017; Khanuja & Steinfeld, 2018; Lindsay & Lamptey, 2019). Certain urban environment "elements" can be used to design and develop the virtual environment for the aspect of implementing and practising spatial knowledge in the sense of spatial learning in an urban environment, such as building blocks, landmarks, routes or paths to connect to the location or landmark, and junctions between routes or paths (Ahmadpoor & Shahab, 2019; Huang et al., 2022; Norgate & Ormerod, 2012). All of these elements are important in exposing autistic people to explore and find their direction in a virtual environment by improving their spatial knowledge and cognitive skills, which they can then transfer and practise in a real environment in future situations.

2.2.5 The Instructional Approach of Spatial Cognition Learning

The majority of autistic people like to acquire their spatial skills based on communication and organization through the shape, color, pictures, and maps of their surroundings, and this will assist the user in visualising the space in their mind's eye (S. E. Lind et al., 2014). Aside from this, autistic people have a good sense of spatial direction and can readily identify or reach a desired destination without becoming lost (Darken & Peterson, 2014; A. Wu et al., 2009). Therefore, the following sub-sections will discuss a few approaches and processes for improving their spatial awareness, which will help them become more aware of their surroundings and improve their navigational skills in the environment. These can be classified according to the following criteria: *Understanding the Acquisition of Spatial Knowledge*, *The Adoption of Wayfinding Method*, and *Learning through Cognitive Mapping* (Ahmadpoor & Shahab, 2019; Cardillo et al., 2020; Caron et al., 2004; Qiu et al., 2020; Thorndyke & Hayes-Roth, 1982; Vaez et al., 2016).

2.2.5.1 Understanding the Acquisition of Spatial Knowledge

According to Pylyshyn's FINST Theory (Pylyshyn, 2000), a person is capable of identifying more than 4 or 5 objects in their immediate environment at any given time. Therefore, autistic people should be able to select an object based on the instruction or brief of the direction given, as well as move within the paths specified with the knowledge of objects/location and the objects' properties/attributes (shape, colour, feel, sound, and so on) through encoding (Pérusseau-Lambert, 2016). The user's perception, visualization, and imagination, which are all represented in their short-term sensory memory, represent their spatial knowledge and help to build spatial awareness in and of themselves (Deuker et al., 2016; Kozhevnikov & Hegarty, 2001b). To put it another way, after a user has acquired spatial knowledge, how does that knowledge become structured in their mind for future use? Also, spatial knowledge should be structured into any way of recall in order to be used by users throughout their daily activities, such as navigation. Cognitive maps are useful in reflecting users' spatial knowledge because it helps people recall and visualize their surroundings (Johns, 2003; Schiller et al., 2015; Thorndyke & Hayes-Roth, 1982; H. Zhang et al., 2014a).

Landmark Knowledge, *Route Knowledge*, and *Survey Knowledge* are three different types of models that can be used to represent spatial knowledge. These different types of models are all connected in some way to one another. The majority of the time, the users obtain landmark information from the surrounding environment of a location, and this information is static and does not establish a connection between them. The development of *Route Knowledge* is dependent on the pathways taken by each landmark (object/location). These paths do not have to be the best or most appropriate paths for a user's navigation in order to be considered as such (Qiu et al., 2020). According to the urban environment, a user may be familiar with the routes from school to bus stop and from bus stop to apartment (in order to return home), but may not be familiar with the routes from school to apartment that are the most direct and efficient (to return to home). On the basis of this scenario, the *Route Knowledge* generated the nodes and edges in the appropriate manner, resulting in a graph of nodes and edges (Ahmadpoor & Shahab, 2019). With the addition of *Survey Knowledge*, the graph of nodes and edges has reached its conclusion. Despite the fact that the user is not travelling down each of the paths, the user is still able to navigate or move because the user has the capacity to estimate the distance and direction between any two objects or locations (Ahmadpoor & Shahab, 2019). Due to the fact that a complete map is provided at the beginning of each spatial orientation activity, the user is allowed to skip or omit learning the *Route Knowledge* phase and can instead focus on practicing *Survey Knowledge*.

(a) ***Acquisition of Landmark Knowledge***

Landmark Knowledge is the ability to record with great imagination and memorable ability the objects surrounding them and their visual features, such as 3D shapes, the size of objects, the texture of objects, and the motion of animation (Thorndyke & Hayes-Roth, 1982). In fact, even people with a high level of knowledge of landmarks will find it difficult to move from one location to another, since landmark knowledge is only useful for recognizing locations.

(b) ***Acquisition of Route Knowledge***

Route knowledge, also known as procedure knowledge, is the process of memorizing the sequence of acts that must be performed in order to construct the path that will lead to the desired locations. Since they perceive the path from the first-person perspective, researchers believe that someone who has route knowledge will be unable to get around obstructions on their route (Witmer et al., 1996).

(c) ***Acquisition of Survey Knowledge***

Survey Knowledge is a view from a third-person perspective, because the user is able to perceive the whole view of their designed location and is well aware of the connectivity of each other's attributes and the surroundings of items (Ahmadpoor & Shahab, 2019). Even if this survey knowledge is encoded with each other's topographical information, knowledge of the distances between the objects, their locations, and attributes is still necessary.

When compared to the other two categories of information, survey knowledge is the most complete when cognitive mapping skills are used, but it takes a long time for people to acquire this type of understanding. If the activity is completed in a virtual environment, it is possible that this survey knowledge will not be required in order for the user to grasp their spatial environment and locate their desired location.

2.2.5.2 The Adoption of the Wayfinding Method

Wayfinding is a way of addressing spatial problems that is used in navigation. Wayfinding will assist an individual in determining where they are in a given environment, knowing their desired location or how to get there from their current location (Ramloll & Mowat, 2001). In a virtual environment, there are numerous ways to apply wayfinding methods, and this method will be used by the user when determining how to get to their desired location or destination. Using Cathryn Jhons' (Johns, 2003) theory and methodology, the following sub-sections will discuss the three steps of wayfinding methods based on urban environment scenarios, as well as how they can be practised and used in the cognitive mapping process of movement and navigation:

(a) The Directional Pointing Task or Orientation Task

This method begins at the environment's entrance, where user (autistic people) is positioned at the environment's entrance doorway and asked to point out the precise location of some selected things or objects. If the user is able to point out or indicate the correct objects or locations to be selected, the user's movement and navigation will be recorded. Meanwhile, if the user is unable to specify the orientation of items or locations, they will be asked to make an assumption using their mental model or imagination. The directional pointing or orientation task is depicted in Figure 2.1.

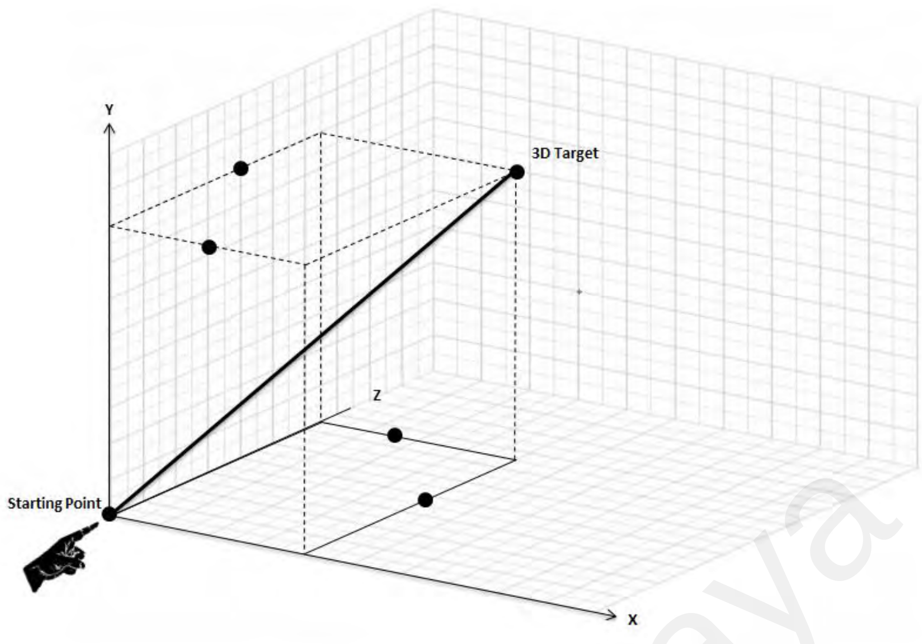


Figure 2.1: The Object/Location Used in the Orientation Task in the Haptic Based Virtual Environment

(b) ***Route Distance Estimation***

Route distance estimation can be approached in two ways: user-to-object and object-to-object. The user will be asked to estimate the route distance (*feet-ft*) between his or her current location and the objects indicated in the preceding orientation task stage (refer to Figure 2.2). As illustrated in Figure 2.3, the user will also be asked to estimate the route distance between any two objects or locations, and if the user is unable to specify the location or objects, they will be asked to assume and estimate the route distance (*feet-ft*) using their mental model or imagination.

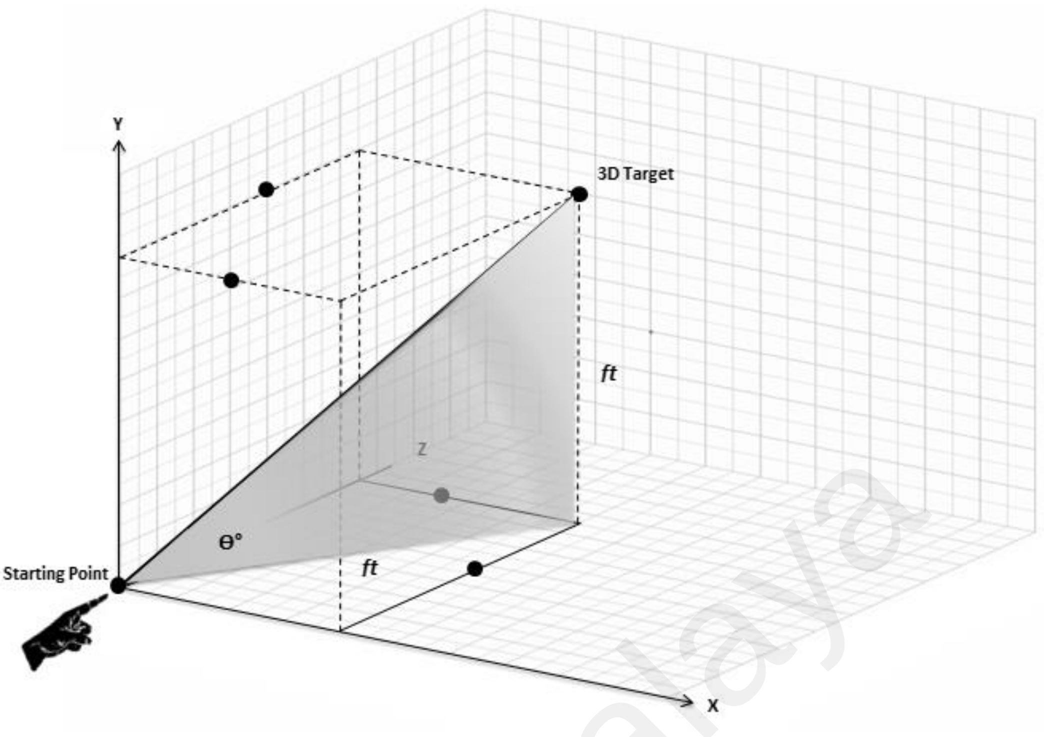


Figure 2.2: The Estimated of Route Distance between Users to Objects/Locations in the Haptic Based Virtual Environment

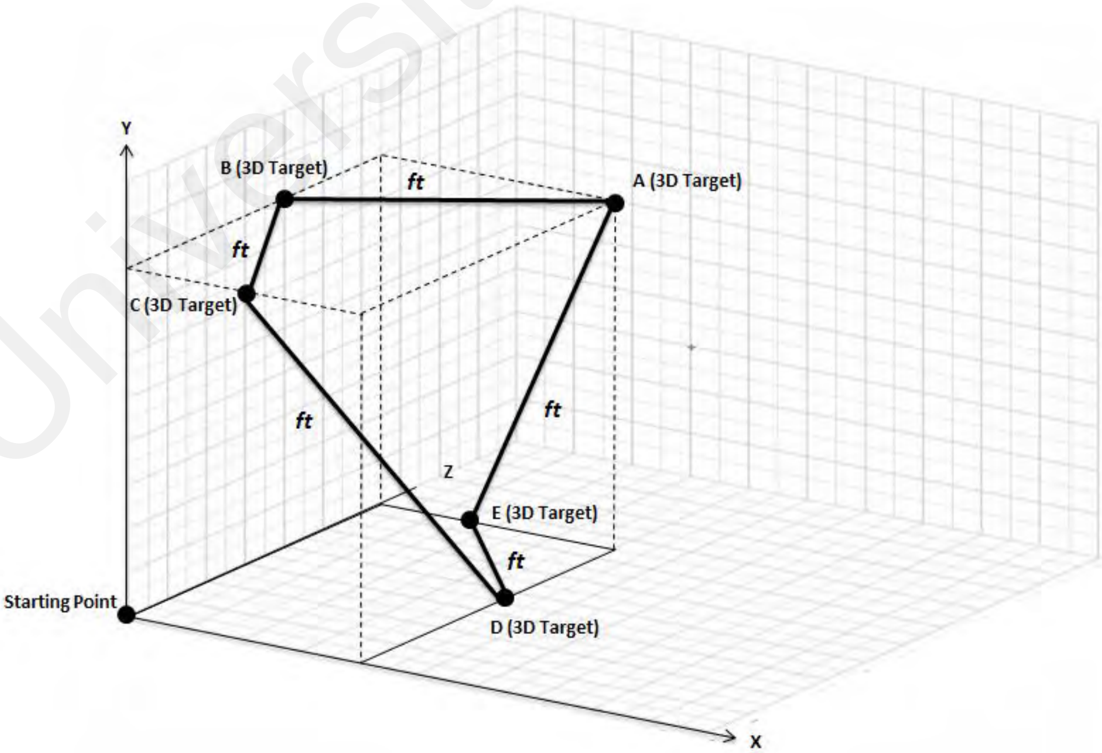


Figure 2.3: The Estimated of Route Distance between Each of Two Objects/Locations in the Haptic Based Virtual Environment

(c) ***Wayfinding Tasks***

Following completion of the preceding two steps, the user will be assessed in the HBVE without the assistance of any maps or paths. This will be assessed in relation to the assigned wayfinding task/activities, and the user will also be able to practise the task using the navigation model proposed by (Susanne Jul & Furnas, 1997), by referring to Figure 2.4 for a simplified navigation and finding process.

Navigation Model from Jul and Furnas (1997):

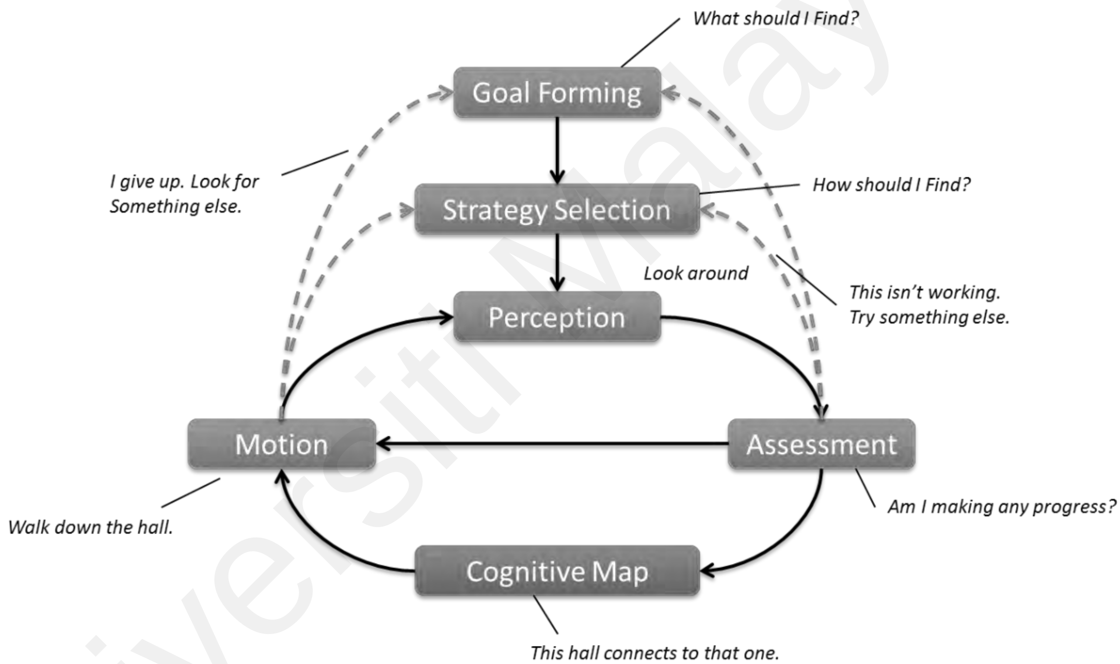


Figure 2.4: The Navigation Model from the Susanne Jul and Furnas (1997)

The user should be able to point in the direction of the objects or locations and choose the shortest route possible by estimating the distance between the objects or locations. The pathways, directions, duration, and the number of errors committed will all be documented. To accomplish each task, they will have five minutes, and if they are unable to reach their targeted location or select the appropriate objects, they will be instructed to proceed to the next task or activity, which will be determined based on the task specified.

This testing will be repeated until the user is able to successfully complete all assigned activities and demonstrates spatial awareness.

2.2.5.3 Learning through Cognitive Mapping

This section focuses on the implementation of cognitive mapping and how it is represented while people are learning about their surroundings (spatial relations). According to (Neisser, 1976) findings, cognitive mapping is defined as a mental representation that seeks and manipulates spatial information in memory/imagination. As previously stated, cognitive mapping is the process through which a person acquires, codes, stores, recalls, and decodes the information acquired about their current location and the attributes of objects in their spatial environment or surroundings (Johns, 2003). Their spatial knowledge is represented by the cognitive map (places, sounds, sights, etc.). In accordance with wayfinding theory, the following sub-sections present a simple set of steps or processes that are established that are involved in the mapping based on the task/activities:

(a) ***Classification and development of Cognitive Mapping***

There are two types of fundamental classes of information, which are information about the locations and information about the attributes of objects (Behrens et al., 2018). Within these two fundamental classes of information, there are recognized subclasses of information, including distance and direction information, as well as descriptive and evaluative information, as depicted in Figure 2.5.

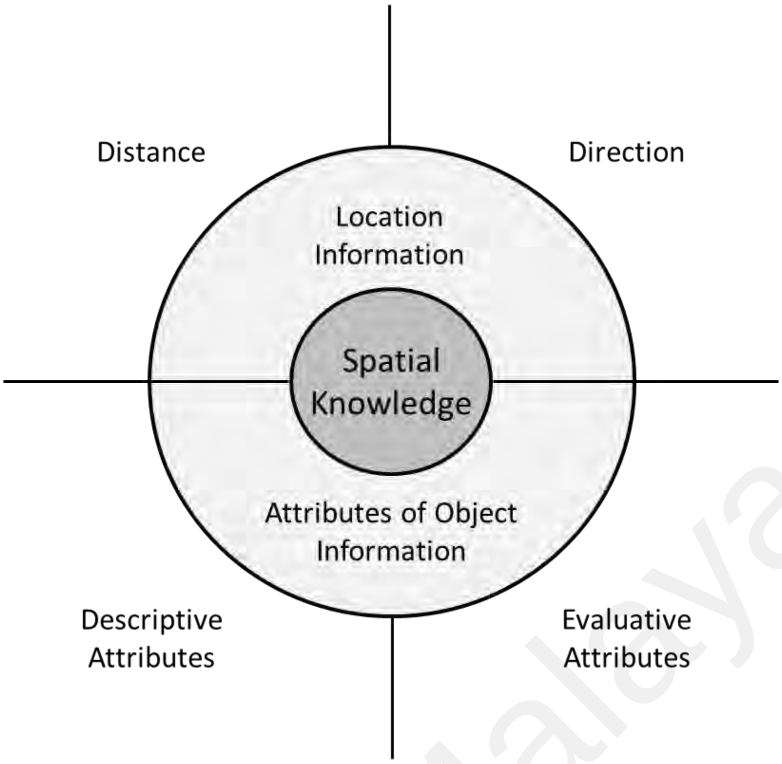


Figure 2.5: The Classification of Cognitive Mapping Process Framework

*(b) **The Subclasses of Location Information***

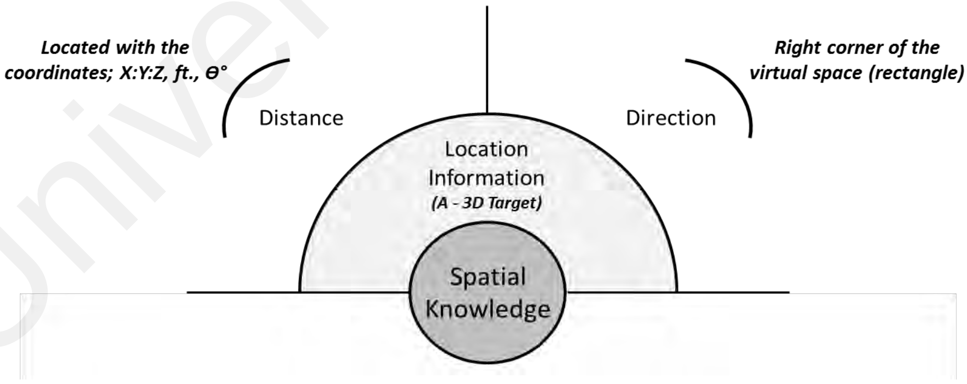


Figure 2.6 : The Subclasses of Location Information from Cognitive Mapping Process Framework

According to the case study Figure 2.6, the user is able to store and retrieve location information by describing where he or she is currently located as well as how to move or navigate to their desired location. In the cognitive mapping technique, this is the process through which spatial environmental information is encoded and represented.

(c) The Subclasses of Attributes of Object Information

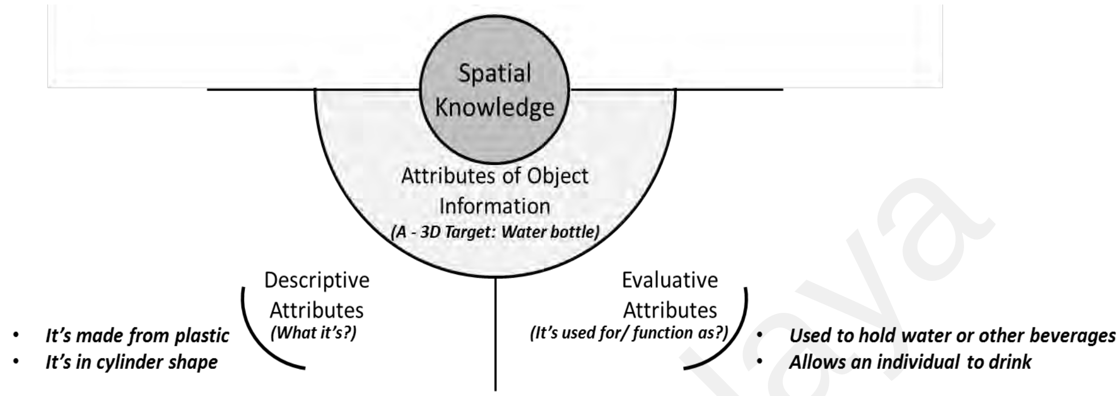


Figure 2.7: The Subclasses of Attributes of Object Information from Cognitive Mapping Process Framework

Other than representing and being aware of the current location in an environment, knowing the relationship between the attributes of objects and their surroundings in an environment is a crucial issue to consider (Johns, 2003; Ramloll & Mowat, 2001; Vaez et al., 2016; Wen et al., 2011; H. Zhang et al., 2014a). Users are able to recognise or recall objects in their mental models by defining their attributes (such as their shape, feel, sound, and appearance), and they are able to evaluate the basic functions and features of those objects (Battaglia et al., 2011; Bos et al., 2019). Descriptive attributes can be defined as the characteristics of the objects; on the other hand, evaluative attributes can be defined as the object's fundamental function and concept. This perception represents the relationship between the objects and specifies their roles or functions, as well as how they will cause an individual to acquire, code, and store the objects surrounding them in their mental model. In Figure 2.7, "descriptive attributes" demonstrate how the user may simply incorporate the target objects' information into their mental model and recognise them in the future. The "evaluate attributes" describe how the user can visualise the beneficial potential and role of the targeted objects. The cognitive mapping method is useful because it identifies the common attributes of an object and defines its basic function.

2.3 The Techniques of Wayfinding in Navigation

According to the cognitive and spatial awareness description, navigation is related to the technique of wayfinding, which can be described as movement by a person through a virtual environment (J. L. Chen & Stanney, 1999). It means, wayfinding is successful when the navigator makes decisions that lead them to their destination. Choices include whether to keep going or turn around, how to proceed when faced with an obstacle, or whether to pause and gather data from the surrounding area to confirm the current course of action. According to the author, wayfinding helps travelers complete larger tasks (Arthur & Passini, 1992). Also, this technique can be grouped into a few phases, such as extracting or gathering information about their environment, forming a mental model, and then using the former model for their initial route planning phase and moving into the virtual environment in accordance (Barker, 2019; J. L. Chen & Stanney, 1999). They have the ability to change or modernise their position and direction in order to get to their target position faster and more efficiently. Overall, wayfinding is a technique for people to learn and remember their route, whether in a virtual environment or in the real world. It is also the capacity to discover their targeted location and, at the same time, to recognise the location, features, or objects once they have reached it.

2.4 The influence of Haptic Technology in Spatial Learning, Cognitive Mapping and Wayfinding

The majority of navigational technologies, particularly those designed for autistic people, rely on audible or visual displays to communicate directions. This is due to the fact that the majority of researchers ignored the haptic modality as a means of navigation and wayfinding in the environment. This modality can be utilised to gain spatial knowledge and improve cognitive mapping skills. Haptic feedback is one of the sensor sources that has the potential to be the most instructive and sustainable provider of navigational information for people while they are navigating their way through an environment (Antolini et al., 2011; Sánchez et al., 2014; Semwal, 2001). In addition to providing a sense of touch when interacting with an object, haptic feedback can also provide a sense of direction. Incorporating haptic feedback into navigational support technologies has the potential to significantly improve autonomy and overall quality of life for autistic people who struggle with sensory sensitivities and find it difficult to navigate in unfamiliar environments.

According to Fritz et al. (1996) definition, the term "haptic feedback" refers to the sense of touch that is associated with kinesthetic information, also known as a sense of position, motion, and force. Haptic feedback in the form of vibration can be used effectively to indicate upcoming obstacles, directional steps, and the location of the destination. Haptic feedback makes navigation more accessible and has the potential to eliminate the feeling of disorientation that some autistic people experience. The route and survey (map) approaches are the primary methods utilised in the processes of navigation and wayfinding in an environment (Ahmadpoor & Shahab, 2019; Lahav & Mioduser, 2003, 2008; Wen et al., 2011). A route approach, which can also be referred to as "route knowledge", involves the static recognition of spatial attributes, whereas a survey approach involves the exploitation of multiple perspectives in order to acquire an allencompassing image of the surrounding environment (Ahmadpoor & Shahab, 2019; Lahav & Mioduser, 2003, 2008). The vast majority of autistic people who have trouble with their spatial knowledge rely primarily on their knowledge of routes to investigate their environments and identify objects or clues that are present in those environments (Ahmadpoor & Shahab, 2019; Waller et al., 1998; Wen et al., 2011). These methods are utilised in the process of constructing a mental representation of the topography of an environment, also known as a cognitive map (García-Catalá et al., 2020; Golledge, 1999). The absence of a familiar environment is a barrier. Meanwhile, the ways in which the environment is represented or structured provide guidance to people in their daily activities. This is thought of as a cognitive representation of the spatial environment. A study showed that people's cognition can influence how they represent their spatial environment and landmarks (Sophie E Lind et al., 2013; Rapp et al., 2018). According to this viewpoint, having different cognitive skills may influence how a person appraises the spatial environment, and as a result, people with cognitive disabilities may require different representation modalities for receiving assistance (Billinghurst & Weghorst, 1995; Ottink et al., 2022; Rapp et al., 2018). Autistic people are classified as having unevenness in cognitive abilities (Azouz et al., 2014; Happé & Frith, 2006; Hong et al., 2023; Howlin et al., 2009; Joseph et al., 2002; Kemper & Bauman, 1998; H.-H. Li et al., 2020; Wei et al., 2012). Therefore, when navigating unfamiliar environments, autistic people who have constructed cognitive maps can influence their navigation in the environment (Fornasari et al., 2013; Maras et al., 2014; Rapp et al., 2018).

When developing a cognitive map, the process of spatial learning typically involves taking into account two distinct types of frames, known as egocentric and allocentric. In an egocentric frame of reference, the location of an object is interpreted in relation to the individual's own location, whereas in an allocentric frame of reference, the location of an object is identified in relation to the locations of other objects (Miniaci & De Leonibus, 2018; Schinazi et al., 2016). Autistic people might have a tendency to navigate their environments by relying on egocentric representation of the environment in order to avoid obstacles (Klin et al., 2002; Laidi et al., 2023; Sophie E Lind et al., 2013; Presley, 2021; Smith, 2015; Umesawa et al., 2020). However, allocentric relies on remembering, recalling, and recognizing environmental landmarks in order to successfully navigate through an environment and reach the desired location (Umesawa et al., 2020). In the author's experiment, high-functioning autistic children showed a strong selective impairment in the spatial representation task, but only with the allocentric perspective. Therefore, they may have difficulty in their ability to predict movement, which may restrict their navigation to reach the target (Turi et al., 2017). As mentioned in Section 2.3, the technique of wayfinding is classified as the individual's capacity to know its own position and location within an environment. Relying on allocentric representation of an environment can help autistic people successfully navigate their surroundings, and this idea ought to be incorporated into the concept of haptic-based navigational assistive technologies for wayfinding and navigation (Castellanos & Hruby, 2021; Castillo Escamilla et al., 2020; Chang & Wang, 2010; Golledge, 1999; Grech et al., 2018; Laidi et al., 2023; Sophie E Lind et al., 2013; Sánchez et al., 2014; Zelek, 2005).

Autistic people will get a cognitive improvement while interacting with a virtual environment since this type of setting can offer positive reinforcement and a higher level of engagement, both of which are important for maintaining autistic people's interests. Thus, the incorporation of haptic technology's sensation of touch enables autistic persons to have better sense engagement. Furthermore, the virtual environment enables autistic people to touch, grip, navigate and handle virtual objects with the use of haptic force feedback devices (Almaguer & Yasmin, 2019). Autistic people typically rely on their vision to process a space in its entirety; however, without complete touch sensitivity, these people are unable to feel detailed information about an object's unique properties, which can be especially challenging when interacting with a virtual world (Robles-De-La-Torre, 2006). An autistic person's cognitive load is increased when they have to remember and recall all of the attributes and spatial elements of their environment (Martinez et al., 2014; Wen et al., 2011; M. Zhang et al., 2020; Zhou et al., 2007). This may cause their attention to be diverted away from performing the tasks that were intended. The use of external representations of a space is one strategy that efficient system designs employ to reduce the cognitive load (Martinez et al., 2014; Zhou et al., 2007).

Additionally, the auditory modality is an appealing choice for the processing of spatial information; however, autistic people already rely heavily on their sense of hearing to avoid collisions. Therefore, haptic feedback is a non-intrusive stimulus that does not affect other important senses for autistic people. Consequently, it should be used to offset the cognitive load of navigation assistive technologies. In order to properly construct a representation of an object, its individual properties have to be individually felt and perceived. When navigating or wayfinding through an environment, it takes a significant amount of mental effort to memorise the attributes of each object or location so that one can remember them and call them to mind when necessary (Colwell et al., 1998; Wen et al., 2011). Recognizing larger or simpler objects requires less cognitive effort than recognising complex objects, which requires the individual touch sensation to process spatial information as well as recognise and recall the objects' attributes in the future (Colwell et al., 1998; M. Zhang et al., 2020). This section was further investigated in Chapter 4 for additional information regarding the influence of haptic technology in navigation assistive technology by taking into consideration the concept of spatial learning and cognitive mapping abilities.

2.5 Perspective of Virtual environment in the Context of Haptic Technology

When it comes to dealing with virtual environment (VE), the majority of the issues arise from barriers and a lack of understanding of the current technology available, particularly when it comes to the implementation of haptic based development; what are the core functions, techniques, and methods available on the current VR platform that can be supported by haptic technology; and how it is going to be supported by haptic technology. If the models, strategies, and methods that are already in use are thoroughly researched, it is possible to avoid these problems and even come up with a new solution.

2.5.1 Understanding the Concept of Virtual Environment in Haptic Environment

A virtual environment (VE) is a computer-simulated environment that allows a user to design their own navigation, interaction, and virtual communication channels. Individuals, particularly those with autism spectrum disorders, can benefit from this since it fosters a more realistic environment. According to the real-world environment concept, this virtual environmental application will be produced with the high features of virtual reality development tools in order that users may accept it as a real space from their inner feelings (Bowman et al., 1998; Steinicke et al., 2006). Virtual environments created by computers have two types of feedback, which are visual feedback and auditory feedback, respectively. Currently, the most effective VE applications are produced using visual perspective, in which case they are developed for computer screen display or with stereoscopic view. However, at some point in the evolution of VE, it will make use of advanced wearable technology to sense and affect qualities such as haptic interaction. VE can be formed either from the perspective of the real-world environment or from the perspective of an individual's imagination. In addition, as a component of non-immersive technology, VE makes use of advanced wearable technologies to produce an immersive experience that gives the impression that the user is participating in real-time interaction with the environment (Ramloll & Mowat, 2001; S. Zhang et al., 2013). The user can navigate and interact with a virtual object in a virtual environment by manipulating it with multi-sensory technologies, such as a haptic device. This can be accomplished using the model-view-control pattern, which allows for real-time interaction to take place. In VE, there are three types of approaches to choose from: immersion, interaction, and representation (Sherman & Craig, 2018).

2.5.2 The Concept of Haptic Based Virtual Environment in Autistic people

A virtual environment (VE) is widely recognized as a learning or training platform for the development of specialized skills or knowledge. Therefore, it can be advantageous for autistic people in terms of learning and practicing any abilities, such as spatial learning on a virtual platform. As previously stated, virtual environments (VE) have significant potential as an educational platform for autistic people. Many researchers believe that autistic people can visualize and control a virtual environment, which may not be conceivable in the real world (Dautenhahn, 2000; Johnston et al., 2019). Furthermore, it has the ability to "cure" autistic people, in cases when these individuals may express a preference for haptic and other learning modalities, and it is thought to be quite valuable for a variety of reasons. Autistic people can benefit from virtual reality by providing amenities such as an error-free learning environment, a safe testing environment, and game aspects to motivate them to finish activities or tasks. These scholars (Almaguer & Yasmin, 2019; Ke & Im, 2013; Parsons & Cobb, 2011; Parsons & Mitchell, 2002), on the other hand, emphasize that the option of VE is extremely beneficial for people who have autism caused by a variety of causes, such as the following: user active control, many forms of social interaction or communication techniques, non-verbal communication can be controlled, behavior and reaction can be practiced and built in the virtual world, which has many similarities with the real world, and a more realistic representation of the social helps improve problem solving, provides better reinforcement and a sense of engagement. VE can also be used to improve edge-based learning tasks, which may be of particular appeal to autistic people. With features such as those mentioned above, VE can assist autistic people in accelerating their learning curve, particularly in the area of spatial learning, which is more difficult to learn in the real world. There are a few contributions from the VE for autistic people, including the following:

2.5.2.1 Capable of Transferring their Knowledge and Skills to their Real World throughout a Training Session

Autistic people can benefit greatly from virtual environments, which allow them to role play by simulating certain social interactions in a designed virtual environment (Witmer et al., 1996). This means that the user will be able to perform the task or activities in a realistic setting in a virtual environment. Users' social skills and understanding of self-skills are improved as a result of this, and they can play a part in issue solving between the training environment and the real-world context.

2.5.2.2 Haptic based Therapies for Autistic People Improve their Ability to Recover

The use of HBVE for autistic people is becoming increasingly popular in the context of learning and training, as well as to accommodate their physical limitations and assist them with virtual object manipulation. The use of haptic technology provides the touch-related properties for autistic people to feel and interact with virtual objects. Autistic people can also benefit from the interaction between a haptic device and a virtual environment since it can assist in rehabilitation, recuperation, or improvement of impairment. As a result, the majority of studies agree that HBVE are an important new component of computer-based therapy for autistic people (Difede & Hoffman, 2002; Manju et al., 2017; Y. D. Yang et al., 2017). It’s used to help autistic people develop or improve the skills necessary to adopt and be independent in the real world.

2.5.3 Recognize The Virtual Reality Systems That Are Available for Haptic Technology

There are a number of virtual reality systems that might be used as platforms for the development of HBVE. There are three major categories of virtual reality systems that have been reviewed based on their performance and the costs associated with their adoption. A few metrics have been defined to evaluate and rank the level of performance of each VR system, including: a sense of immersion, a field of view, a sense of situational awareness (navigation skills), perception, interaction, and the cost of implementing each system. Based on the findings of this domain of research, the type of virtual reality system that will be utilised to construct a HBVE application is an important factor that will help to meet the needs and solve the domain of this research problem.

2.5.3.1 Non-Immersive Virtual Reality System

Non-immersive systems, often known as desktop VR systems, are VR systems that provide the least amount of immersion. Due to its lower sense of immersion and perception of scale, this desktop system employs VRML as a 3D model data transfer and virtual world technique via the internet platform (Robertson et al., 1993). This will boost the popularity of using this type of VR system in the development of desktop-based haptic virtual environment applications in the future. PC desktop users with fewer navigation skills can benefit from VRML technology, and even many commercial VR software products on the market today are nurtured and supported by the inclusion of VRML capability in their software. Due to concerns about the safety of autistic people and the cost of implementation, most of the studies intends to use non-immersive virtual reality systems as a learning platform (Bryant et al., 2020; Irish, 2013; Jeffs, 2010; Martirosov & Kopecek, 2017).

2.5.3.2 Semi-Immersive Virtual Reality System

VR systems that are semi-immersive are significantly clones of VR technologies from the flight simulation field, but with a higher level of computing graphics performance. These systems can be presented in three ways: on a large-screen monitor, on a large-screen projector system, and on multiple television projection systems (Van de Pol et al., 1998). This type of system can increase the user's sense of immersion due to its wide field of view.

2.5.3.3 Fully-Immersive Virtual Reality System

In a fully immersive system, a user is completely immersed in their HBVE and has the sense of being inside it while also being able to interact with it. Moreover, author (Bowman et al., 1998) stated that being unaware of their real surroundings while immersed or present in their existence within the haptic based virtual environment is referred to as an "effective" aspect of virtual reality (VR). The "depth of information" and the "breadth of information" are the two most important components of immersion. The amount and quality of data signals received by a user when interacting within a HBVE is referred to as the "depth of information." The number of sensory dimensions that are offered at the same time is referred to as the breadth of information.

2.6 Perspectives Predominantly on Haptic Technology

Haptics is a term that derives from the Greek concepts "hapto" and "haptesthai," which translate as "to touch and feel an object or a surface." Aside from that, the use of haptic technology provides the opportunity for an individual to mechanically touch and feel an object or surface through the interaction of computers. When it comes to human-computer interaction, this technology is defined as one of the modality components, which can be further subdivided into two types of perception: tactile and proprioception. These two different types of perception can be distinguished by their processing of sensation information, with tactile perception defined as the process of detecting tactile information such as vibrations, pressure, and temperature in order to recognise objects or the texture of their surfaces. Proprioception, on the other hand, is primarily concerned with recognising an object's shape through the processing of information about the user's position and movement in a particular environment.

2.6.1 Applications of Haptic Technology in Daily Life

Haptics technology is widely utilised in various fields, and the need for this technology is extremely significant in people's current day-to-day activities or practices. Through the use of this technology, users are able to explore and engage with virtual objects in a virtual environment, as well as communicate and interact with real-world environments (Bowman et al., 1998; Strickland, 1996). There have been plenty of haptics applications produced, and they cover a wide range of research fields. The following are some examples of haptics technology applications that are currently in focus and in high demand: gaming environment; aviation environment; and medical environment (Bowman et al., 1998; Choi et al., 2017; Robles-De-La-Torre, 2006; Waller et al., 1998). Haptics technology is often implemented in gaming environments, where wearing a suit or glove equipped with haptic sensors provides a real-world experience and the sensation of touch as tactile feedback while engaging with the gaming environment. Haptic technology can be used due to safety concerns or to gain experience flying an aircraft before operating in a real-world environment, and it can also provide a similar experience with haptic feedback during training sessions. A telepresence method with haptic technology can assist a medical doctor in performing operations with a haptic control device or robotic arm at distant events while not physically present. This process can be carried out with high accuracy or at a detailed level at a low cost. Aside from this, other types of applications in fields such as art and design, robot design and control, holographic interaction, entertainment, biomechanics, neuroscience, software engineering, physical rehabilitation and for other training purposes (industry or to improve individual skills) also make use of this haptic technology for the purpose of experiencing real-world environments and receiving haptic feedback in the form of a sensation of touch.

2.6.2 Overview of the Haptic Interface

A haptic interface is a device that allows users to interact and communicate within a HBVE and with the end-user. This sensible input-output device processes sensations and movements as feedback during the interaction with the virtual environment (Carvalheiro et al., 2016; Kirkpatrick & Douglas, 2002). A haptic interface is a device that receives and processes sensation feedback using sensors and actuators (Ozioko et al., 2020). A haptic interface typically contains an equal number of sensors and actuators in a single haptic interface. However, due to lower costs, certain haptic interfaces have fewer actuators than sensors. In the context of virtual object interaction, a degree of freedom (DOF) is defined as the dimensionality of positioning or orientation ability rendered by a haptic interface (Leonard & Villeneuve, 2019; C. Salisbury et al., 2009). DOF is typically integrated using three degrees of freedom (3-DOF) or six degrees of freedom (6-DOF). 3-DOF generates force feedback that is integrated with a movable grip that is capable of interacting with three arms at the same time. Meanwhile, utilising a stylus and force feedback, 6-DOF is created with positional sensing in three distinct axes, such as roll, pitch, and yaw, and is used to create a sensation of touch experience. Furthermore, there are three types of haptic interfaces: graspable, touchable, and wearable (Leonard & Villeneuve, 2019; K. Salisbury et al., 2004b; A. Song et al., 2008). Graspable haptic interfaces operate in the same way as a joystick, and they can be used to control and sense the shape of virtual objects. This form of interface creates force feedback by transmitting sensations to the user's nerves in their muscles, tendons, and joints. For example, Sensable Technologies' PHANTOM Desktop, which operates on 6 or 3 degrees of freedom (DOF). Most of the time, a wearable haptic interface communicates with a virtual object through generating vibration feedback. These types of interfaces are equipped with a specific number of sensors and the ability to generate vibrations, which can be used to guide the user in the direction of achieving the targeted goal. Among the many types of wearable haptic interfaces available, the MYO armband is one example, which will be discussed in more detail in the following subsection (Javaid et al., 2021; Sathiyanarayanan & Rajan, 2016). Touchable haptic interfaces, on the other hand, are based on "data-driven haptics," which can provide bumps and buzzes during interaction with virtual objects via a projecting screen. In these types of interfaces, the user can feel different kinds of textures on a surface, which are usually dependent on the patterns of vibrations that are produced or processed by the stylus pen. The vibration feedback will vary depending on the speed of the movement of the stylus pen or the pressure applied by the user during the interaction (Dennerlein & Yang, 2001; C. Salisbury et al., 2009). The following section discusses two types of haptic interfaces as well as the most appropriate haptic interface for this research.

2.6.2.1 Haptic Interface: PHANTOM Desktop

PHANTOM Desktop is a haptic interface with the dimensions of 160 mm in width, a height of 120 mm, and a depth of 120 mm as measured. When used in conjunction with a positional sensor system, the force can be applied up to 8 N with a resolution of more than 1100 DPI. This interface can be used in combination with either a 3-DOF force feedback system or a 6-DOF positional sensing system (Silva et al., 2009).

2.6.2.2 Haptic Interface: MYO Armband by Thalmic Labs

The MYO armband, developed by Thalmic Labs, is a wearable sensor gesture recognition device with haptic feedback that allows users to interact with applications through numerous spatial sensors derived from a person's hand gestures and arm movements (Javaid et al., 2021; Sathiyanarayanan & Rajan, 2016). These sensor transmission processes are referred to as electromyography (EMG), and they are used to detect arm muscle gesture movements. A total of eight EMG sensors are integrated into the MYO armband, which allows us to process haptic feedback as an electrical signal from the user's muscles while interacting with virtual objects (Krishnan et al., 2017; S. R. Kurniawan & Pamungkas, 2018). Furthermore, the MYO armband is capable of detecting the movements of the arm with the use of nine Inertial Measurement Units (IMU), which are divided into three sub-groups of axes: gyroscope, accelerometer, and magnetometer (Krishnan et al., 2017; Sathiyanarayanan & Rajan, 2016). During calibration with a HBVE, the MYO armband uses vibrotactile as haptic feedback, and this haptic feedback data is retrieved through three types of intervals: short, medium, and long vibrotactile. Meanwhile, to communicate with the HBVE, this haptic device made use of a Bluetooth Low Energy network sensor to establish a connection. The haptic device generates haptic feedback through the use of the Bluetooth adapter, which connects to the eight EMG sensors and the IMU (Javaid et al., 2021; Sathiyanarayanan & Rajan, 2016; Visconti et al., 2018). The MYO armband is designed with the internal and external surfaces, as well as the measurement axis. The MYO armband enables the user to assist with interaction and manipulation tasks in HBVE by waving, focusing, rotating, panning, and zooming. The haptic feedback data from the eight EMG sensors and IMU will be recoded and saved in a temporary haptic data repository. The EMG sensors and IMU data collected through the muscles are used to read the user's nerve system (Javaid et al., 2021; Krishnan et al., 2017; Visconti et al., 2018). In the course of an interaction with HBVE, each user's gesticulation has an impact on the fibres of his or her skeletal muscle, which encourages the nerve system to generate a sense of touch among users. For the haptic feedback measurements, the collected data is processed through the MYO server and the MATLAB software function.

2.7 Classification of Real-time Haptic Rendering Interaction Techniques

The realism of communication in a HBVE is directly affected by the interaction between a user and virtual objects through the use of a haptic device. Despite the fact that a significant amount of study and experimental research has been done on haptic devices and technologies, there has only been a small amount of research done on the interaction techniques used for haptic feedback. Interaction techniques in HBVE can be classified into two groups: exocentric haptic techniques and egocentric haptic techniques (Kahol et al., 2006). Exocentric haptic techniques are well known for their outside-in-world interaction, which allows the user to interact with the virtual object from a different perspective (outside viewpoint). Consider the World-in-Miniature technique, which enables the user to interact with and manipulate the life-world size of a virtual environment through the use of a small-scale virtual environment representation (Stoakley et al., 1995). This entails changing or interacting with mini virtual objects in terms of orientation or position, as well as directly representing the virtual objects in a life-size world (VE). Meanwhile, the egocentric haptic technique, which is well-known for allowing interaction with the inside world, is also being explored further (Kahol et al., 2006). Both the virtual hand and virtual pointer techniques are common sub-techniques that fall under the main technique of egocentric in the context of a HBVE (Steinicke et al., 2006). A virtual pointer is used to select and manipulate a virtual object by pointing to the object's direction, which is accomplished via the vector that enchantingly appears from the virtual pointer (Steinicke et al., 2006). When compared to other techniques, this one can be distinguished by the direction in which the virtual pointer is directed, the selection of volume, and the mechanism employed for the purpose of disambiguating the selected virtual object by the user as desired. This means that the orientation and position of the virtual hand can be used to define the direction of the technique's application. This technique can also be classified into two types of pointers, which depend on the user's eye position and the manipulation of tracker location. One of the types of techniques under the virtual pointer umbrella is the ray-casting technique, which employs a laser pointer (ray) to point and select a virtual object. Meanwhile, the flash light technique employs the same method as the ray-casting technique, with the only difference being the mechanism by which it is applied, where the flash light technique employs an infinite cone rather than a laser pointer to accomplish the activity (Bowman et al., 1998; De Boeck et al., 2005; Steinicke et al., 2006; Van de Pol et al., 1998). Additionally, this technique is restricted in terms of selection tasks since it exhibits inaccuracy when selecting any close virtual objects, despite the fact that it is capable of performing the most fundamental selection tasks, such as remote selection or selection of small objects. Users can also control virtual objects using the virtual hand technique, which allows them to grab and move objects in the HBVE (Bowman & Hodges, 1997). One such technique is the classical-simple virtual hand technique, which is used to perform the most fundamental selection and manipulation tasks by directly interacting with the virtual objects to create a tactile-based interaction (Dangxiao et al., 2019; De Boeck et al., 2005). This technique is classified as a "one-to-one" mapping technique because it involves direct interaction between the virtual hand and the physical hand. When compared to the Go-Go technique, also known as the arm-extension technique, it is preferable to use a non-one-to-one linear mapping method as the process of interaction between the virtual hand and the user's physical hand (Carvalheiro et al., 2016; Dangxiao et al., 2019; Halarnkar et al., 2012; Kirkpatrick & Douglas, 2002; C. Salisbury et al., 2009). These techniques, which include classical-simple virtual hand and Go-Go, are used to execute selection and manipulation tasks with virtual objects. However, they are extremely difficult to implement when performing tasks with remote or small objects.

2.8 Taxonomy of Haptic Interaction Tasks

There are several taxonomies of haptic interaction tasks that have been introduced and studied in the HBVE, and these are intended to create interaction between users and virtual objects using haptic interaction techniques. Therefore, this study concentrated on and evaluated the spatial visualisation task interaction among autistic people using the taxonomy of haptic interaction tasks developed by (Kirkpatrick & Douglas, 2002). There were a few external aspects that were focused on during the application of this taxonomy, such as the task, the environment, the user, and system features that have the potential to have an impact or influence the user's performance, and these will be discussed in greater detail in the following section, 6.5.5. In this taxonomy, the modes are divided into two groups: motor control and perception (Barker, 2019; Samur et al., 2007). These two groups of modes are designed in accordance with the concept of haptic interaction techniques and the user's haptic feedback. Also under the motor control haptic modes, (Bowman & Hodges, 1997; Bowman et al., 1998) established four types of general interaction tasks such as navigation, selection, manipulation, and release. For this study, the navigation general task was used to investigate the movement of the user's perspective, and this general task separated the interaction into four sub-tasks: targeting, exploration, kind of motion, and change of own position (Kagawa et al., 2014; Youngstrom & Strowbridge, 2012). Meanwhile, the selection task was used to identify and select the targeted virtual object, and this task divided the subtasks into two types: indication of object and indication to select (Moya et al., 2013; Steinicke et al., 2006). A general manipulation task is used to change and control the position and orientation of the selected virtual object, and it can be divided into subtasks based on the type of virtual object being attached, the position of the object, and the orientation of the virtual object being controlled. Additionally, the release general task is used to notify users that the manipulation of virtual objects has come to a conclusion (Dangxiao et al., 2019; Stansfield et al., 1995). This can be accomplished through one of the following two subtasks: indication to drop and final location of the object. User threshold perception can be studied and evaluated using three types of general tasks using haptic perception modes: sense detection, object material discrimination, and object geometry identification. Sense detection is one of the most used haptic perception tasks. Sense detection is used to explore and measure the somatosensation that occurs between the user and virtual objects, and it comprises the following subtasks: position, viscosity, velocity, pressure, force, and stiffness (Bowman & Hodges, 1997; Samur et al., 2007). When interacting with a virtual object, the object material discrimination is a differential threshold that focuses on the user's somatosensory system at a minimum level of sensation detection difference. In this general task, the same subtask components as in the sense detection general task are shared, but three more subtasks are added: the texture, weight, and hardness of the virtual object. The final general task performed by the haptic perception mode is object geometry identification. It is used to measure the object's environmental surfaces, such as the shape and size of virtual objects. Comparing this general task to the other general task (material discrimination), which has limited perception in terms of structural cues, this general task concentrates on the geometrical cues that the object provides (Carvalheiro et al., 2016; Sreelakshmi & Subash, 2017). Therefore, to obtain an accurate assessment of the efficiency of haptic rendering interactions on virtual objects, the tasks of object material discrimination and object geometry identification should be measured as separate task components. During haptic interaction tasks between the user and the haptic device, the haptic device generates various types of somatosensory feedback, which can be divided into three types of feedback groups: haptic feedback, visual feedback, and audio feedback

(MacLean, 2000; Sigrist et al., 2013). Tactile feedback and kinaesthetic feedback (also known as force) are the two sub-components of haptic feedback (MacLean, 2000; Pfeiffer & Rohs, 2017; Sigrist et al., 2013).

2.9 Influence of Haptic Sensory Modalities

This study, which is part of a systematic literature review (SLR) on this research, investigates the effectiveness and efficiency of using sensory modalities in spatial learning among autistic people (Bosseler & Massaro, 2003). Autistic people frequently have problems processing sensory information, which leads them to frequently use interventions to regulate themselves in their daily lives (Case-Smith et al., 2015). However, according to Dawson and Watling (2000), although this condition is not unique to ASD, it is disproportionately prevalent in ASD, necessitating more attention. Consequently, the use of modalities in HBVE use may differ from one person with autism to another, and a review is needed to investigate the modalities that have been integrated into the virtual environment, as well as the efficiency and effectiveness of utilising these types of modalities in the virtual environment platform among autistic people. Thus, the study explores, using a systematic literature review (SLR) method, the use of modalities in high-fidelity virtual environments (HBVEs) for autistic people, as well as the capacities of skills taught through the practices and experiments.

2.10 Systematic Review on the use of haptic modalities as Somatosensory in Haptic Based Virtual Environment (HBVE) for Autistic people

Autism spectrum disorder (ASD) is a neurodevelopment disorder, characterized by impairments in social interaction e.g., social communication; verbal and non-verbal communication, restricted and repetitive behavior, interests and activities e.g., spatial ability or navigation, and atypical sensory behavior. There are numerous definitions of the word "Haptic" which was derived from the Greek words (haptesthai and haptikos) which means, a sense of touch. In addition, it is well-known as "Tactile" which has become the most important aspect of individual in an attempt to interact with their surroundings (Barnett, 1972). Recent findings showed that, there was a somatosensory among ASD and the somatosensory was also diverse according to the use of haptic interface (Baranek, 1999; Cecil et al., 2017). The presence of somatosensory among autistic people which indicates imbalance, and also, there is lack of adaptation in somatosensory (Blakemore et al., 2006; Crane et al., 2009). Meanwhile, based on clinical identification, some scholars argued that, with a change in the GABAergic system, through haptic interface, it is likely that, somatosensory to autistic people will be influenced (Tavassoli, Auyeung, Murphy, Baron-Cohen, & Chakrabarti, 2012). Tactile feedback is known as touch and kinesthetic feedback, and this can as well be referred to as force, are the two feedback of haptics interface. Haptic interface is a sensory modality, where it is used as an intermediate platform for exchanging the information between human and the virtual environment. A typical sensory behavior may be discovered among autism, and it is described as one of the autism diagnosis criteria. Majority of those studies were focused on the auditory and visual modalities, among autism and it is narrow to haptic modality (Tang, McMahan, et al., 2014). The haptic modality used to be one of the primary factors for human to explore and interact with object in their surroundings through a sense of touch. Thus, the somatosensory system provides perceptual information about the object in the user's surroundings through two discrete perceptions, namely, tactile perception and proprioception perception. Tactile perception provides the texture, shape, weight or temperature information through the interaction with the object, while proprioception perception describes the user's positions and movements. However, these two discretized perceptions were interacted in haptic modality to generate a sensation among autism.

2.10.1 Method

This review was examined based on the process introduced by Ha et al. (2014) with the following stages:

2.10.1.1 Stage 1: Formation of Review Question

During this systematic literature review (SLR) process, some research questions were asked to examine the state of research and to identify the effectiveness of haptic based somatosensory modality among autistic people. The questions asked by this study were:

(1) How does somatosensory impairment in autistic people through provide any clinical evidence?

(2) How these tactile and proprioception perceptions interact and comprise the somatosensory stimuli through haptic modality to provide haptic feedback on virtual environment for autistic people?

2.10.1.2 Stage 2: Selection of Review Source

The following renowned review sources were used to carry out searches on all the empirical evidence interrelated to review questions: (1) IEEE Xplore; (2) ACM Digital Library; (3) Google Scholar; (4) Science Direct; (5) Springer Link; (6) EBSCO; (7) SAGE. In addition, individual databases and journals that related to autism aspects such as; autism, journal of autism and developmental disorders, behavioural sciences, molecular autism, and American journal of occupational therapy were equally included.

2.10.1.3 Stage 3: Process of resource concentration

The selected articles from the renowned search engine were concentrated upon, based on different review stages as shown in Table 2.1. The articles were selected based on these three criteria: Articles written in English, Mere peer-reviewed articles, and the publication periods from January 2008 to January 2022 (refer to Figure 2.8). The resource concentration stages are described as follows:

(1) First Stage: The following search criteria keywords were used to search all the primary articles that were interrelated to haptic modality, somatosensory and autism. To retrieve the article source, the researcher applied Boolean expressions "AND" and "OR" between the keywords. The pattern of search expression was used, based on these substring keywords, such as (autism OR ASD OR autistic people OR autism spectrum disorder OR atypical development OR pervasive developmental disorder OR Asperger syndrome OR PPD-NOS) AND (somatosensory OR sensory stimuli OR sensory processing OR sensation OR sensory modalities OR hands sensibility) AND (haptic OR kinesthetic OR haptic modality OR tactile OR haptic perception OR proprioceptive OR touch OR haptic object recognition OR tactual). All this substring criteria searched was based on the articles' Title or Abstract in the prominent search engine, as the first stages of the results are shown as "First Stage" column of Table 2.1.

(2) Second Stage: Based on the citation counts from the "First Stage", the representation of articles on each site were selected, and this was shown in "Second Stage" column of Table 2.1.

(3) Third Stage: This stage acts to find intersection articles as obtained from two different sources of site. The intersected articles were included as final selected articles to conduct the research review, and this is shown as in "Third Stage" column of Table 2.1.

Table 2.1: Selection of articles according to the selection procedure by each stage

Resource	*First Stage*	*Second Stage*	*Third Stage (Final Selection)*	*Keyword*	*Adjustment*	*Organizing*
IEEE Xplore	43	15	2	#	Abstract	Citation Count
Google Scholar	1380	28	0	#	All	Relevance
Science Direct	55	18	3	#	All	Relevance
Springer Link	34	3	0	#	All	Relevance
EBSCO	47	11	0	#	All	Relevance
SAGE	28	3	0	#	Abstract	Relevance
Individual Databases:				#		
Autism	31	6	1	#	All	Relevance
Journal of Autism and Development Disorders	24	8	2	#	All	Relevance
American Journal of Occupational Therapy	5	2	1	#	All	Relevance
Behavioral Sciences	3	1	1	#	All	Relevance
Molecular Autism	7	3	1	#	All	Relevance
Total:			11			

#Keyword: (autism OR ASD OR autistic people OR autism spectrum disorder OR atypical development OR pervasive developmental disorder OR Asperger syndrome OR PPD-NOS) AND (somatosensory OR sensory stimuli OR sensory processing OR sensation OR sensory modalities OR hands sensibility) AND (haptic OR kinaesthetic OR haptic modality OR tactile OR haptic perception OR proprioceptive OR touch OR haptic object recognition OR tactual)

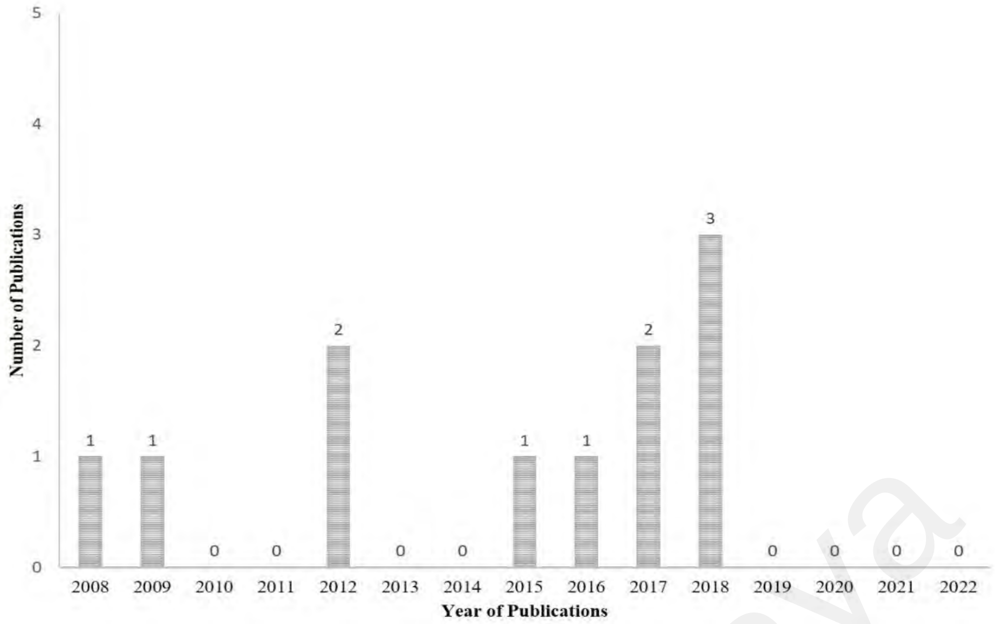


Figure 2.8: Publication Trend of Studies Included

2.10.1.4 Stage 4: Information extraction planning

The data extraction process began by identifying important information from the selected papers, according to a set of guidelines. The following data attributes were extracted from the selected articles as part of the data extraction process to recede as studies information: (1) Title; (2) Information about the author; (3) Publication year; (4) Participant characteristics; (5) Modalities used; (6) Description of treatment based on intervention and treatment intensity; (7) Description of results. During this process, there were few inclusion criteria that were being focused on to determine the inclusion of the articles should in this review section:

(1) The article must focus on haptic interface and haptic based somatosensory modality.

(2) The article must have involved at least one participant with a diagnosed of autism or atypical development or Asperger syndrome.

(3) In order to measure the effectiveness of haptic based somatosensory modality among autistic people participants, the article must have measured at least one dependent variable.

In addition, the following two exclusion criteria were recognized during the article's extraction planning process:

(1) The study that is strictly focused on architecture and design, model or framework of haptic interface or system.

(2) The study that is strictly focused on analysis and presented based on analysis of interviews or observation instead of quantitative analysis of haptic modality.

2.10.1.5 Stage 5: Extracting information

The selected articles must be wisely recited and be studied, based on the articles' contents and extracted the appropriate information to conduct analysis of the results.

2.10.1.6 Stage 6: Conduct analyzing

After following the above stages, the collected articles will be analyzed according to the research questions and these were analyzed and reported more details in the next section.

2.10.2 Results

Through the electronic database search process, a total of eleven studies were shortlisted, based on the effectiveness of haptic somatosensory modality among autistic people. In order to make certain credibility of the results, all the selected studies were classified into two different categories of studies; five of the studies were based on the clinical implication (non-performance based experimental studies) as shown in Table 2.2 and 6 of the studies were based on the haptic interface implication in virtual reality (quasiexperimental or experimental studies) as shown in Table 2.3. Four of the studies were excluded, due to the required information that could not meet the selected criteria. The included studies were extracted and categorized into two different aspects namely; haptic modality n = 1 and discretized haptic modality; tactile perception n = 7, proprioception perception n = 3. All the eleven studies used cross-sectional analyses to define the respective results, with total number of 442 autism spectrum disorder participants from the combination of studies. Out of this 442, 9 participants with haptic modality with (age range = 4-63 years), 406 participants for tactile perception (age range = 4-23 years), meanwhile, 259 participants for proprioception perception with (age range = 4-55 years). All the participants met the selection criteria of autism spectrum disorder. Based on the following research questions, which was presented in stage 1, the results of systematic review were analyzed:

2.10.2.1 Research Question 1: How does somatosensory impairment in autistic people thru providing any clinical evidence?

The results pooled and compared between the treatment and control group to identify the impairment of somatosensory in autistic people. To measure the performance of tactile perception used the standardized Sensory Processing Measure (SPM) test based on the parent-reported somatosensory processing in autistic people, meanwhile to measure the tactile sensitivity based on the performance level, the Tactile Detection Threshold used. The study reported that in the children of ASD ages between 5 to 12 years, there has medium effect size by increase of 71% in tactile sensitivity from the sub-scale of T-Score compared to Raw Score in a parent-reported based on the SPM test (95% CI: 0.16–0.93, SMD = 0.547). In contrast, standardized mean difference (SMD) in Tactile Detection Threshold reported large effect size by decreased as 88% in tactile sensitivity based on the performance level (95% CI: -1.89–-0.48, SMD =-1.183) and this due to the present of fixed tactile detection threshold and lacking of sensitivity effect enthusiastically increasing the adapting stimulus (Wodka et al., 2016).

The Short Sensory Profile (SSP) test based on parent-report used to investigating on the sensory ability among ASD based on the caregiver questionnaire, and this reported that small effect size by 58% decreased in tactile perception with the average standardized mean difference (95% CI: -0.59–0.16, SMD =-0.216) and this represents a typical performance occurred on tactile perception among autistic people (Tavassoli et al., 2012). On the contrary, an additional new study was reported that medium effect size by 76% increase in tactile perception during the comparison between Achenbach System of Empirically Based Assessment Teacher Report Form (ASEBA: TRF) and Conners' Teacher Rating Scale–Revised: Long Version (CTRS–R: L) for the two types of constructs; inattention and cognitive problem (95% CI: 0.18–1.26, SMD =0.717) (Ashburner et al., 2008).

Simultaneously behavioral test used the Semmes Weinstein Von Frey Aesthesiometer with the force method indicated there has small effect size by 66% increase in tactile perception as an average range of standardized mean difference (95% CI: -0.40–0.86, SMD =0.408), and this illustrates that, the higher the tactile sensitivity indicate the higher in haptic/touch ability in autistic people (Tavassoli et al., 2012). While the other two studies demonstrated there has optimistic impact of tactile sensitivity to the autistic people compared to the control group at three different levels of effect size by increased as 59%, 89% for tactile sensitivity/sensory sensitivity (95% CI: -0.30–0.75, SMD =0.223; 95% CI: 0.54–1.97, SMD =1.251) and 94% for sensation avoidance (95% CI: 0.81–2.30, SMD =1.555) (Ashburner et al., 2008; Crane et al., 2009).

However, although recognized higher quadrant scores for these particular two factors; tactile sensitivity/sensory sensitivity and sensation avoidance in autistic people, the

Adult/Adolescent Sensory Profile (AASP) test established there were impaired sensation seeking with lower guardant scores in adults with ASD by decreased at 89% (95% CI: -1.93–-0.50, SMD =-1.221) and this was supported by the study (Suzuki et al., 2018) in the tactile perception with reported insignificant effect size by decreased as 55% (95% CI:-0.28–0.01, SMD =-0.135) for young children age group (11-18 years) compared to for old children age group (4-10 years). To view this relation more bottomless, data through the Short Sensory Profile (SSP) with the mental health of primary caregivers in children with ASD has been collected in two other stages; sensory under responsive and movement sensitivity (proprioception perception) along with the age groups (Ashburner et al., 2008; Suzuki et al., 2018). Although, there is remained significant in tactile perception for the old children age group, but for movement sensitivity and sensory under responsive reported impairment sensitivity for both age groups with their respective values as movement sensitivity reported insignificant effect size by decreased as 53% (95% CI: -0.23–0.07, SMD =-0.079) and sensory under responsive reported insignificant effect size by decreased as 50% (95% CI: -0.17–0.13, SMD =-0.019) and small effect size by decreased as 60% (95% CI: -0.79–0.27, SMD =-0.259). Therefore, the authors concluded that, due to sensory difficulties in ASD can give impact on the attention and cognitive skills during their interaction with objects or environment (Ashburner et al., 2008; Suzuki et al., 2018).

2.10.2.2 Research Question 2: How these tactile and proprioception perceptions interact together and comprise the somatosensory stimuli via haptic modality to provide haptic feedback in virtual environment for autistic people?

Sensitivity of haptic modality among autistic people was also measured with various types of sensory outcome measures and this was compared between Haptic based VR treatment group and control group. The 'Grading of Force (GoF) test used by Elisabeth

Söchtinga (Söchting et al., 2015) to measure the accuracy of the force/haptic feedback of the participants demonstrated insignificant effect size decreased by 56% (95% CI: -1.20–0.07, SMD =-0.154) in haptic perception, while from the same study, taking a sub sequence test of 'Grading of Movement (GoM) to measure proprioceptive sensor feedback, among typically developing children which is focused on the user's arm movement without taking control of visual had shown large effective size with decreased by 82% (95% CI: -2.13–0.26, SMD =-0.936) in second test compared to the first test.

The authors also concluded that, this measurement would discriminate between children with ASD and typical developing children, in terms of proprioception perception (Garzotto & Gelsomini, 2018). This creates the perception or awareness of the position and movement of the children with ASD and typical developing children. In addition, the authors believed that, this had given importance of proprioception perception in understanding social, communicative, and motor impairments (Garzotto & Gelsomini, 2018). Reported significant improvements in haptic modality and proprioception perception; comparison between pre-test and post-test, using MAT Boards as haptic interface which was integrated with smart objects to measure the haptic feedback had shown small effect size by increased as 51% (95% CI: -0.60–0.67) with SMD=0.036 for the task 'Stimuli-interaction-stimuli' (Garzotto & Gelsomini, 2018).

Compared with the both sensory therapies of Keyboard Piano (physical device) and Bendable Sound (haptic interface), the authors found that, the autism participants paid 73% (95% CI: 0.03–1.19, SMD = 0.613) of their attention to the haptics therapy, by using Bendable Sound when it was compared to the Keyboard Piano, and moreover, the study also showed that there has large effect size on sensory therapy by increased as 64% (95% CI: -0.22–0.92, SMD = 0.353) where the spending time on Bendable Sound higher than Keyboard Piano (Cibrian et al., 2017). Based on the outcome measures by this study, the authors also interpreted that, the use of haptic modality and discretized modality such as tactile perception provides a better sense of touch for autistic people compared to the control group (Cibrian et al., 2017).

The effectiveness of haptic modality could differ with the type of interaction in a virtual environment, and this reported by authors Zapata-Fonseca et al. (2018) as compared to the interaction between a set of haptic groups of ObjectType (Fixed, Lure, and Avatar) with the number of clicks (haptic feedback) and total movements as to measure the tactile and proprioception perception. For haptic interaction effects by the number of clicks as haptic feedback, the study found large sized decreased as 93% (95% CI: -2.46–-0.48, SMD = -1.468) from the people with high-functioning autism (HFA), compared to control group. Similarly, from the same study, for the effect of haptic ObjectType with total movements, showed a large sized decrease as 60% (95% CI: -0.48–-0.03, SMD = -0.252) from Fixed to Lure + Avatar (haptic movement) compared to Lure to Avatar (reactivity) at three different test session, and these determined that, people with HFA presented various somatosensory patterns with minimum haptic movements during the interaction in virtual environment as well as control group. Reported outcome measure for ASD participants' proprioception perception was tested via Rubber hand illusion (RHI) of haptic interface in a virtual reality (Paton et al., 2012). In the context of proprioception perception, the author discovered that, autistic people had more accurate proprioception when it was compared to control group, and believed this would bring more movement sensitivity to their virtual interaction even thought that had reported large sized decreased with 70% of effects (95% CI: -1.24–0.13, SMD = -0.553) (Cecil et al., 2017). Three learning cycles tests on the effect of haptic modality of spatial density of virtual objects reported (Cecil et al., 2017). The outcome measures were divided into two different learning, focused on an interaction of virtual environment which indicated greater improvement with large sized increase as 100% for the both level test cases; basic density (95% CI: 1.73–6.70, SMD = 4.213) and advanced density (95% CI: 1.73–6.70, SMD = 4.213) in autistic people.

In general, the result of the articles revealed that, haptic feedback showed significant improvement in terms of haptic ability and somatosensory of autistic people in interaction with virtual environments (Cecil et al., 2017; Cibrian et al., 2017; Garzotto & Gelsomini, 2018; Paton et al., 2012; Söchting et al., 2015; Zapata-Fonseca et al., 2018). Although, there were some articles that indicated an existence of impairment in the somatosensory for the autistic people (Ashburner et al., 2008; Crane et al., 2009; Suzuki et al., 2018; Tavassoli et al., 2012).

Table 2.2: Description of included studies of investigating tactile sensitivity impairments in ASD

Reference	*Haptic modality*	*Sensory Measure(s)*	*Characteristic and Sample*	*Diagnosis Assessment*	*Description of results*
Ashburner et al. (Ashburner et al., 2008)	Tactile perception	Short Sensory Profile (SSP)	N =28 Aged range = 6–10 years Male = 10 Female = 4	HFA GARS+GADS	**Statistically non-significant** High levels of tactile sensitivity, sensory under responsiveness, and total SSP score
Kanae Suzuki et al. (Suzuki et al., 2018)	Tactile perception; Proprioception perception	Short Sensory Profile (SSP) Social Responsiveness Scale-2 (SRS2)	N = 159 Aged range = 4-18 years Male = 116 Female = 43	Caregiver mother and ASD	**Young children age:** Statistically remained significant in tactile perception and non-significant in proprioception perception (movement sensitivity). **Older children age:** Statistically non-significant in tactile perception and proprioception perception (movement sensitivity).
Teresa Tavassoli et al. (Tavassoli, Auyeung, Murphy, Baron-Cohen, & Chakrabarti, 2012)	Tactile perception	Short Sensory Profile (SSP) and a behavioural touch	SSP tactile (N =87 Mean age = 9.00 years ± 3.22 years Male =44 Female = 43) Behavioral Touch measure (N =39 Mean age = 11.51 years ± 0.87 years Male = 21 Female = 18)	ASD	**Statistically non-significant** Average levels of tactile sensitivity and behavioral tactile sensitivity, and parent-report total SSP score
Wodka et al. (Ericka L. Wodka et al., 2016)	Tactile perception	Sensory Processing Measure (SPM) Tactile Sensitivity Measurement (TSM)	N = 57 Age range = 7–14 years Male = 48 Female = 9	ASD	**Statistically non-significant** No correlation between parent-reports of tactile processing and psychophysical assessments.
Crane et al.(Crane et al., 2009)	Tactile Perception	Adult/Adolescent Sensory Profile (AASP)	N = 18 Mean age = 41.8 Male = 10 Female = 8	ASD	**Statistically non-significant** High levels of tactile sensitivity, sensory avoidance, but lower level in sensation seeking

Table 2.3: Description of included studies of investigating haptic modality effectiveness through VR

Reference	*Haptic modality*	*Sensory Measure(s)*	*Characteristic and Sample*	*Diagnosis Assessment*	*Type of Haptic Interface*	*Description of results*
Elisabeth Söchtinga et al. (Söchting et al., 2015)	Proprioception perception	Grading of Force test (GoF), Grading of Movement test (GoM)	N =7 / 6 Age range = 7-11years	ASD	GoF and GoM	**Statically significant** GoF: Improvement in participant grades force. GoM: Improvement in participant grades an arm movement without visual control.
Franca Garzotto & Mirko Gelsomini.(Garzotto & Gelsomini, 2018)	Proprioception perception	Stimuli-interaction-stimuli	N =19 Age range = 8-13 years Male =14 Female = 5	ASD – NDD	MAT - Boards integrated with smart objects pressure sensors	**Statistically significant** Indicate improvements in navigation in the VR (Magic Room) than during regular activities.
Franceli L. Cibrian.(Cibrian et al., 2017)	Tactile perception	Wilcoxon Signed Rank-test	N =24 Mean age = 6.6 or range = 3-11 years Male = No data Female = No data	ASD	BendableSound Haptic Sensor	**Statistically significant** The combination of tactile and proprioception perception as haptic modality increases children's curiosity and improve their overall experience during in VR.
Zapata-Fonseca, Froese et al.(Zapata-Fonseca et al., 2018)	Tactile perception	Object Type and Case of Clicks, and Ratio of Clicks to Encounters	N =10 Mean age = 42.32 Male = 5 Female = 5	HFA ASD	Tactos devices and Braille-stimulator	**Statistically significant** Performed equally during the interaction in virtual environment as well as control group.
Paton, Hohwy et al. (Paton et al., 2012)	Tactile perception Proprioception perception	Rubber hand illusion task	N =17 Mean age = 32.06 Male = 14 Female = 3	ASD	Rubber hand illusion (RHI) -Synchrony, Machine Touch Stimulator and Goggles	**Statistically significant** Have more accurate proprioception when compared to control group.
Cecil, Sweet-Darter et al.(Cecil et al., 2017)	Haptic Modality	Density measure	N =9 Age range = 8 – 12 years Male = No data Female = No data	ASD	No data provided	**Statistically significant** Both basic density and advance density showed improvement during interaction in VR.

2.10.3 Discussion

The purpose of this systematic review was to describe the impairment of somatosensory among autistic people spectrum disorder, and also to study the effectiveness use of haptic interface as modality to sense and experience with the object(s). The development of somatosensory of haptic modalities in autism seems to be mature. But according to the present study, it was difficult to describe the effectiveness since the use of haptic interface as haptic feedback was diverse and still depending on the measure of the outcome that was employed and the haptic somatosensory aspect was measured. Most of the articles on haptic modality showed a good prescription, where there was a correlation between autism users and haptic modality in terms of sensation while using the haptic interface in a virtual environment. These outcomes provision the current evidence of developments in haptic modality among autistic people spectrum disorder.

2.10.3.1 Somatosensory Impairments in ASD

The importance of touch was given to the autistic people in their early stage of development, and this importance of touch was established in the relationship between the social interactions with physical objects in their surroundings. In addition, the impairment of tactile perception was expected, based on social interaction, restricted and repetitive behavior of autistic people. However, some of studies examined somatosensory impairment and results indicated inconsistent in terms of tactile perception. This was evident in a study that used AASP (Ashburner et al., 2008; Crane et al., 2009) as a measure of tactile perception, where some of the ASD participant claimed that, under-responsiveness was dependent of poor social interaction. Meanwhile, seeking sensation was evident by repetitive behavior and increasing age of the autistic people (Crane et al., 2009; Tavassoli et al., 2012). While other studies also supported that, there was a relationship between tactile sensitivity and a behavioral touch in ASD (Suzuki et al., 2018; Tavassoli et al., 2012). In the context of physiological metrics, there was lack of disclosure with respect to the tactile perception in terms of detection and discrimination between the social interactions in autistic people. But, with altered detection threshold, it was possible to contribute in terms of haptic modality to people with symptom of somatosensory in ASD (Tavassoli et al., 2012; Zapata-Fonseca et al., 2018).

In the recent study, it was reported that, behavioral regulation was indirectly influenced by the tactile sensation. This was proven, based on the correlation of tactile impairment in performance-based tasks impact on the attention but did not show any correlation with parent-reports (Wodka et al., 2016). However, these findings do not imply that, perceptual differences about tactile do not contribute to autism. On the other hand, the studies have to do with more interventions in terms of tactile measurement in social interaction, behaviors coupled with an interest and activities components of autistic people, while help to reduce the tactile impairments among autistic people.

2.10.3.2 Effectiveness of Haptic Interface through VR as Sensation in ASD

Somatosensory feedback could be detected from the user, if they handled a physical object and this would give a haptic sensation. But this is different for autistic people in which these groups are exposed to sensational disturbances. Therefore, with the interaction of a stimulation object in virtual environment, through the haptic interface, it could change and recognize the sensation among autistic people. In addition, it could bring a sense of control over their interactions by giving haptic sensory modality (Cibrian et al., 2017). Studies also support the existence of this interaction control, by facilitating sensory processing and provide haptic feedback to the autistic people (Longo & Haggard, 2009; J. W. Moore & Fletcher, 2012).

A significant improvement in proprioception perception was discovered in autistic people, during the movement and body position in virtual reality (Riederer et al., 2014; Söchting et al., 2015). Haptic interfaces such as MAT - Boards are used to measure force feedback, through the movement of participants in virtual reality. This allows autistic people to engage in social interaction and possibly, allow them to show interest and get involved in activities (Garzotto & Gelsomini, 2018). In fact, it also allows them to learn and control the amount of force production, while in the real environment. An example is to hold something like writing material e.g. a pencil by using the same force, and thereby create body awareness among ASD and also, adapt itself while in different environment. It was discovered that the movement in the virtual environment, with the avoidance of obstacles through adjusting and treating the body, could increase motor skills for autistic people (Cecil et al., 2017; Garzotto & Gelsomini, 2018; Paton et al., 2012). Also, this proprioception ability would discriminate between children with ASD and typical developing children (Cecil et al., 2017; Garzotto & Gelsomini, 2018). The discrimination comes in terms of proprioception perception which creates the awareness of the position and movement of the children with ASD and typical developing children. In addition, the authors believed that, the importance of proprioception perception in understanding social, communicative and motor impairments should be given (Cecil et al., 2017; Cibrian et al., 2017; Söchting et al., 2015).

In fact, exposure in tactile perceptions also brings various influences from numerous perspectives to autistic people. This had also been measured and defined through a range of haptic interfaces in virtual reality. The ability to understand somatosensory in autistic people via tactile perception reported significant improvement. The recent studies had shown that, these tactile sensitivity impairments were related to abnormality of the stochastic sensorimotor patterns in autistic people (Zapata-Fonseca et al., 2018). In another study, it was reported that, soft touch sensations and sensory input of the skin and hand, is responsible for social awareness and identification of texture and temperature. The texture and temperature were measured and reported that, they had presented with tactile perception during the interaction of ASD with virtual object through haptic interface (Paton et al., 2012). The combination of tactile and proprioception perception as haptic modality had significantly improved the overall experience during the interaction in virtual reality among the autistic people. This was noted during the participants spent more than 2 minutes, while interacting with Bendable Sound haptic interface (Cibrian et al., 2017). This means that, the combination of tactile perception and proprioception perception as haptic modality in virtual reality, had given a good impression by improving their interactions and the study also showed the possibility of using haptic modality as somatosensory was better accepted by autism (Sitdhisanguan et al., 2012). The presence of the haptic interface on autistic people had developed their perception skills, through interaction with virtual reality. Thus, with this modality, they were increasingly searching for various paths, by exploring various haptic feedbacks as somatosensory. This means, by using haptic modality as haptic feedback, it could create more exploration and engagement among autistic people, during interactions in virtual environments.

2.11 Discussion

According to the research presented in this chapter, autism spectrum disorder is a neurodevelopmental condition that manifests itself in a variety of ways, including difficulties in social interaction or communication, restricted interests and activities, and uneven cognitive capacities (Charman, 2011). Autistic people exhibit a wide range of signs and symptoms, which can be diagnosed using a variety of methods such as standard ASD evaluations, observation of their behaviors, and professional knowledge (Manning-Courtney et al., 2013). As highlighted especially for children, there are only a few symptoms that can be recognised at their earlier stage, but both groups of people, whether children or adults, face different levels of symptoms (Rowland & Schweigert, 2009). Anyhow, the Autism Diagnostic Interview-Revised Questionnaire will be utilised in this study in order to diagnose autistic people and gain a better understanding of their symptoms. Furthermore, according to Greenspan and Wieder (1997), autistic people have difficulties with spatial awareness and cognitive mapping skills. For example, autistic people have trouble discriminating between left and right and are often confused about their position in relation to an object. They also have trouble visualising the particulars of an object, such as its size, colour, and shape, and have a limited capacity to acquire, store, and apply spatial knowledge (Alvino, 2008; Coulter, 2009). Therefore, these aspects should also be investigated within the context of this study. When it comes to having spatial knowledge, it is not enough to simply understand one's current position in relation to an object; rather, one must also comprehend the relationship that exists between the different objects (Ahmadpoor & Shahab, 2019; Waller et al., 1998). It indicates that the capacity to maintain spatial knowledge is not something that the majority of autistic people are born with, but rather something that can be learned and improved upon day by day with a specific approach (Edgin & Pennington, 2005; S. E. Lind et al., 2014; Melanie Ring et al., 2018). Cognitive mapping is one of the approaches that is typically highlighted by researchers (Johns, 2003; Vaez et al., 2016). This method allows individuals to process the information that they have gained from their spatial environment and recall that information when it is necessary to support their day-to-day activities, such as navigation. Therefore, the purpose of this study was to concentrate on autistic people who particularly struggle with the problems of high-functioning autistic individuals who still require support: poor non-verbal communication, nonverbal learning disorders that struggle with spatial awareness, abnormal sensitivity, poor spatial awareness that has difficulty differentiating between directions and prepositions and accurately defining distance, and poor cognitive mapping skills. Instead of practising or learning in a real environment, autistic people should use a suitable platform to transfer the knowledge in order to gain the spatial knowledge and cognitive mapping skills that are required (Dong et al., 2017; Waller et al., 1998; Witmer et al., 1996). This is due to the fact that most parents and carers of autistic people are concerned about their children's safety when it comes to engaging with real objects, particularly in urban environments (D. Li et al., 2019). Because of this, the chapter brought attention to the fact that a virtual environment can be acknowledged as an educational or training platform for the development of specialised skills such as spatial knowledge and cognitive mapping. Researchers have an argument that autistic people are capable of visualising and controlling a virtual environment, which might not be possible in the real world (Halarnkar et al., 2012; C. Kurniawan et al., 2019; Manju et al., 2017; Robles-De-La-Torre, 2006; Stansfield et al., 1995). In addition, this chapter discussed the various types of virtual reality systems that are currently on the market, each of which has the potential to be incorporated into the development of an HBVE application for the purpose of resolving the problems associated with their respective domains. The majority of researchers concentrated their attention on the level of performance, the costs involved in implementation, and how well it could support their objective and meet their requirements, particularly for autistic people (Hamza-Lup et al., 2019; Kirkpatrick & Douglas, 2002; D. Li et al., 2019; K. Salisbury et al., 2004c; Sherman & Craig, 2018; A. Song et al., 2008; Strickland, 1996; Tang, P. McMahan, et al., 2014). Therefore, this study came to the conclusion that the safest option for autistic people would be to use a non-immersive virtual reality system. Additionally, the researchers decided to use an urban environment as a scenario environment in order to facilitate the transfer of spatial knowledge and cognitive mapping to autistic people (Amon et al., 2018; Norgate & Ormerod, 2012; Urmson et al., 2008; Vaez et al., 2016; Zomer et al., 2019). Furthermore, the authors emphasised the fact that the use of haptic technology can act as a form of therapy by enhancing autistic people's capacity to recover from impairment (Cibrian et al., 2017; Fazlioğlu & Baran, 2008). The use of haptic devices allows autistic people to feel and process the sensation during movement or interaction with virtual objects (Bouyer et al., 2017; Minogue & Jones, 2006). These haptic devices provide touch-related properties such as haptic feedback (Sagardia et al., 2015). There are plenty of haptic devices available, such as the Phantom Desktop and Myo Armband (K. Salisbury et al., 2004b). However, due to the same reason of lower costs as virtual reality systems and the fact that certain haptic interfaces have fewer actuators than sensors, this study decided to use the MYO armband interface in order to achieve the development and evaluation objectives (Sathiyanarayanan & Rajan, 2016). This chapter also includes an investigation and analysis of the profound knowledge regarding the haptic modalities as somatosensation feedback and the two subcomponents (tactile feedback and kinaesthetic feedback) (Minogue & Jones, 2006). This comprehensive review enables or provides a framework for this study to focus on one of the objectives: evaluating the effectiveness of haptic modality among autistic people in terms of sensation during interaction and manipulation tasks in a virtual environment. The goal of this study is to see if autistic people benefit from the use of haptic modality.

2.12 Summary

This chapter highlights the major domain of this research by identifying who the autistic people are, what spatial learning is, and how haptic technology can be used in conjunction with virtual environments to assist them in developing and improving their spatial learning and cognitive mapping skills. This chapter explains and highlights the importance of haptic rendering methods in real-time, and it recognises which haptic rendering interaction techniques should be used in order to have an effective impact on the user in terms of communication between the haptic interface and the virtual environment. A systematic review was carried out to determine the efficacy of the haptic somatosensory modality towards autistic people. It also discussed how the virtual environment could be used as an intermediary between autistic people and haptic interfaces in order to develop haptic feedback as a sensation. Furthermore, in this chapter, the various types of virtual environment systems are discussed, as well as the virtual environment systems that are most suitable for the development of HBVE applications are identified.

CHAPTER 3: EXPLORING THE REAL-TIME HAPTIC RENDERING TECHNOLOGIES AND INTERACTION COMPONENTS

The purpose of this chapter is to define the components that are involved in designing a haptic-based virtual environment (HBVE) for autistic people who require spatial knowledge and cognitive mapping skills. The following three elements serve as the basis of this chapter's investigation: a study of the existing HBVE-Framework, a study of the interaction components of a haptic-based virtual environment, and a study of the components of spatial cognition mapping.

3.1 Study of Exiting Haptic Based Virtual Reality Framework

This section focused on the existing frameworks that are used to facilitate autistic people. There are several methods that are being utilized to review the existing framework, and these are presented as stages in the following section:

Stage 1: Selection of review source

The following well-known databases were used to identify the precise articles for this review section: (a) IEEE Xplore; (b) ACM Digital Library; (c) Google Scholar; (d)Science Direct; (e) Springer Link; (f) EBSC0; (g) SAGE.

Stage 2: Process of resource concentration

The process of resource selection is based on the publication periods from January 2008 to January 2022 and the following search criteria keywords were used to search all the related articles: autism, haptics, virtual reality, spatial learning, cognitive map and framework. The following Boolean expressions "AND" and "OR" are used in between the search criteria keywords and these are demonstrated based on this search expression pattern: (autism OR ASD OR autistic people OR autism spectrum disorder OR atypical development OR pervasive developmental disorder OR Asperger syndrome OR PPD-NOS) AND (spatial learning OR spatial ability OR spatial visualization OR visio-spatial OR cognitive map OR cognitive skill OR cognitive mapping OR cognition) AND (haptic OR kinaesthetic OR tactile OR haptic perception OR proprioceptive OR touch OR haptic technology OR haptic interface OR haptic interaction) AND (virtual reality OR virtual environment OR virtual simulation OR non-immersive) AND (framework OR model).

Stage 3: Information extraction planning

There are also several criteria that have been assigned to evaluate the appropriateness of the articles for this study, and these are described below:

1) Framework that examines and evaluates the theoretical views that were considered during the framework's development.
2) The Framework has conducted a review of the components that are required for the design of a HBVE-Framework.
3) The non-immersive environment has received increased attention in the Framework.

This study was conducted based on the following objectives:

1) Identify the existing components of the framework that are relevant to autism spectrum disorders, spatial learning, cognitive mapping, virtual reality, and haptic technology.
2) Determine the sub-components that integrate with the main components of the framework in addition to the main components.
3) Recognize the type of framework structure that was used during the development of the framework itself.

3.2 Identify components based on haptic rendering technology and interaction framework in autism

This section focuses on the study and recognizes the components that have been used in ASD in terms of haptic technology. In other words, the study will place a strong emphasis on the haptic technology components that have been shown to have an impact on autistic people, either explicitly or implicitly, in the development of a framework. In accordance with the objectives of this study, all existing frameworks and integrated components have been reviewed and listed in the order in which they were discovered.

3.3 Results

The following are the fourteen main frameworks that have been identified based on article extraction criteria, and following by additional eight remaining frameworks, and individual components from relevance studies from each of which has been documented and explored in detail.

3.3.1 Haptic Rendering Technology Framework

The subsection discussed the framework that exists and is currently used in the context of haptic technology, as well as its rendering approach.

3.3.1.1 A haptic rendering technology framework by Le et al. (2016)

The framework developed by Le et al. (2016) (refer to Figure 3.1) is intended to assist autistic people in their interaction and manipulation of haptic technology in the context of the social environment. The three-tier software architecture serves as the foundation for this framework's design. Specifically, for the sensory sensitivity, the author used three different types of rendering engines: a visual renderer for the visual feedback, a sound renderer for the auditory feedback, and a haptic renderer for the feeling of touch (haptic feedback). Aside from that, this framework includes two physics components, such as collision detection and force feedback computation, that are part of the haptic APIs, which are located beneath the application logic tier and are used for sensor integration and measurements. The framework is designed with sensor integration in order for the haptic devices to communicate with the real-world environment and sensory data. Also included is a real-time database repository that is coupled with the controller component to allow for the development of the core logic of the VR application. Another component of the framework was the inclusion of a synchronization component, which enabled the development tools used to develop the virtual environment application to generate virtual objects and environmental scenes in real time, while autistic people users were able to integrate and communicate with haptic devices in real time.

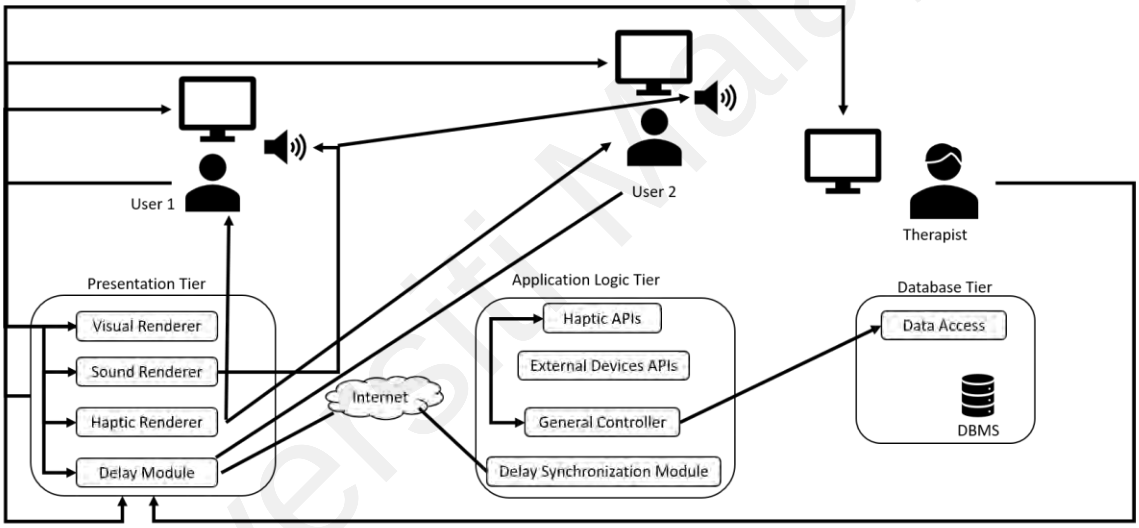


Figure 3.1: Multi-modal haptic framework for autistic people by Le et al. (2016)

3.3.1.2 A haptic rendering technology framework by Orozco and El Saddik (2008)

Using a haptic rendering framework (see Figure 3.2), Orozco and El Saddik (2008) attempted to solve the problem of the combination of multiple haptic devices by adapting automatically to the HBVE application, as well as storing and retrieving real-time haptic data for measurement purposes. This indicates that these authors presented this framework to assist users in interacting with the HBVE application using several haptic devices that are based on distinct APIs. This framework consists of four main components: Application Factory (AF); Software/Hardware Application (SHA); Intelligent Ambient Engine (IAE); and Behavioral Data Repository (BDR). AF is designed to support the development of new HBVE applications, and its core component is comprised of a sub-component that allows users to create new virtual objects or environments rather of relying on any existing inbounded virtual environment. Meanwhile, the SHA component was developed to distinguish between different types of haptic and APIs based on the haptic devices that were utilized. The majority of haptic devices are dependent on a variety of different APIs, which forces users and developers to develop a virtual environment that allows them to support the API that has been adopted appropriately. The functionalities of the haptic device are responsible for the majority of haptic interactions. This means that, throughout the construction of HBVE, users/developers must manually apply haptic attributes to the virtual objects/environment in order for them to function properly with the haptic devices. Therefore, the HBVE that has been constructed is limited by the capabilities of the haptic devices or the API itself. In order to address this issue, the authors introduced the SHA component, which allows multiple haptic APIs to interact with the HBVE application. The IAE component, on the other hand, is intended to assist in the structuring and integration of the haptic device's API into the HBVE implementation by connecting to the haptic devices. A total of five sub-components are included in this IAE main component, including visual scenario/configuration, collision detection, multi-point force feedback, single contact point force feedback, and haptic data content service, which is responsible for processing task transactions for the AF and SHA components. The BDR component was developed to record, store, and retrieve haptic interaction data collected during user interaction with a HBVE.

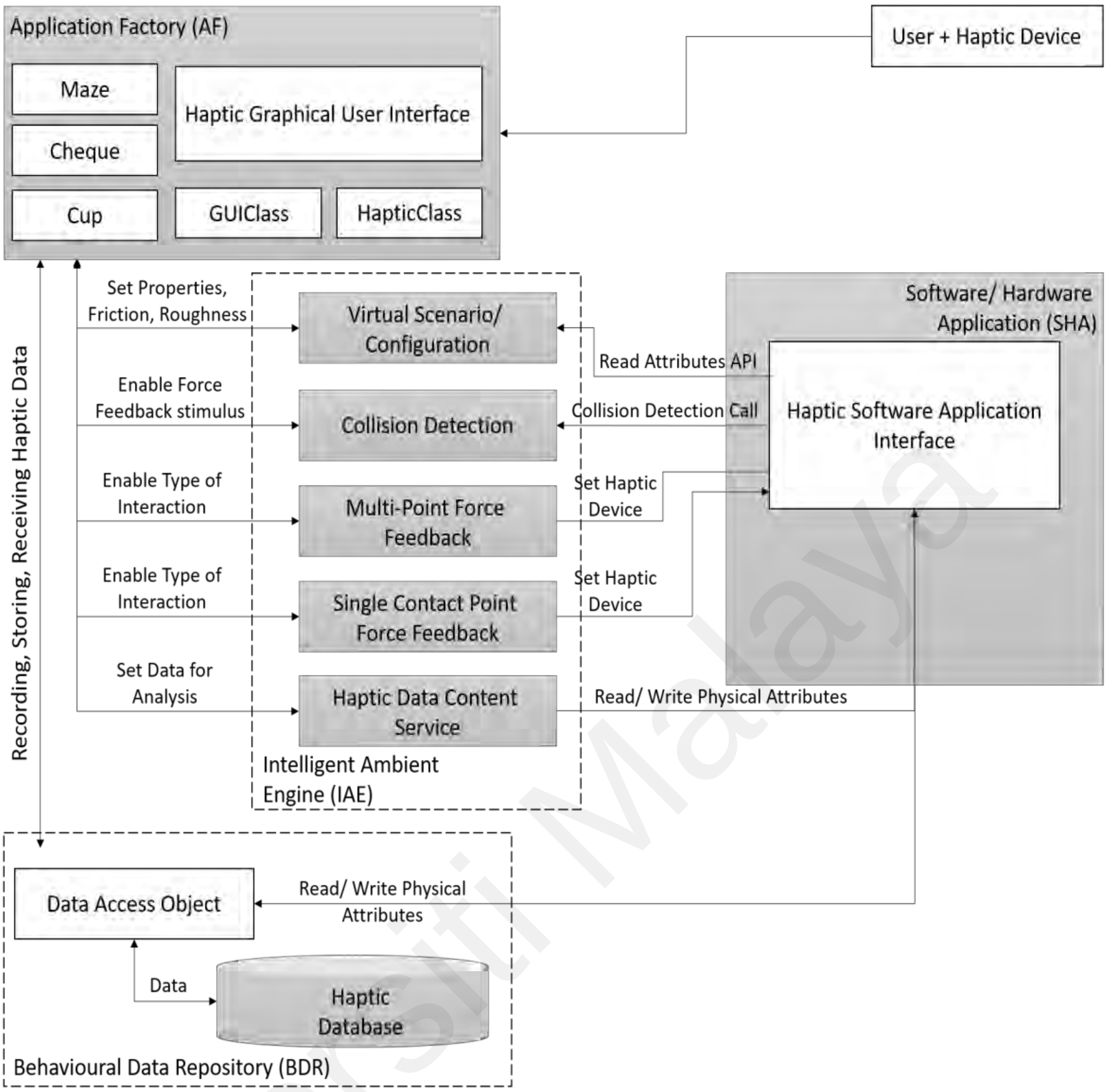


Figure 3.2: Adaptive haptic application framework by Orozco and El Saddik (2008)

3.3.1.3 A haptic rendering technology framework by Eck and Sandor (2013)

Eck and Sandor (2013) has proposed a haptic rendering framework (refer to Figure 3.3) for the design and development of haptic-based virtual objects. This framework is intended to allow for real-time interaction with virtual objects while maintaining a minimal latency during the interaction. Tracing, simulation, visual rendering, and haptic rendering are the four major components of the framework. The simulation component is able to support users by providing the feasibility to load virtual objects or environments through X3D files, and this is assisted by the two sub-components of simulation: world model and simulation engine. The haptic rendering component, on the other hand, is capable of rendering and generating virtual objects from the haptic library, while the sub-components of collision detection, force feedback, and control algorithms assist users in interacting with virtual objects through the use of haptic devices. Using the visual rendering component, it was able to simplify the process of synchronization and real-time haptic data exchange between haptic-based virtual objects and haptic devices for users.

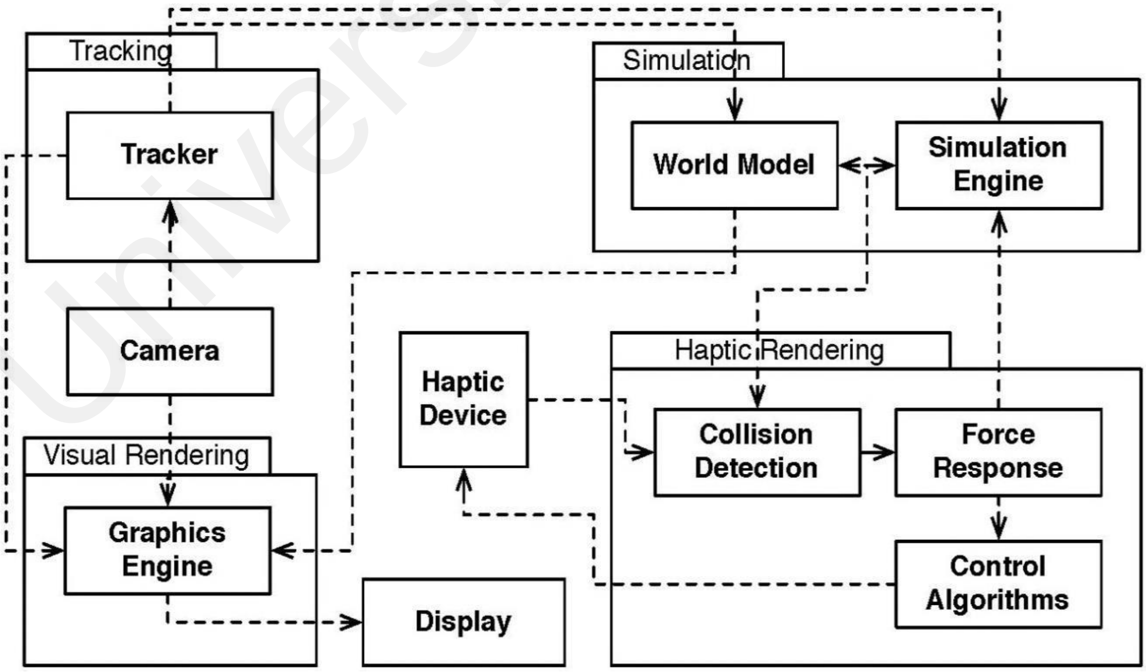


Figure 3.3: Haptic enabled virtual objects framework by Eck and Sandor (2013)

3.3.1.4 A haptic rendering technology framework by Choi et al. (2017)

Choi et al. (2017) developed a framework that focuses on two aspects of haptic feedback: force feedback and visual feedback as interaction components between the user and the virtual environment (as depicted in Figure 3.4). Aside from that, this framework is comprised of ten major components that work together to construct the entire interaction process between the user and the virtual environment, which is accomplished through the use of haptic devices. Decimation and Convex Decomposition (D&CD) and CT-reconstructed models are two sub-components of the three-dimensional (3D) modelling component as the input data for the virtual scenes. Under Virtual Scenes, there are five components (Collision Response: Virtual Coupling, Collision Detection, Fit Assessment, Graphical User Interface, and Scene Rendering) that allow us to support and process virtual scenes/objects in order to determine the position and orientation information as input data from the haptic device, as well as to simulate the force information as output data from the haptic device. A virtual coupling component is utilized to control the virtual objects and to make the haptic rendering process as smooth as possible. The fit assessment component was utilized to construct the accurate fit position and orientation for virtual objects in the virtual scenes, and this was aligned with the graphical user interface component in order to produce better interactive virtual scenes. In order to prevent virtual objects from penetrating one other, the collision detection component is utilized to identify when virtual objects intersect with other objects. In order to provide a real-time haptic effect during the interaction process, virtual objects or scenes are drawn from three different points of view (top, axial, and perspective). This process is referred to as the scene rendering component.

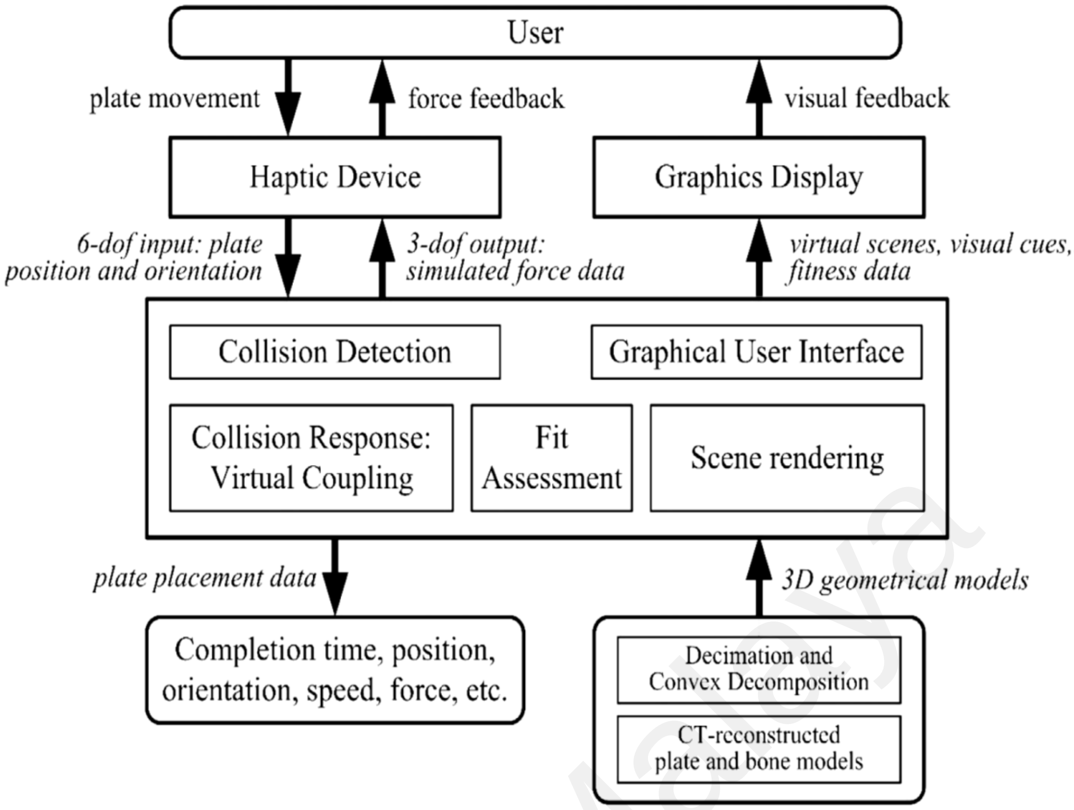


Figure 3.4: Virtual haptic system framework by Choi et al. (2017)

3.3.1.5 A haptic rendering technology framework by Jia et al. (2013)

A new structure framework (see Figure 3.5) was proposed by Jia et al. (2013) as a training platform to assist the interaction between people and the virtual environment through three commonly used modalities: haptics, visuals, and auditory. Through the connection between the haptic modality and the virtual environment, this framework increases the capability of the user in terms of skills development and cognitive learning. These framework components are designed based on haptic hardware, which enables them to provide force feedback to the user during the interaction. Additionally, the CAD data repository component, which is meant to retrieve and store virtual objects for the purpose of positioning them into virtual training systems through the graphics registration component. The collision detection engine component is utilized in order to detect the interaction of a virtual object with other virtual objects within the virtual training system. During the navigation process in the virtual training system, the event logger component is activated to provide audio-visual feedback to assist the user in accomplishing the assigned task and to guide the user through the navigation process.

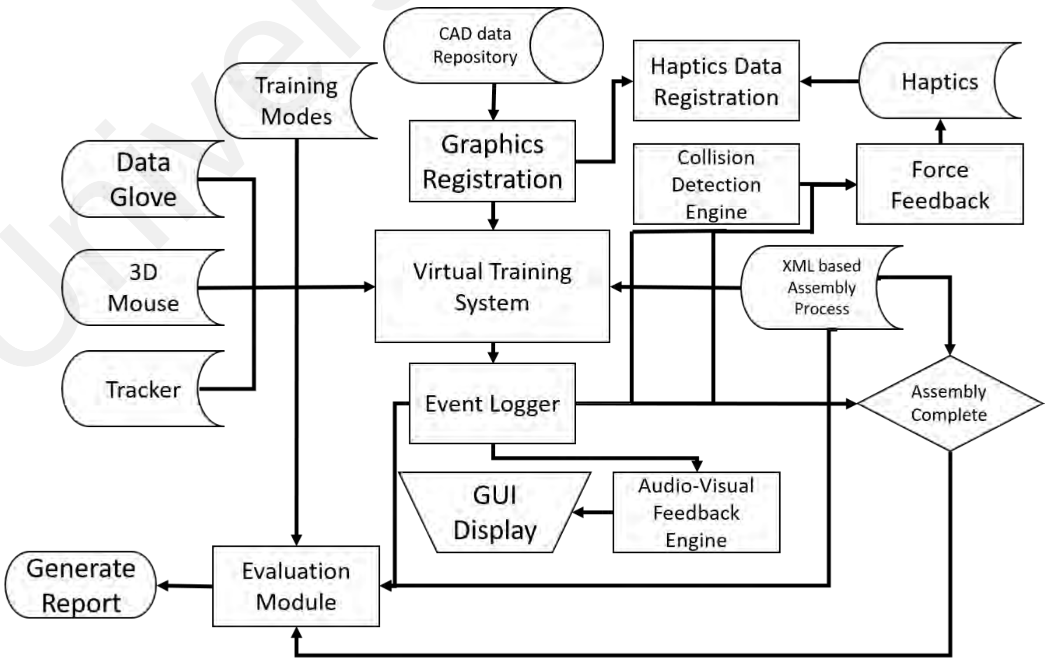


Figure 3.5: Haptic audio and visual framework by Jia et al. (2013)

3.3.1.6 A haptic rendering technology framework by S. Y. Chung and H. Yoon (2011)

The framework has shown in Figure 3.6 designed by S. Y. Chung and H. Yoon (2011) to determine whether autistic people are suffering from emotional disturbances or not. This framework consists of three major components: virtual interactive environment, bio-sensing and virtual environment interface. The virtual interactive environment component is designed to generate a treatment situation to develop the interaction between the avatar and virtual agents. Meanwhile, the bio-sensing (tactile feedback) component measures the emotional status of autistic people through electroencephalogram (EEG), electrocardiogram (ECG), electromyogram (EMG) and skin temperature (SKT) signals. The virtual environment interface component is presented to create an immersive environment and effective interaction between autistic people and the virtual environment. The haptic device was used to control the position of autistic people in a virtual environment and also for the purpose of receiving force/tactile feedback.

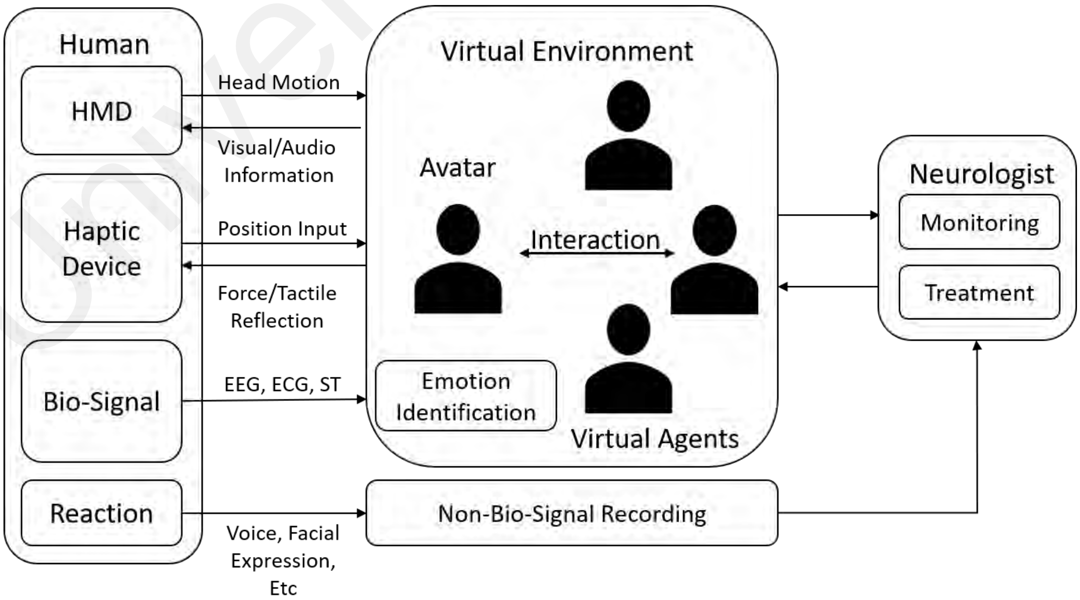


Figure 3.6: Effective haptic technology and autism framework by S. Y. Chung and H. Yoon (2011)

3.3.1.7 A haptic rendering framework by K. Salisbury et al. (2004b)

A unique haptic rendering framework, developed by K. Salisbury et al. (2004b), is comprised of three main blocks (see Figure 3.7): haptic rendering, simulation, and visual rendering. The haptic rendering component's main goal is to integrate the interaction between the haptic interface device and the virtual objects in the virtual environment, as well as to ensure that the haptic interface device renders correctly by providing force or tactile feedback to the user during the interaction. These three types of subcomponents make up the collision detection component, which is responsible for detecting collisions between users and virtual objects in the virtual environment; force response, which is responsible for computing and validating the interaction force between users and virtual objects during a collision; and finally, the control algorithms subcomponent, which is responsible for processing collisions between users and virtual objects in the virtual environment. The component of the simulation engine that is responsible for processing the virtual environment's activities during the interaction that occurs between haptic rendering and visual rendering. Meanwhile, the graphics engine will generate virtual scenes for the user using bitmap image techniques in order to provide visual feedback to the user.

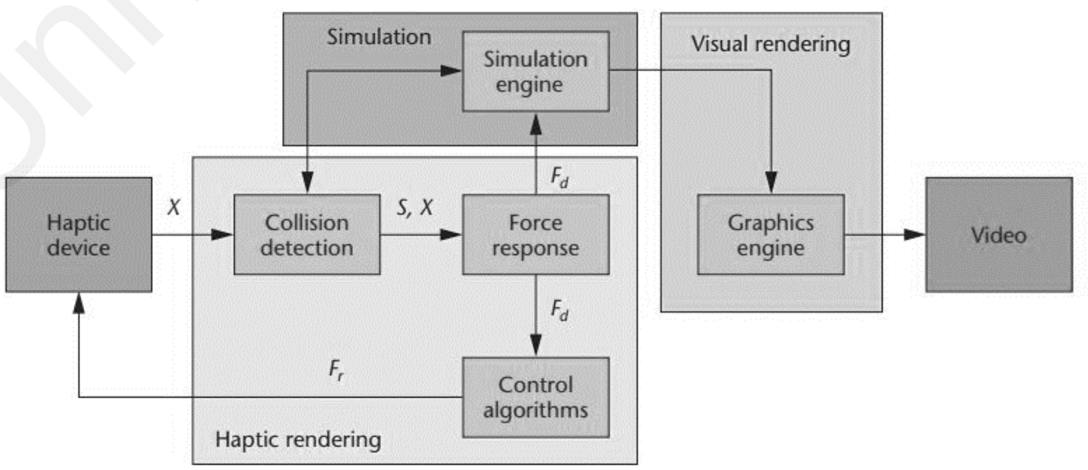


Figure 3.7: Haptic rendering framework by K. Salisbury et al. (2004)

3.3.2 Virtual Reality Framework

The subsection discussed the two most commonly used types of frameworks in the field of virtual reality.

3.3.2.1 A virtual reality framework by Halarnkar et al. (2012)

Figure 3.8 depicts a typical virtual reality (VR) framework that was created by (Halarnkar et al., 2012). This framework is divided into two main components: internal design of VR and external design of VR. In total, there are six sub-components that make up these two main components. The internal design's sub-components can be divided into four categories: virtual world, simulation engine, graphics engine, and user interface. Meanwhile, the sub-components of the external design can be divided into two categories: inputs and outputs. The virtual world sub-component functions as a scene database, allowing us to create a virtual environment from the perspective of the user by combining virtual objects and attributes. Through the rendering process, the simulation engine sub-component allows users to engage with the virtual environment in a variety of ways, such as performing navigation and controlling the objects in their immediate surrounding area. By utilizing the scene database, as well as the user's current orientation information, the graphics engine sub-component allows us to construct virtual objects and attributes. Furthermore, the user interface sub-component serves as an intermediary between the virtual world and the inputs and outputs sub-components, allowing users to interact with and provide feedback on the virtual world.

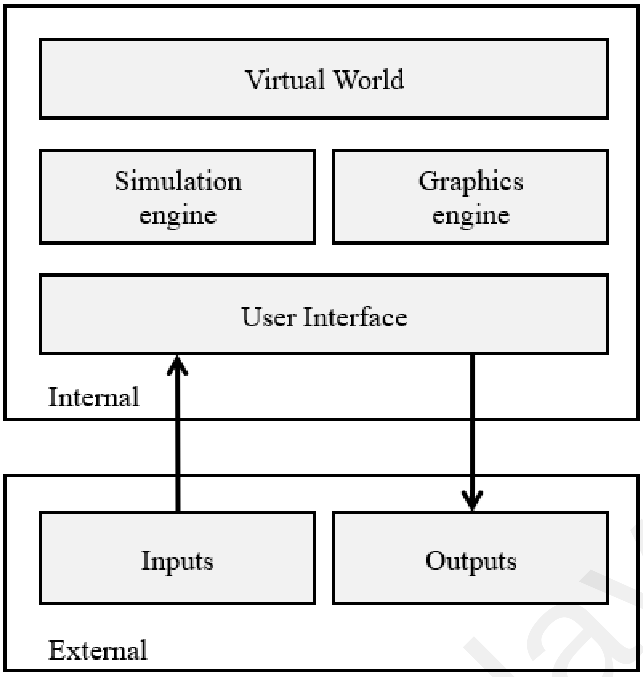


Figure 3.8: Internal and external virtual reality framework by Halarnkar et al. (2012)

3.3.2.2 A virtual reality framework by Romli and Yaakob (2017)

Romli and Yaakob (2017) developed a new theoretical framework for desktop-based VR based learning environments, which is depicted in Figure 3.9. The instructional elements, interaction, navigation, and fidelity components of this framework were chosen as the foundation for its development. In the field of education, the instructional element is defined in terms of the four specifications listed below: learning style, abstract concepts, motivation, and learning tools. Object selection and object manipulation are two sub-components of the interaction component, which was created to allow users to interact with objects or attributes in a virtual environment. Object selection means selecting the object through a controller or wearable device, and object manipulation is defined as the ability of the user to change the position of the selected object from one location to another, rotation, and also the ability to change the behavior of the object. The navigation component is the ability of the user to move within the VR environment, and this navigation component is divided into three sorts of sub-components, which are as follows: the layout of the environment, directional cues, and key location points. The layout of the virtual environment should be built in a reasonable zone so that users can move around in the virtual environment in an effective way. This can help to improve the navigation process while also reducing the likelihood of becoming disoriented or losing track of the course or direction. The sub-component of directional cues, on the other hand, is concerned with the creation or provision of landmarks or indications to aid in navigating inside a virtual environment. A key location point is a sub-component that assists users in terms of movement in the virtual environment by automatically creating several key points in the virtual environment as location nodes. They believed that this component alleviated the majority of navigation concerns. However, this sort of component does not allow users to freely navigate in a virtual environment, unless the suggested virtual environment is intended to serve educational purposes. It is fidelity that allows the user to perceive a realistic environment, and it can be divided into five different sub-components, such as: frame rate, which determines the viewpoint of the virtual environment; point of view, which is defined as the user's perspective based on egocentric and exocentric viewpoints, color or texture, which represents the effects of the natural environment in the virtual environment; sound, which is used to create realistic effects in the virtual environment; and finally, the sub-component of temporal change, which is defined as the eminence of dynamic objects in the virtual environment, such as weather and movement of water waves.

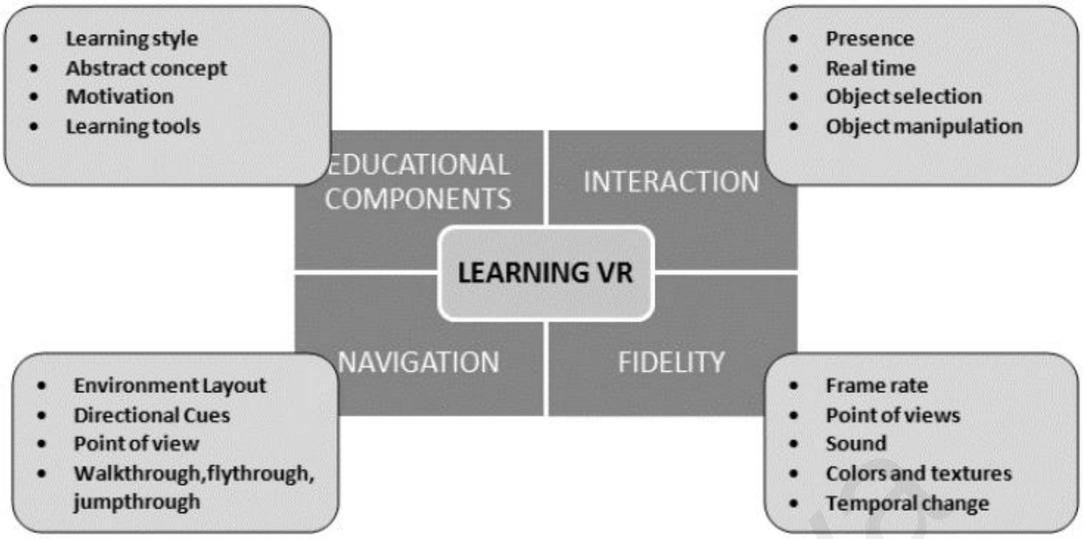


Figure 3.9: Desktop based virtual reality framework by Romli and Yaakob (2017)

3.3.3 Spatial Learning and Cognitive Mapping Abilities Framework

The frameworks that are associated with spatial learning and cognitive mapping abilities are identified and described in further detail in this portion of the section.

3.3.3.1 A spatial learning and cognitive mapping abilities framework by Cho (2017a)

The framework, shown in Figure 3.10, was developed by Cho (2017a) to assess the performance of design studios by analyzing spatial ability and visual cognitive style. This framework is comprised of three major components: spatial ability, visual cognitive style, and creativity, which are all interconnected. This framework's main components are spatial ability and visual cognitive style. There are three sub-components to spatial ability, which are spatial visualization, mental rotation, and spatial perception. Spatial visualization is the most common. It is the ability of an individual to undertake multistep manipulations of an object by visualizing the spatially presented information, as well as the ability to understand the relationship between distinct sets of spatial representations.

Meanwhile, mental rotation allows a person to analyses spatial knowledge based on the rotation of three-dimensional representations. When an individual can determine the spatial relationship between themselves and their surrounding objects and environment based on the orientation of their body, they are said to have spatial perception. The visual cognitive style, on the other hand, is a component that helps an individual to process information related to objects in their immediate context and the surrounding environment. A total of two sub-components makes up this component: the object visualizer and the spatial visualizer. It is possible to conceive and recode the attributes of objects, such as their colors, shapes, and sizes, using the sub-component of the object visualizer. In the meantime, the spatial visualizer's sub-component, which allows an individual to visualize the spatial relationships between objects and the surrounding environment.

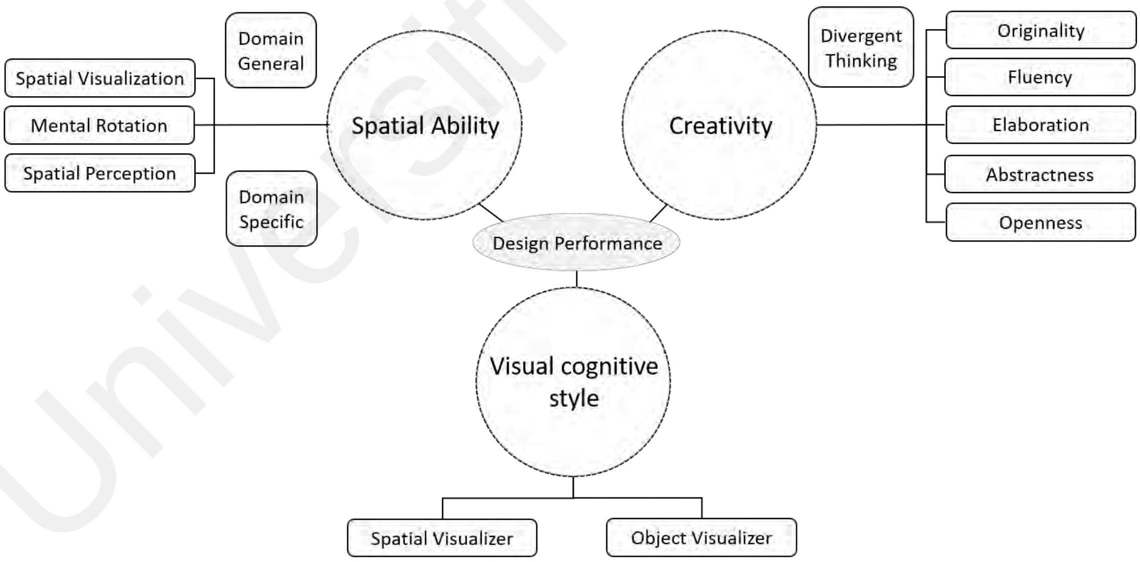


Figure 3.10: Spatial learning and cognitive mapping abilities framework by Cho (2017b)

3.3.3.2 A spatial learning and cognitive mapping abilities framework by Buckley and Seery (2016)

To aid an individual in enhancing their spatial thinking skills through the use of a cognitive map, Buckley and Seery (2016) developed the spatial cognition framework (see Figure 3.11). The elements of this framework are divided into two categories: static spatial factors and dynamic spatial actors. These are the static spatial factors that are unchanging in terms of their impact on the individual during the acquisition of spatial information. This static spatial factor component can be further subdivided into 19 sub-components, with some of the sub-components being dependent on one another. Additionally, dynamic spatial factors function as changeable in terms of their impact on the individual during the acquisition of spatial knowledge. These dynamic spatial factors can be classified into eight sub-components. However, even though these two major components are split into two groups, several of the subcomponents are interchangeable between the two categories, including visual memory, perceptual integration, spatial scanning, perceptual alternations, and perceptual speed. The primary goal of this proposed framework is to validate each individual capability in spatial cognition within each of the sub-components of the proposed framework.

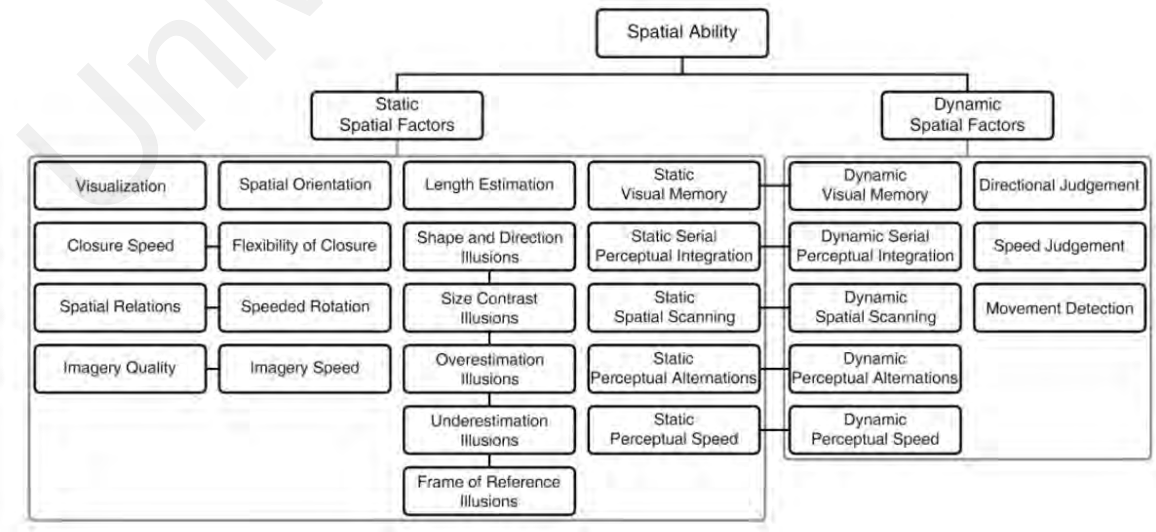


Figure 3.11: Spatial cognition abilities framework by Buckley and Seery (2016)

3.3.4 Spatial Cognition and Navigation Framework

This subsection investigates the idea of navigation in the context of its spatial cognition aspect in order to have a better knowledge of it.

3.3.4.1 A spatial cognition and navigation framework by S. Jul (2002)

Figure 3.12 shows a framework developed by S. Jul (2002) for spatial cognition and navigation in the virtual environment. The navigation component is classified as the primary component in this framework, and it is further subdivided into three sub-components, which are as follows: wayfinding, spatial knowledge preservation, and locomotion. The navigation component, in its most basic form, shows the actions associated with finding objects and determining how to reach them. Wayfinding is a sub-component that serves as an intermediary between the other two sub-components in order to solve the spatial ability problem and to assist in decision-making as well as other functions. It is the goal of the sub-component of spatial knowledge preservation to transform and store spatial information for navigation in a virtual environment. Meanwhile, the locomotion sub-component is intended to control movement in a virtual environment by specifying what movement is significant and what navigational decisions should be made in the virtual environment.

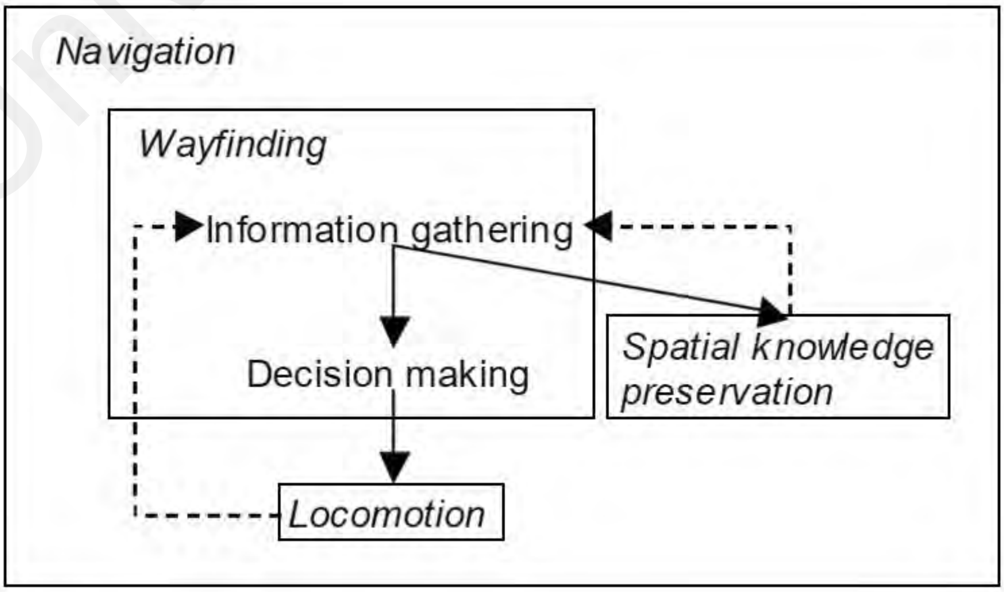


Figure 3.12: Spatial cognition and navigation framework by S. Jul (2002)

3.3.4.2 A spatial cognition and navigation framework by Martinez-Martin et al. (2014)

Martinez-Martin et al. (2014) presented a spatial coding system framework to understand how an individual can encode spatial information such as objects, locations, and routes in their surroundings, especially in a new environment (see Figure 3.13). The spatial coding system can be divided into two types of spatial representation: allocentric and egocentric. Allocentric is relatively referred to as object to object, where it is worked based on the coordinate system of the individual's current location in a virtual environment, whereas egocentric is self-to-object, which means the spatial information is encoded based on the object's directions relative to the individual's current location in the virtual environment.

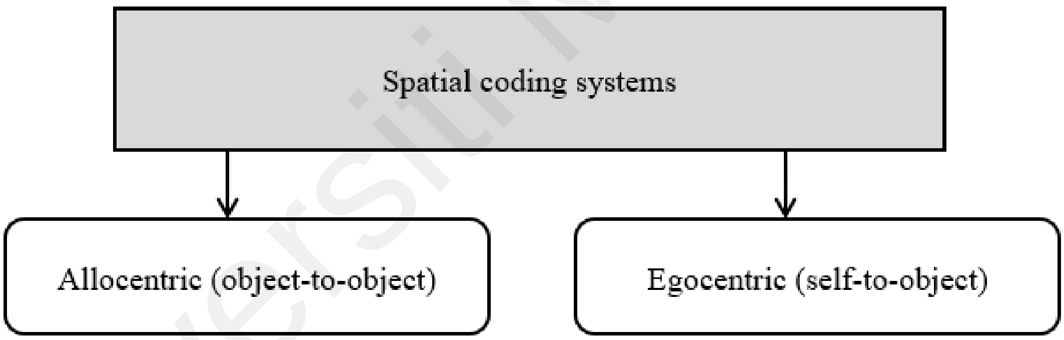


Figure 3.13: Spatial cognition and navigation framework by Martinez-Martin et al. (2014)

3.3.4.3 A spatial cognition and navigation framework by Kozhevnikov and Hegarty (2001a)

Using the concept of visualization ability, Kozhevnikov and Hegarty (2001a) developed a framework (see Figure 3.14). In the virtual environment, visualization ability is described as the ability of an individual to mentally manipulate virtual objects and landmarks in order to encode spatial information. There are two basic components to this skill, which are spatial visualization and object visualization, which can be distinguished. It is the process of analyzing spatial information between objects and performing mental manipulations that is referred to as spatial visualization. There are two sub-components to this spatial visualization component: allocentric, which allows an individual to mentally manipulate virtual objects from their current position of view, and egocentric, which allows an individual to imagine virtual objects from a different perspective in the virtual environment. The object visualization component is defined as the process by which an individual is able to process the physical information of a virtual object or landmark in the virtual environment, such as its shape, texture, and color, among other things.

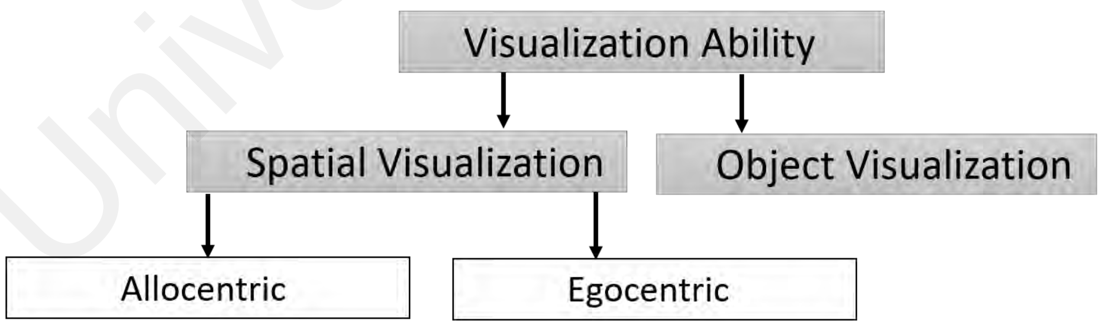


Figure 3.14: Spatial cognition and navigation framework by Kozhevnikov and Hegarty (2001a)

3.3.5 A compiled list of collective components from remaining haptic and virtual environment frameworks

The following tables (Table 3.1, Table 3.2, Table 3.3, and Table 3.4) show a compiled list of components from remaining relevance frameworks based on the following criteria: haptic technology, virtual environment, spatial learning, cognitive mapping and autism.

Table 3.1: A compiled list of haptic rendering technology components from remaining frameworks

Source Citation: (W. Wu et al., 2017)		
Component	Objective	Model
Graphics Rendering	This component is used to render the both upper and lower part of the virtual objects in the virtual environment.	Independent Framework
BVH Update	This component is intended to provide the current position and orientation information of the virtual object to the collision detection for processing.	
Collision Detection	This component is used to determine the interaction between the virtual objects in order to verify the real-time interaction with force feedback computation occurs on virtual objects.	
Haptic Rendering	Provide continuous interaction between user and virtual environment by generating the sense of presence in virtual environment.	
Force Computation	It’s used to compute the force feedback by measuring the mass and acceleration.	
Source Citation: (Leonard & Villeneuve, 2019)		
Component	Objective	Model
Visual Feedback	This component is used to render the both upper and lower part of the virtual objects in the virtual environment.	Independent Framework
Audio Feedback	Process based on real-time sound function to generate the audio response.	
Haptic Interaction	To create interaction between virtual objects and user through the haptic device.	
Virtual Rendering Process	This component is used to process the virtual scene which referred to mass-type and the interaction elements.	
Virtual Physics Scene	To process the virtual scene which referred to mass-type and the interaction elements.	
Audio Synthesis Process	To providing audio information of physical model via callback API.	
Haptic Device	Used hapticInput3D to transfer force signal in real time haptic interaction and the position information is derived based on haptic device’s sensor data.	
Virtual Scene Renderer	To render both the upper and lower part of the virtual objects in the virtual environment.	

Source Citation: (MacLean, 2000)		
Component	Objective	Model
User	The user (outermost layer) is notable as an individual who manipulate and interact with environment.	Independent Framework
Physical Interface	This main component (second layer) functioned as integrating the multi-sensory thru three different haptic interactions from different set of sub components: physical haptic interface, physical audio interface, and other physical interfaces as well. This component has ability to receive the input and provide the output thru all the sensory modalities functions to user.	
Physical Haptic Interface	This sub component classified as haptic interface for seeks to sensory modality thru touch.	
Physical Audio Interface	This sub component classified as audio interface for seeks to sensory modality thru voice.	
Other Physical Interfaces	The visual physical interface considered as other sensory modality which bring the visual feedback to user.	
Interaction Model	This main component (third layer) act as intermediate platform to form to interaction between the physical devices and VR environment thru the interaction and manipulation activity. This component can be divided into three subcomponents: haptic interaction model, auditory interaction model, and other interaction model. In general, this component has the capabilities to process the input modality such as touch or voice and transmit to user as output sensory modality feedback.	
Haptic Interaction Model	This sub component is intended to process the touch feedback for user sensation during the interaction with environment thru physical haptic interface.	
Auditory Interaction Model	This sub component is intended to process the audio feedback for user sensation during the interaction with environment thru physical auditory interface.	
Other Interaction Models	This sub component is intended to process the visual feedback for user sensation during the interaction with environment thru physical visual interface.	
Interaction Model Integration	Overall, this main component intended to integrate all the types of interaction models together and provide the multi-sensory feedback to user during the interaction with environment.	
Environment	This component refers to CAD representation of solid-body model or real-world physical model which intended to provide the ability interaction and manipulation in many possible ways.	

Table 3.2: A compiled list of virtual environment components from remaining frameworks

Source Citation: (S. Zhang et al., 2013)		
Component	Objective	Model
3D Modelling Data	This component is designed to produce the digital models.	Independent Framework
VE Modelling	This component able to support in terms of creating the basic elements in virtual environment such as terrain and buildings.	
VE Display	For the purpose of spatial data rendering such as texture mapping and materials, and also for landmark rendering.	
VE Interface	In order to bring the navigation and interaction abilities in virtual environment.	
Source Citation: (Tanriverdi & Jacob, 2001)		
Component	Objective	Model
Interface Objects	This refers to the entities that can be defined as roles and identities in VR interface.	Independent Framework
VR Data	The data is process based on the input received from users during the interaction with virtual objects in VR system.	
Dialog Control	This component is worked as mediator to bring the interaction between the VR application and VR interface.	
Graphics	In order the interface objects represent the graphical scene based on the characteristic and behaviors of objects.	
Interaction	This component is used to form the interaction between the user and VR system. This component able to receives the input and interprets into a meaningful information which able to manipulate the object behavior in VR System.	
Composite Behavior	This component can be categories into two groups: physical behaviors for presents the changes of the objects in real world, and magical behaviors rarely or not able to presents the changes of the objects in real world.	
Source Citation: (Sarmiento & Collazos, 2012)		
Component	Objective	Model
3D Design	This component is discovering the elements such as characters, VR scenarios, and interaction modes which able support the VR software development.	Independent Framework
Visualization and Interaction Model	This component focused on the interaction and communication between the users and VR software. This component able to allow the user interacts with the VR environment and virtual objects by navigation and object selection.	
VR Software Development	This component allows integrating all the elements such as 3D models, dynamic behaviours, and visualization and interaction models into a single VR software application.	

Table 3.3: A compiled list of spatial learning and cognitive mapping components from remaining frameworks

Source Citation: (Roca-González et al., 2017)		
Component	Objective	Model
Spatial Ability	This component is responsible for mentally managing the virtual objects.	Independent Framework
Spatial Relations	This component is designed to perform virtual object rotations and comparisons.	
Spatial Visualization	This component is used to manage complex visual information so that a person can see or generate accurate resolution of virtual objects.	
Spatial Orientation	This component is used in a virtual environment to manage and perform physical and mental orientation.	

Table 3.4: A compiled list of autism spectrum disorder (ASD) components from remaining framework

Source Citation: (Grzadzinski et al., 2013)		
Component	Objective	Model
Social Communication	This component is intended to investigate and comprehend the communication challenges encountered in social situations.	Independent Framework
Restricted and Repetitive Interests or Behaviors	This component is conducted to determine and understand the repetitive movements and sensory sensitivities of autistic people.	

3.3.6 A compiled list of collective components from relevance studies

The Table 3.5 shows a list of components from relevance studies. These components were identified based on the following criteria: learning modality, training environment, spatial learning, and cognitive mapping.

Table 3.5: A compiled list of components from relevance studies

Component	Objective	Source Citation
Scenario Environment	This component is intended to describe the significance of the virtual scenario as well as how the virtual objects and their relationships are integrated to complete the virtual design.	(C. J. Chen, 2010), (Leonard & Villeneuve, 2019)
Training Transfer Environment	This component is used to describe the significance of the training environment and how the relevant elements should be prioritised in order to transfer knowledge from the virtual to the real world.	(Darken & Peterson, 2014)
Cognitive Skills	This component is intended to define the individual's interaction and communication skills.	(Rowland & Schweigert, 2009), (Filipek et al., 2000), (Keown et al., 2013), (Manning-Courtney et al., 2013), (D. L. Christensen et al., 2018)
Cognitive Ability	To comprehend an individual's abilities in terms of uneven cognitive development.	(Joseph et al., 2002)
Cognitive Mapping	This component refers to the concept of internally representing external aspects such as objects or landmarks.	(Tolman, 1948), (H. Zhang et al., 2014a), (Golledge, 1999)
Spatial Awareness	This component refers to spatial awareness of the environment, with a focus on the concept of orientation and wayfinding tasks.	(Klippel et al., 2010), (Charman, 2003), (Mitchell & Ropar, 2004), (Golledge, 1999)
Visual Spatial Skills	This component is known as an individual's awareness, which is how they orient themselves in a specific environment and with other objects in their surroundings, as well as their logical reasoning.	(Coulter, 2009)
Spatial Knowledge	This component is used to comprehend spatial knowledge that is based on landmarks, routes, or survey information.	(Pylyshyn, 2000)
Haptic Modality	This component encompasses all three types of sensory modalities: visual, audio, and haptic or tactile.	(Tang, McMahan, et al., 2014), (S. Zhang et al., 2013)

3.4 Discussion

The following sub-sections present the main outcomes of the analysis of the fourteen existing frameworks and the remaining frameworks and individual components from relevance studies.

3.4.1 Classification of the components of the existing framework

One of the components of autism that has been focused on for autistic people is their behaviors and capabilities, and this component is drawn from the frameworks for autism research (Hulusic & Pistoljevic, 2012; Sophie E Lind, 2010; D. Moore et al., 2000). Meanwhile, when it comes to the aspect of spatial learning and cognitive mapping skills in terms of user ability, a total of three sub-components (spatial knowledge, wayfinding behavior, and cognitive mapping skills) are recognized under the main component of spatial ability. Learning modality is also one of the components to understanding the sensory channels of autistic people. Using the existing HBVE-Frameworks for autistic people, 24 main components and 26 sub-components were discovered in total.

3.4.2 The structure of the existing framework

Most of the existing frameworks use their own structures, but the framework by Choi et al. (2017) uses an input, process, output (IPO) model.

3.4.3 The categories of the existing framework

Among all these existing frameworks, the framework by Le et al. (2016) is a haptic based specialized group of frameworks for autistic people to improve their learning skills, whereas the remaining frameworks are classified as generic groups of frameworks for designing HBVE.

3.5 Clustering of components from existing frameworks

For advanced analysis and synthesis, the clustering of components from existing HBVE-Frameworks is handled in four stages, as shown in Figure 3.15. The 165 components identified during the previous review section were analyzed according to the similarities and significance of the component to this research domain, and they were also placed into the four stages according to their significance to this research domain to determine the final components.

The components of each framework were placed according to different sets of groups in the first stage (refer to Figure 3.16): group circle (1) for Le et al. (2016), group circle (2) for Orozco and El Saddik (2008), group circle (3) for Eck and Sandor (2013), group circle (4) for Choi et al. (2017), group circle (5) for Jia et al. (2013), group circle (6) for S. Y. Chung and H. Yoon (2011), group circle (7) for K. Salisbury et al. (2004b), group circle (8) for Halarnkar et al. (2012), group circle (9) for Romli and Yaakob (2017), group circle (10) for (Cho, 2017a), group circle (11) for Buckley and Seery (2016), group circle (12) for S. Jul (2002), group circle (13) for Martinez-Martin et al. (2014), group circle (14) for Kozhevnikov and Hegarty (2001a), group circle (15) for W. Wu et al. (2016), group circle (16) for Leonard and Villeneuve (2019), group circle (17) for MacLean (2000), group circle (18) for S. Zhang et al. (2013), group circle (19) for Tanriverdi and Jacob (2001), group circle (20) for Sarmiento and Collazos (2012), group circle (21) for Roca-González et al. (2017), group circle (22) for Grzadzinski et al. (2013) and nine individual components from relevance studies. Meanwhile, during the second stage, the components that were similar and those that were dissimilar were discovered. Aside from that, during the third stage, all of the main and sub components were identified based on the functionality of the component under consideration. Last but not least, during the fourth stage, all of the relevant components of the HBVE-Framework were discovered.

The process of identifying components that are similar and dissimilar to one another is covered in further depth in section 3.5.1 of this chapter.

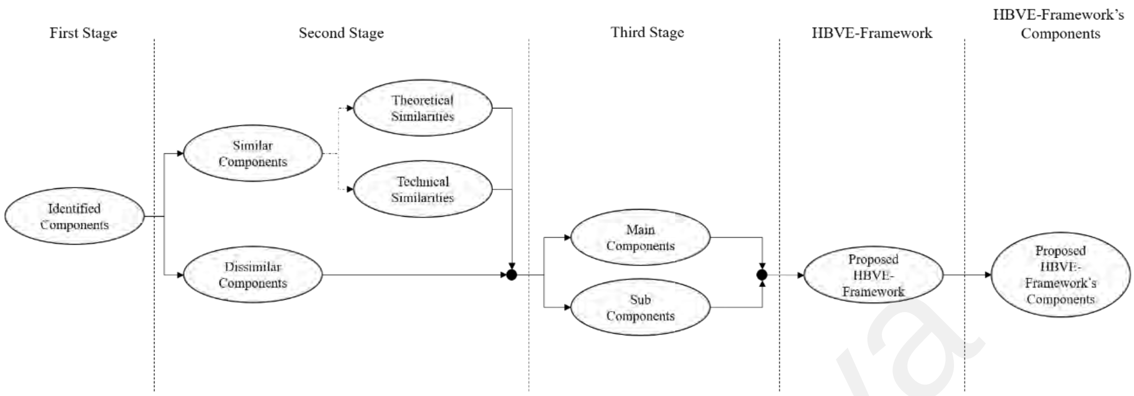
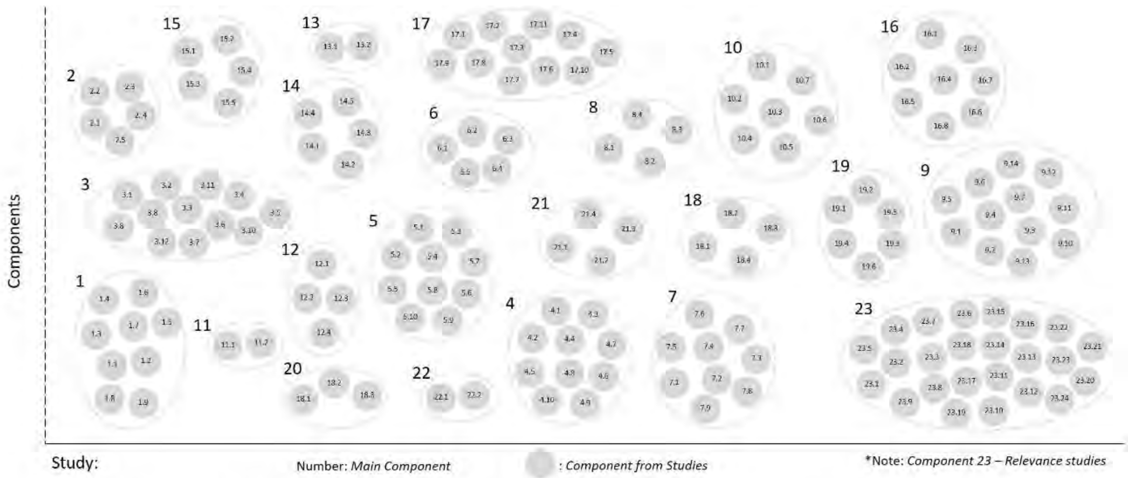


Figure 3.15: The process of clustering components



1) Le et al. (2016)
1.1: Visual Renderer
1.2: Sound Renderer
1.3: Haptic Renderer
1.4: Collision Detection
1.5: Force Feedback
1.6: General Controller
1.7: Delay Synchronization Module
1.8: Data Access
1.9: Haptic APIs

2) Orozco and El Saddik (2008)
2.1: Application Factory (AF)
2.2: Software/ Hardware Application (SHA)
2.3: Intelligent Ambient Engine (IAE)
2.4: Behavioral Data Repository (BDR)
2.5: Haptic Device

3) Eck and Sandor (2013)
3.1: Tracking
3.2: Simulation
3.3: Visual Rendering
3.4: Haptic Rendering
3.5: World Model
3.6: Simulation Engine
3.7: Haptic Device
3.8: Graphic Engine
3.9: Collision Detection
3.10: Force Response
3.11: Control Algorithms
3.12: Display

4) Choi et al. (2017)
4.1: Three-Dimensional (3D) Modelling
4.2: Graphical User Interface
4.3: Virtual Coupling
4.4: Fit Assessment
4.5: Collision Detection
4.6: Scene Rendering
4.7: Graphics Display
4.8: Force Feedback
4.9: Visual Feedback
4.10: Haptic Device

5) Jia et al. (2013)
5.1: Haptic Hardware
5.2: CAD Data Repository
5.3: Collision Detection Engine
5.4: Event Logger
5.5: Graphics Registration
5.6: Virtual Training System
5.7: GUI Display
5.8: Force Feedback
5.9: Audio-Visual Feedback Engine
5.10: Training Modes

6) Chung and Yoon (2011)
6.1: Virtual Interactive Environment
6.2: Force/Tactile Feedback
6.3: Virtual Environment Interface
6.4: Haptic Device
6.5: Visual/Audio Information

7) Salisbury et al. (2004)
7.1: Haptic Rendering
7.2: Collision Detection
7.3: Force Response
7.4: Control Algorithms
7.5: Simulation
7.6: Simulation Engine
7.7: Visual Rendering
7.8: Graphics Engine
7.9: Video

8) Halarnkar et al. (2012)
8.1: Virtual World
8.2: Simulation Engine
8.3: Graphics Engine
8.4: User Interface

9) Romli and Yaakob (2017)
9.1: Instructional Element
9.2: Interaction
9.3: Object Selection
9.4: Object Manipulation
9.5: Navigation
9.6: Layout of Virtual Environment
9.7: Directional Cues
9.8: Key Location Points
9.9: Fidelity
9.10: Frame Rate
9.11: Point of View
9.12: Colors and Textures
9.13: Sound
9.14: Temporal Change

10) Cho (2017)
10.1: Spatial Ability
10.2: Spatial Visualization
10.3: Mental Rotation
10.4: Spatial Perception
10.5: Visual Cognitive Style
10.6: Object Visualize
10.7: Spatial Visualizer

11) Buckley and Seery (2016)
11.1: Static Spatial Factors
11.2: Dynamic Spatial Factors

12) Jul (2002)
12.1: Navigation
12.2: Wayfinding
12.3: Spatial Knowledge Preservation
12.4: Locomotion

13) Martinez-Martin (2014)
13.1: Allocentric
13.2: Egocentric

14) Kozhevnikov and Hegarty (2001)
14.1: Visualization Ability
14.2: Spatial Visualization
14.3: Allocentric
14.4: Egocentric
14.5: Object Visualization

15) Wu et al. (2017)
15.1: Graphics Rendering
15.2: BVH Update
15.3: Collision Detection
15.4: Haptic Rendering
15.5: Force Computation

16) Leonard and Villeneuve (2019)
16.1: Visual Feedback
16.2: Audio Feedback
16.3: Haptic Interaction
16.4: Virtual Rendering Process
16.5: Virtual Physics Scene
16.6: Audio Synthesis Process
16.7: Haptic Device
16.8: Virtual Scene Renderer

17) MacLean (2000)
17.1: User
17.2: Physical Interface
17.3: Physical Haptic Interface
17.4: Physical Audio Interface
17.5: Other Physical Interfaces
17.6: Interaction Model
17.7: Haptic Interaction Model
17.8: Auditory Interaction Model
17.9: Other Interaction Models
17.10: Interaction Model Integration
17.11: Environment

18) Zhang et al. (2013)
18.1: 3D Modelling Data
18.2: VE Modelling
18.3: VE Display
18.4: VE Interface

19) Tanriverdi and Jacob (2001)
19.1: Interface Objects
19.2: VR Data
19.3: Dialog Control
19.4: Graphics
19.5: Interaction
19.6: Composite Behaviour

20) Sarmiento and Collazos (2012)
20.1: 3D Design
20.2: Visualization and Interaction Model
20.3: VR Software Development

21) Roca-González et al. (2017)
21.1: Spatial Ability
21.2: Spatial Relations
21.3: Spatial Visualization
21.4: Spatial Orientation

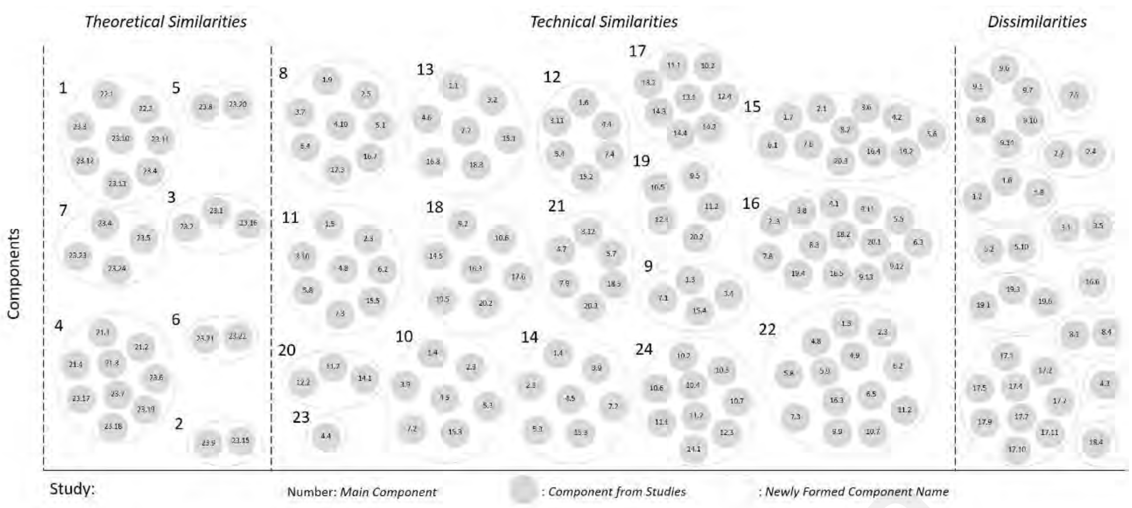
22) Grzadzinski et al. (2013)
22.1: Social Communication
22.2: Restricted and Repetitive Interests or Behaviors

23) Relevance Studies
23.1: Scenario Environment - Chen & Education (2010)
23.2: Training Transfer Environment - Darken & Peterson (2014)
23.3: Cognitive Skills - Rowland & Schweigert (2009)
23.4: Cognitive Ability - Joseph et al. (2002)
23.5: Cognitive Mapping - Tolman (1948)
23.6: Spatial Awareness - Klippel et al. (2010)
23.7: Visual Spatial Skills - Coulter & Development (2009)
23.8: Spatial Knowledge - Pylyshyn (2000)
23.9: Haptic Modality - Tang et al. (2014)
23.10: Autism Behaviour - Filipek et al. (2000)
23.11: ASD Behaviour - Rowland & Schweigert (2009)
23.12: ASD Social and Repetitive Behaviour - Keown et al. (2013)
23.13: ASD Behavioural - Manning-Courtney et al. (2013)
23.14: Autism Features and Behaviour - Christensen et al. (2018)
23.15: Modality - S. Zhang et al. (2013)
23.16: Environment - Leonard & Villeneuve (2019)
23.17: Attention Skills – Charman (2003)
23.18: Spatial Ability - Mitchell et al. (2004)
23.19: Spatial Processes and Information – Golledge (1999)
23.20: Spatial Knowledge – Golledge (1999)
23.21: Wayfinding Behaviours – Golledge (1999)
23.22: Wayfinding - Sarmiento & Collazos (2012)
23.23: Cognitive Map - H. Zhang et al. (2014)
23.24: Cognitive Mapping – Golledge (1999)

Figure 3.16: The clustered components from existing framework during the first stage

3.5.1 The process of clustering the similar and dissimilar of components

Through an understanding of each of the component descriptions, it was possible to identify multiple components that were conceptually similar to one another during the framework review process. As a result, at the second stage (as depicted in Figure 3.17), those components that are similar to one another are discovered and clustered together as individual components by using the clustering network method depicted in the diagram. Also, these components arranged based on theoretical and technical components. Based on the component's descriptions, this grouped component is handled as a new component with a different subject name than the original component. The subject name of the new component can still be derived from the existing similar component within the same framework, or it can be from a different framework, as long as the features of the component in both descriptions must be similar for it to be considered a valid subject name. The newly formed component name is represented by a dashed circle that has been clustered. Furthermore, to illustrate this, Table 3.6 lists all of the similar components from existing frameworks that were combined to form new components. In the meantime, there are a few components that do not share any characteristics with other components, and these components are classified as emancipated or dissimilarities components in the context of the overall framework. Following the clustering process, a total of 24 main components are shown in Table 3.6, out of a total of 165 components.



Theoretical Components:

1) Autism Behaviours and Capabilities
22.1: Grzadzinski et al. (2013)
22.2: Grzadzinski et al. (2013)
23.3: Rowland & Schweigert (2009)
23.10: Filipek et al. (2000)
23.11: Rowland & Schweigert (2009)
23.12: Keown et al. (2013)
23.13: Manning-Courtney et al. (2013)
23.14: Christensen et al. (2018)

2) Learning Modality
23.9: Tang et al. (2014)
23.15: S. Zhang et al. (2013)

3) Environment
23.1: Chen & Education (2010)
23.2: Darken & Peterson (2014)
23.16: Leonard & Villeneuve (2019)

4) Spatial Ability
21.1: Roca-González et al. (2017)
21.2: Roca-González et al. (2017)
21.3: Roca-González et al. (2017)
21.4: Roca-González et al. (2017)
23.6: Klippel et al. (2010)
23.7: Coulter & Development (2009)
23.17: Charman (2003)
23.18: Mitchell et al. (2004)
23.19: Golledge (1999)

5) Spatial Knowledge
23.8: Pylyshyn (2000)
23.20: Golledge (1999)

6) Wayfinding Behaviours
23.21: Golledge (1999)
23.22: Sarmiento & Collazos (2012)

7) Cognitive Map
23.4: Joseph et al. (2002)
23.5: Tolman (1948)
23.23: H. Zhang et al. (2014)
23.24: Golledge (1999)

Technical Components:

8) Physical Haptic Interface
1.9: Le et al. (2016)
2.5: Orozco and El Saddik (2008)
3.7: Eck and Sandor (2013)
4.10: Choi et al. (2017)
5.1: Jia et al. (2013)
6.4: Chung and Yoon (2011)
16.7: Leonard and Villeneuve (2019)
17.3: MacLean (2000)

9) Haptic Rendering
1.3: Le et al. (2016)
3.4: Eck and Sandor (2013)
7.1: Salisbury et al. (2004)
15.4: Wu et al. (2017)

10) Haptic Collision Detection
1.4: Le et al. (2016)
2.3: Orozco and El Saddik (2008)
3.9: Eck and Sandor (2013)
4.5: Choi et al. (2017)
5.3: Jia et al. (2013)
7.2: Salisbury et al. (2004)
15.3: Wu et al. (2017)

11) Haptic Feedback
1.5: Le et al. (2016)
2.3: Orozco and El Saddik (2008)
3.10: Eck and Sandor (2013)
4.8: Choi et al. (2017)
5.8: Jia et al. (2013)
6.2: Chung and Yoon (2011)
7.3: Salisbury et al. (2004)
15.5: Wu et al. (2017)

12) Control Algorithm
1.6: Le et al. (2016)
3.11: Eck and Sandor (2013)
4.4: Choi et al. (2017)
5.4: Jia et al. (2013)
7.4: Salisbury et al. (2004)
15.2: Wu et al. (2017)

13) Visual Rendering
1.1: Le et al. (2016)
3.2: Eck and Sandor (2013)
4.6: Choi et al. (2017)
7.7: Salisbury et al. (2004)
15.1: Wu et al. (2017)
16.8: Leonard and Villeneuve (2019)
18.3: Zhang et al. (2013)

14) Virtual Collision Detection
1.4: Le et al. (2016)
2.3: Orozco and El Saddik (2008)
3.9: Eck and Sandor (2013)
4.5: Choi et al. (2017)
5.3: Jia et al. (2013)
7.2: Salisbury et al. (2004)
15.3: Wu et al. (2017)

15) Simulation Engine
1.7: Le et al. (2016)
2.1: Orozco and El Saddik (2008)
3.6: Eck and Sandor (2013)
4.2: Choi et al. (2017)
5.6: Jia et al. (2013)
6.1: Chung and Yoon (2011)
7.6: Salisbury et al. (2004)
8.2: Halarnkar et al. (2012)
16.4: Leonard and Villeneuve (2019)
19.2: Tanriverdi and Jacob (2001)
20.3: Sarmiento and Collazos (2012)

16) Graphics Scene Activity
2.3: Orozco and El Saddik (2008)
3.8: Eck and Sandor (2013)
4.1: Choi et al. (2017)
5.5: Jia et al. (2013)
6.3: Chung and Yoon (2011)
7.8: Salisbury et al. (2004)
8.3: Halarnkar et al. (2012)
9.11: Romli and Yaakob (2017)
9.12: Romli and Yaakob (2017)
9.13: Romli and Yaakob (2017)
16.5: Leonard and Villeneuve (2019)
18.2: Zhang et al. (2013)
19.4: Tanriverdi and Jacob (2001)
20.1: Sarmiento and Collazos (2012)

17) Spatial Processing Coding System
10.2: Cho (2017)
11.1: Buckley and Seery (2016)
12.4: Jul (2002)
13.1: Martinez-Martin (2014)
13.2: Martinez-Martin (2014)
14.2: Kozhevnikov and Hegarty (2001)
14.3: Kozhevnikov and Hegarty (2001)
14.4: Kozhevnikov and Hegarty (2001)

18) Interaction and Manipulation
9.2: Romli and Yaakob (2017)
10.6: Cho (2017)
14.5: Kozhevnikov and Hegarty (2001)
16.3: Leonard and Villeneuve (2019)
17.6: MacLean (2000)
19.5: Tanriverdi and Jacob (2001)
20.2: Sarmiento and Collazos (2012)

19) Cognitive Map Navigation
9.5: Romli and Yaakob (2017)
10.5: Cho (2017)
11.2: Buckley and Seery (2016)
12.1: Jul (2002)
20.2: Sarmiento and Collazos (2012)

20) Wayfinding
11.2: Buckley and Seery (2016)
12.2: Jul (2002)
14.1: Kozhevnikov and Hegarty (2001)

21) Rendring Content
3.12: Eck and Sandor (2013)
4.7: Choi et al. (2017)
5.7: Jia et al. (2013)
7.9: Salisbury et al. (2004)
18.3: Zhang et al. (2013)
20.3: Sarmiento and Collazos (2012)

22) Sensory Modality
1.5: Le et al. (2016)
2.3: Orozco and El Saddik (2008)
4.8: Choi et al. (2017)
4.9: Choi et al. (2017)
5.8: Jia et al. (2013)
5.9: Jia et al. (2013)
6.2: Chung and Yoon (2011)
6.5: Chung and Yoon (2011)
7.3: Salisbury et al. (2004)
9.9: Romli and Yaakob (2017)
10.7: Cho (2017)
11.2: Buckley and Seery (2016)
16.3: Leonard and Villeneuve (2019)

23) User Achievement
4.4: Choi et al. (2017)

24) Spatial Representation Information
10.2: Cho (2017)
10.3: Cho (2017)
10.4: Cho (2017)
10.6: Cho (2017)
10.7: Cho (2017)
11.1: Buckley and Seery (2016)
11.2: Buckley and Seery (2016)
12.3: Jul (2002)
14.1: Kozhevnikov and Hegarty (2001)

Figure 3.17: The clustered components based on similarities and dissimilarities

Table 3.6: The shape of new components derived from previously existing components

MC. No.	Similar Components	New Component
1	Social Communication (Grzadzinski et al., 2013) Restricted and Repetitive Interests or Behaviors (Grzadzinski et al., 2013) Cognitive Skills (Rowland & Schweigert, 2009) Autism Behaviour (Filipek et al., 2000) ASD Behaviour (Rowland & Schweigert, 2009) ASD Social and Repetitive Behaviour (Keown et al., 2013) ASD Behavioural (Manning-Courtney et al., 2013) Autism Features and Behaviour (D. L. Christensen et al., 2018)	Autism Behaviours and Capabilities
2	Haptic Modality (Tang, McMahan, et al., 2014) Modality (S. Zhang et al., 2013)	Learning Modality
3	Scenario Environment (C. J. Chen, 2010) Training Transfer Environment (Darken & Peterson, 2014) Environment (Leonard & Villeneuve, 2019)	Environment
4	Spatial Ability (Roca-González et al., 2017) Spatial Relations (Roca-González et al., 2017) Spatial Visualization (Roca-González et al., 2017) Spatial Orientation (Roca-González et al., 2017) Spatial Awareness (Klippel et al., 2010) Visual Spatial Skills (Coulter, 2009) Attention Skills (Charman, 2003) Spatial Ability (Mitchell & Ropar, 2004) Spatial Processes and Information (Golledge, 1999)	Spatial Ability
5	Spatial Knowledge (Pylyshyn, 2000) Spatial Knowledge (Golledge, 1999)	Spatial Knowledge
6	Wayfinding Behaviours (Golledge, 1999) Wayfinding (Sarmiento & Collazos, 2012)	Wayfinding Behaviours
7	Cognitive Ability (Joseph et al., 2002) Cognitive Mapping (Tolman, 1948) Cognitive Map (H. Zhang et al., 2014a) Cognitive Mapping (Golledge, 1999)	Cognitive Map
8	Haptic APIs (Le et al., 2016) Haptic Device (Orozco & El Saddik, 2008) Haptic Device (Eck & Sandor, 2013) Haptic Device (Choi et al., 2017) Haptic Hardware (Jia et al., 2013) Haptic Device (S. Y. Chung & H. Yoon, 2011)	Physical Haptic Interface

	Haptic Device (Leonard & Villeneuve, 2019) Physical Haptic Interface (MacLean, 2000)	
9	Haptic Renderer (Le et al., 2016) Haptic Rendering (Eck & Sandor, 2013) Haptic Rendering (K. Salisbury et al., 2004b) Haptic Rendering (W. Wu et al., 2017)	Haptic Rendering
10	Collision Detection (Le et al., 2016) Intelligent Ambient Engine (IAE) (Orozco & El Saddik, 2008) Collision Detection (Eck & Sandor, 2013) Collision Detection (Choi et al., 2017) Collision Detection Engine (Jia et al., 2013) Collision Detection (K. Salisbury et al., 2004b) Collision Detection (W. Wu et al., 2017)	Haptic Collision Detection
11	Force Feedback (Le et al., 2016) Intelligent Ambient Engine (IAE) (Orozco & El Saddik, 2008) Force Response (Eck & Sandor, 2013) Force Feedback (Choi et al., 2017) Force Feedback (Jia et al., 2013) Force/Tactile Feedback (S. Y. Chung & H. Yoon, 2011) Force Response (K. Salisbury et al., 2004b) Force Computation (W. Wu et al., 2017)	Haptic Feedback
12	General Controller (Le et al., 2016) Control Algorithms (Eck & Sandor, 2013) Fit Assessment (Choi et al., 2017) Event Logger (Jia et al., 2013) Control Algorithms (K. Salisbury et al., 2004b) BVH Update (W. Wu et al., 2017)	Control Algorithm
13	Visual Renderer (Le et al., 2016) Simulation (Eck & Sandor, 2013) Scene Rendering (Choi et al., 2017) Visual Rendering (K. Salisbury et al., 2004b) Graphics Rendering (W. Wu et al., 2017) Virtual Scene Renderer (Leonard & Villeneuve, 2019) VE Display (S. Zhang et al., 2013)	Visual Rendering
14	Collision Detection (Le et al., 2016) Intelligent Ambient Engine (IAE) (Orozco & El Saddik, 2008) Collision Detection (Eck & Sandor, 2013) Collision Detection (Choi et al., 2017) Collision Detection Engine (Jia et al., 2013) Collision Detection (K. Salisbury et al., 2004b) Collision Detection (W. Wu et al., 2017)	Virtual Collision Detection
15	Delay Synchronization Module (Le et al., 2016) Application Factory (AF) (Orozco & El Saddik, 2008)	Simulation Engine

	Simulation Engine (Eck & Sandor, 2013) Graphical User Interface (Choi et al., 2017) Virtual Training System (Jia et al., 2013) Virtual Interactive Environment (S. Y. Chung & H. Yoon, 2011) Simulation Engine (K. Salisbury et al., 2004b) Simulation Engine (Halarnkar et al., 2012) Virtual Rendering Process (Leonard & Villeneuve, 2019) VR Data (Tanriverdi & Jacob, 2001) VR Software Development (Sarmiento & Collazos, 2012)	
16	Intelligent Ambient Engine (IAE) (Orozco & El Saddik, 2008) Graphic Engine (Eck & Sandor, 2013) Three-Dimensional (3D) Modelling (Choi et al., 2017) Graphics Registration (Jia et al., 2013) Virtual Environment Interface (S. Y. Chung & H. Yoon, 2011) Graphics Engine (K. Salisbury et al., 2004b) Graphics Engine (Halarnkar et al., 2012) VE Modelling (S. Zhang et al., 2013) Graphics (Tanriverdi & Jacob, 2001) 3D Design (Sarmiento & Collazos, 2012)	Graphics Scene Activity
17	Spatial Visualization (Cho, 2017a) Static Spatial Factors (Buckley & Seery, 2016) Locomotion (S. Jul, 2002) Allocentric (Martinez-Martin et al., 2014) Spatial Visualization (Kozhevnikov & Hegarty, 2001a)	Spatial Processing Coding System
18	Interaction (Romli & Yaakob, 2017) Object Visualize (Cho, 2017a) Object Visualization (Kozhevnikov & Hegarty, 2001a) Haptic Interaction (Leonard & Villeneuve, 2019) Interaction Model (MacLean, 2000) Interaction (Tanriverdi & Jacob, 2001) Visualization and Interaction Model (Sarmiento & Collazos, 2012)	Interaction and Manipulation
19	Navigation (Romli & Yaakob, 2017) Visual Cognitive Style (Cho, 2017a) Dynamic Spatial Factors (Buckley & Seery, 2016) Navigation (S. Jul, 2002) Visualization and Interaction Model (Sarmiento & Collazos, 2012)	Cognitive Map Navigation
20	Dynamic Spatial Factors (Buckley & Seery, 2016) Wayfinding (S. Jul, 2002) Visualization Ability (Kozhevnikov & Hegarty, 2001a)	Wayfinding
21	Display (Eck & Sandor, 2013) Graphics Display (Choi et al., 2017)	Rendering Content

	GUI Display (Jia et al., 2013) Video (K. Salisbury et al., 2004b) VE Display (S. Zhang et al., 2013) VR Software Development (Sarmiento & Collazos, 2012)	
22	Force Feedback (Le et al., 2016) Intelligent Ambient Engine (IAE) (Orozco & El Saddik, 2008) Force Feedback (Choi et al., 2017) Visual Feedback (Choi et al., 2017) Force Feedback (Jia et al., 2013) Audio-Visual Feedback Engine (Jia et al., 2013) Force/Tactile Feedback (S. Y. Chung & H. Yoon, 2011) Visual/Audio Information (S. Y. Chung & H. Yoon, 2011) Force Response (K. Salisbury et al., 2004b) Fidelity (Romli & Yaakob, 2017) Spatial Visualizer (Cho, 2017a) Dynamic Spatial Factors (Buckley & Seery, 2016) Haptic Interaction (Leonard & Villeneuve, 2019)	Sensory Modality
23	Fit Assessment (Choi et al., 2017)	User Achievement
24	Spatial Visualization (Cho, 2017a) Mental Rotation (Cho, 2017a) Spatial Perception (Cho, 2017a) Object Visualize (Cho, 2017a) Spatial Visualizer (Cho, 2017a) Static Spatial Factors (Buckley & Seery, 2016) Dynamic Spatial Factors (Buckley & Seery, 2016) Spatial Knowledge Preservation (S. Jul, 2002) Visualization Ability (Kozhevnikov & Hegarty, 2001a)	Spatial Representation Information

3.5.2 The process of recognition of sub-components

In a manner similar to that described in Section 3.5.1, this process will be carried out using clustering methods, which will be used to group the recognised subcomponents and place them under the main components. This clustering process was also implemented based on the descriptive technique, which allowed for the determination and selection of the appropriate subcomponent under the main component. It is meant that this technique is applied based on detailed descriptions of each component, as well as relationships between the component and other components within a specific frame or set of studies.

Furthermore, because the majority of the subcomponents described are too generic, the subcomponents will be discovered and presented in greater detail by each component during the initial stage of the framework development (refer to Chapter 5), in order to avoid any overlooked subcomponents. The following are the steps that were taken in order to complete this process:

(1) Recognize the main components that interact with the subcomponents from existing frameworks or relevant studies and how they relate to one another.

(2) Determine the relevance of recognised subcomponents based on the role of the recognised subcomponent in the existing framework or relevant studies.

(3) Filtration should be used to determine the final subcomponents in order to avoid redundancy in terms of role and features.

(4) List all of the components that have been defined as filtered subcomponents under the main component.

(5) Evaluate with expertise whether those recognised subcomponents are acceptable or not, and this step will be carried out in Chapter 5 through the use of a usability assessment.

The recognised subcomponents with their main components are presented in Figure 3.18.

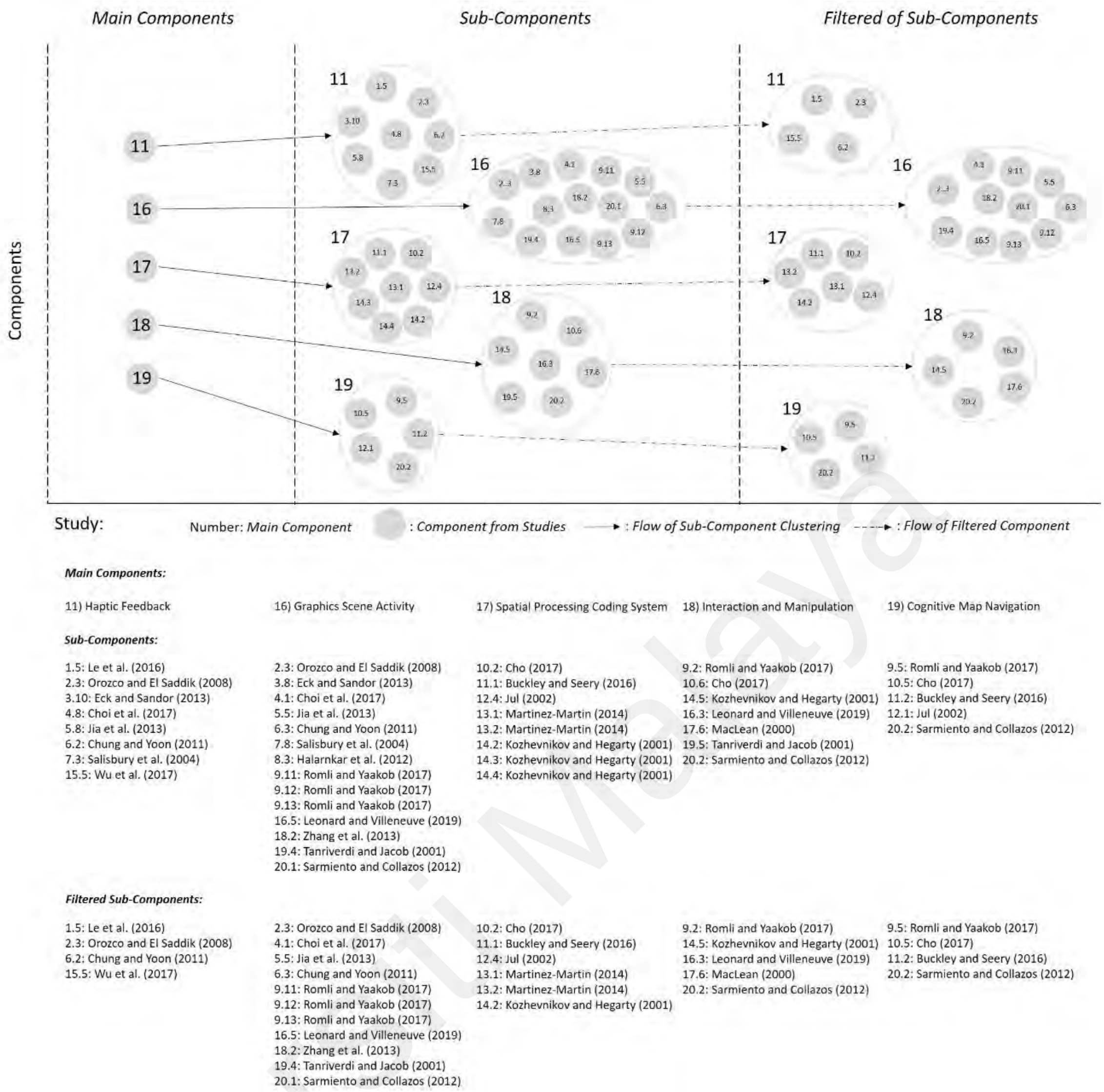


Figure 3.18: The subcomponents were detected based on their description and relationship

3.6 Discussion

This review makes a contribution to two different sets of expanding research areas: (i) the application of haptic technology to autistic people in order to support embodied interaction and manipulation; and (ii) the improvement of spatial learning and cognitive skills among autistic people. This chapter specifically investigated the potential of components involved in terms of autistic abilities in the sense of spatial knowledge and cognitive mapping skills; a component of haptic technology and its integrated subcomponents as a controller; the components of virtual reality, which act as model aspects and mediated tools or applications; and the impactful components of spatial knowledge and cognitive mapping abilities. This research leads us to believe that the effectiveness of an autistic person's learning process is directly related to the degree to which a physical haptic interface or device is tightly coupled with a simulation engine. This is especially true when it comes to spatial knowledge and cognitive mapping. This can be broken down into four different ideas for a more in-depth comprehension: haptic technology and rendering, sensory feedback, virtual elements, and knowledge transfer and interaction.

Haptic technology and rendering: In order to engage and configure the dynamic interactions between the haptic device and virtual environment, the majority of the studies introduced the haptic rendering, which is capable of generating virtual objects from the haptic library (Eck & Sandor, 2013), and these can be processed through other subcomponents such as collision detection (Eck & Sandor, 2013; Jia et al., 2013), a control algorithm (Eck & Sandor, 2013), and the force response. In highlight, the collision detection component is one of the more important components in any HBVE application development where this assist not only for detecting collision between users and virtual object but also with the interaction of a virtual object with other virtual object (Jia et al., 2013; K. Salisbury et al., 2004b). However, it has been reported that other subcomponents, such as haptic data content service (Orozco & El Saddik, 2008) and haptic data registration (Jia et al., 2013), may be required to understand and process what types of haptic feedback the haptic device is capable of reproducing at a specific time relative to or during the action taken by the user. As we can see, most of the components which related haptic technology especially haptic rendering, collision detection, control algorithm, and force response are the fundamental components for any HBVE development. Therefore, this study will take note all these fundamental components as compulsory component for the proposed framework development in this study.

Virtual elements: Concerns have been raised regarding the implementation of certain APIs in virtual environments. This is due to the fact that the majority of haptic devices rely on APIs, and these APIs require appropriate adaptation in order to properly support the development of virtual environments that are expected to function as intended. Even so, it has been reported that there has been manual application of haptic attributes to the virtual objects in order to ensure that the virtual object and the haptic attributes align with one another and function correctly in order to have a successful HBVE application (Orozco & El Saddik, 2008). In the meantime, researchers have also asserted that there is a requirement for a component such as a visual scenario for the processing of task transactions (Choi et al., 2017; Orozco & El Saddik, 2008). This highlights the fact that this research ought to take into consideration aspects such as graphic scene activity and environment, which describe the significance of task transactions in the development of HBVE. The Eck and Sandor (2013) framework also reported that the importance of components such as the world model should be focused on having minimal latency during the interaction in real-time. This was done to prevent any problems related to low performance as well as to simplify the process of synchronization and to have smooth haptic data exchange between virtual objects and haptic devices (Choi et al., 2017; Eck & Sandor, 2013). Furthermore, researcher Choi et al. (2017) reported that scene rendering is required to provide a real-time effect with the display of virtual objects from different angles. In addition, components such as object selection and manipulation are required in order to carry out any interaction within the virtual environment. Examples of such interactions include changing the position of any object, rotating an object, or even having the ability to change the behavior of an object (Halarnkar et al., 2012; Romli & Yaakob, 2017). The purpose of this research was specially to concentrate on the capability of learning in terms of spatial awareness. It means the use of the component, such as object selection and manipulation, is essential because the user will be able to interact with the object by changing or rotating virtual objects in order to get a better view or perspective, and they will also be able to understand the attributes of the object.

Sensory feedback: The sensory feedback received by the human nervous system from the visual, vestibular, and somatosensory systems was used to produce an internal schema of the individual's orientation and movement of the body, which of course is connected to the external environment. This indicates that each of the sensory modalities contributes a unique set of sensory information that can be incorporated into the internal schemas. In addition, this sensory feedback can be generated in a number of different forms, including haptic feedback, audio feedback, and visual feedback. It means that the determination of the type of sensory feedback given to the user depends on the haptic device that is being used to interact. This is due to the fact that the majority of researchers believe that haptic devices are responsible for haptic response and interaction (Eck & Sandor, 2013; Orozco & El Saddik, 2008). According to the findings of this study, there is significant untapped potential in the use of tactile sensory as haptic feedback in a non-immersive environment.

Knowledge transfer and instructional elements: Romli and Yaakob (2017) mentioned in their framework that the instructional element as an educational component is one of the foundations for their development. This can provide a huge platform for either the developer or the user themselves to select the appropriate learning style and aspects for the knowledge transfer. When developing an application for autistic people who need to improve and gain knowledge in terms of spatial information, a developer should take into consideration the major two components that the researcher highlighted in his framework (Cho, 2017b). Spatial ability and visual cognitive style are two of these components. The use of a spatial ability component as one of the components will, in essence, improve the user's ability to spatially visualise, mentally rotate, and perceive their surroundings, particularly with regard to comprehending the relationships and attributes of any objects that are present in their surroundings. According to what researchers describe in their framework, this component can be classified into two categories: the static and the dynamic (Buckley & Seery, 2016). The need for understanding both static and dynamic spatial information improves or has an impact on autistic people when they acquire spatial information. For the development of any HBVE application that is related to autistic people, even components such as allocentric and egocentric should be considered. This is because, due to its simplicity, it can help autistic people understand and explore the relationship between object and object, as well as the relationship between self and object. The use of both allocentric and egocentric as components of the spatial coding system in this research has the potential to significantly improve the processing of spatial knowledge and has the potential to make it easier for autistic individuals to make navigational decisions while navigating in a virtual environment.

3.7 Summary

This chapter addressed the existing frameworks based on autistic people, HBVE, spatial learning, and cognitive mapping. There were a number of components relevant to this research domain that were identified during the course of this review section and Chapter 2. All of the components identified from the frameworks were classified based on their similarities, and those recognised relevant components were defined and arranged as main and subcomponents. Finally, all relevant components for the HBVE-Framework development were recognised, which will be covered in Chapter 5.

CHAPTER 4: AUTONOMOUS HAPTIC SPATIAL ORIENT-NAVIGATE ALGORITHM AS A CHANNEL OF FRAMEWORK

This chapter proposes an effective autonomous algorithm based on haptic and spatial orientation for autistic people to control their movement during navigation in virtual environments by performing activities like reaching the target and avoiding obstacles. The purpose of this chapter is to examine the elements that are associated with the proposed algorithm and demonstrate how the proposed algorithm was developed. Furthermore, as a navigation supporting element, this proposed algorithm will be treated as one of the subcomponents under the "Wayfinding" main component.

4.1 Introduction of the Proposed Autonomous Algorithm

In terms of spatial learning, the haptic-based virtual environment (HBVE) provides better opportunities for training and education, especially for autistic people. HBVE can immerse autistic people in a virtual world through navigation to educate them to understand and be aware of their surroundings by knowing the spatial attributes and objects. However, novice users, especially autistic people, face difficulties in terms of navigation and orientation in HBVE (Bozgeyikli et al., 2016). Two factors that lead to autistic people experiencing difficulty in terms of navigation in virtual environments (VE). First, the users face difficulties in terms of sensory acquisition in VE, where in the real environment, many signals can provide information about the position of the object (Ahmadpoor & Shahab, 2019; Battaglia et al., 2011; K.-E. Jung et al., 2006; Riederer et al., 2014). In terms of implicit feedback sensors, many users do not fully explore with available signals during navigation in VE and this shows poor performance with poor sensitivity, while the other groups of novice users shows that with explicit feedback sensors, the users show good improvements in terms of navigation and interaction in the virtual environment (Che et al., 2020; Leonard & Villeneuve, 2019). This shows that explicit feedback sensors, such as haptic sensors, provide better dynamic interaction and navigation for autistic people in VE when compared with passive navigation. Meanwhile, the second issue is the inability of autistic people to understand their surroundings when they need to visit a new and unfamiliar environment due to their impairment in the formation of mental maps of such a new and unfamiliar environment (Ahmadpoor & Shahab, 2019; Carpenter et al., 2002; Melanie Ring et al., 2018; Smith, 2015). Studies also found that many autistic people do not explore independently in real environments (Sophie E Lind et al., 2013; Parsons & Mitchell, 2002). Mental map formation is the process of accumulating spatial knowledge by allowing an individual to visualise objects in their surroundings and understand the relationship between the objects or landmadrks (Behrens et al., 2018; Johns, 2003; Ramloll & Mowat, 2001). Generally, mental map formation is done to stimulate spatial awareness through learning through repeated visits to a new environment (Bertone et al., 2005b; Pearson et al., 2014). Although a number of studies have been conducted by using assistive technology for formation or mental mapping while visiting a new environment, no specific solution has been provided for autistic people as per the investigation and knowledge obtainable (S. E. Lind et al., 2014; Qiu et al., 2020; Melanie Ring et al., 2018; Smith, 2015). Therefore, the use of haptic technologies has become the most promising technology, especially for autistic people, since it provides the user with sensation through force or tactile feedback during interaction with their surroundings (Changeon et al., 2012; Pérusseau-Lambert, 2016; Tang, P. McMahan, et al., 2014; H. Zhao et al., 2017). One of the core objectives in the field of haptic technologies in the development of VE is to provide better navigation and interaction support for end-users (De Boeck et al., 2005; G. S. Ruthenbeck et al., 2016). Autonomous navigation in a VE needs to be fortified with a suitable haptic interface to achieve the objective (Lv et al., 2018; K. Salisbury et al., 2004b; Vaucelle et al., 2009). The haptic interface is supposed to have haptic-based navigation algorithms in order for the users to be able to move from one destination to another destination while avoiding obstacles and also be able to move towards a desired targeted location without getting lost during the navigation (Kagawa et al., 2014; Megalingam et al., 2018). Therefore, in this research, a haptic spatial orient-navigate (AHSON) algorithm was introduced, and this algorithm is referred to as an automatic algorithm, which should be able to move independently and acquire spatial knowledge by identifying objects, landmarks, and obstacles in HBVE with the haptic sensors. Therefore, this proposed algorithm uses haptic interface-based Inertial Measurement Unit (IMU) sensors as part of interaction and navigation support for autistic people in virtual environments. An IMU is an explicit type of haptic sensor that is used to measure the orientation of the body based on the combination of accelerometers and gyroscopes (Ahmad et al., 2013; Choi et al., 2017; Hamza-Lup et al., 2019; Megalingam et al., 2018; Suzuki et al., 2018). The IMUs are usually incorporated into a haptic interface or device that is used to measure the angular rate, velocity, and position of the current movement based on the raw IMU measurements (Ahmad et al., 2013; Megalingam et al., 2018; G. S. Ruthenbeck et al., 2016). That means, with this IMU sensor data, it allows tracking of current user orientation and can also become a part of navigational support for users in virtual environments (Andreasen et al., 2019; Darken & Peterson, 2014; Iwamoto et al., 2020). In navigational applications, the IMU data is used to calculate the angular position based on a gyroscope, while accelerometers are used to estimate the attitude and velocity of the navigation by the user in a VE (Ahmad et al., 2013). Also, it will combine with landmarks or objects' attributes data as a cognitive mental map to identify objects or landmarks to reach their desired location (or simply classified as moving from one location to another location) in a virtual environment with a sensation (Cliburn et al., 2007; Norgate & Ormerod, 2012; Youngstrom & Strowbridge, 2012).

4.2 Related Work

The demands for assistive navigation technology in virtual reality development are growing, especially for autistic people spectrum disorder (ASD) who lack spatial knowledge. The assistive navigation technology in VE can be used for gaining spatial knowledge such as auditory cues (Dodiya & Alexandrov, 2008), dynamic landmark placement (Cliburn et al., 2007), cognitive maps (Johns, 2003), cognitive web browsers (Ramloll & Mowat, 2001), and haptic sensor systems (Lahav & Mioduser, 2008). The introduction of a haptic sensor system in a VE for navigation purposes can reduce the loss of direction or route for a user, and this can be implemented through various types of sensors like compass, LIDAR, and IMU (inertial measurement units). However, the introduction of haptic sensor-based autonomous navigation algorithms for indoor environments was not specially developed for people with disabilities (Kagawa et al., 2014). The authors also proposed an autonomous navigation algorithm based on localization, which shows the current location and direction of the user by using a compass sensor (Kagawa et al., 2014). This proposed algorithm calculates the number of steps and gets the direction by compass to reach the desired destination. Meanwhile, in the research paper (Megalingam et al., 2018), the authors used the SLAM algorithm with Hokuyo laser scan sensor data as an autonomous system to navigate in an indoor environment, and this was also done by the authors (Voisan et al., 2015) in their development, where the authors used the agmapping algorithm to find the direction with the laser scan data processed from a LIDAR sensor. Despite the fact that there has been a focus on various types of sensory systems for navigation purposes, there is a need for low-cost sensors, such as electromyographic EMG electrodes and 9-axis IMU sensors from the Myo Armband device, with a strong navigation algorithm that can assist autistic people to find the route or direction in a virtual environment without losing their direction (Jafari et al., 2016; Sathiyanarayanan & Rajan, 2016). This IMU sensor from the Myo

Armband device is able to produce data based on 3-axes gyroscope, 3-axes acceleration, and 3-axes magnetometer, which can be used to find accurate positioning in a virtual environment (Krishnan et al., 2017; Sathiyanarayanan & Rajan, 2016).

4.3 The Haptic Spatial Orient-Navigate Algorithm

The autonomous haptic spatial orient-navigate (AHSON) algorithm can be defined as "by using haptic sensors and the mapping objects or landmarks' attributes by the relationship, recognising directions with an understanding of the surroundings and moving towards the desired end point while avoiding obstacles." Besides, for the implementation of the understanding of the users' spatial orientation, the most important aspect is the haptic sensors, which lead to the loss of the sensors during navigation. For this reason, the implementation of this algorithm is based on the spatial orientation towards the desired end point using mapping methods as well, which are responsible for the retention of navigation and manipulation of spatial information. Figure 4.1 shows the proposed pseudocode of the autonomous haptic spatial orient-navigate algorithm. The proposed algorithm consists of four actions / procedures, and these will be explained in more detail in the following sections 4.4 and onwards:

- Detection of haptic sensor
- Obstacle and detection and avoidance
- Object or landmark detection via haptic sensor by verify based on the attribute's details collected from objects or landmarks
- Reach to targeted object or landmark with create haptic feedback (vibration) towards autism

In addition to the basic action of this proposed algorithm, this proposed algorithm also has three complex actions to consider:

- Able to navigate towards the target
- Able to move around the obstacle
- Able to change orientation according to movement

Also, there are three well-defined environmental situations:

- The target can be seen.
- There has an obstacle in front of the autistic people user while navigating.
- The landmarks in a virtual environment can be seen.

Algorithm 1: Haptic Spatial Orient-Navigate Algorithm

Input : x, y = center point axis coordinates; x, y, z = axis coordinates/directions/positions; cw = clockwise; acw = anticlockwise; Δ = distance between autism and obstacle; d_t = distance between autism and target; f = accelerometer; a = focus point (axis coordinates); ϕ = roll; e = ellipse; c = distance of creation of ellipse between centre point and focus point (haptically extending the ellipse vertically); b = distance of creation of ellipse between centre point and focus point (haptically extending the ellipse horizontally);Xω = that allow the calculation of the vibration; Fω = input force (amplitude/ frequency);Hω = frequency response (mass/stiffness); ObjL = next targeted object; tObjL = desired targeted object

Output: asd = autism spectrum disorder/autistic people/autism; ω = gyroscope; f = accelerometer; o = orientation; $obst$ = obstacle; ObjL = next desired targeted object e = ellipse

//Initialization values;

foreach $asd \in S$ **do**
  Initialize asd ← (x,y); ω ← x,y,z; f ← x,y,z; o ← x,y,z;
end
//Perform haptic sensor (IMU) detection
while $(0.001 \leq \omega, f, o \leq 0.001)$ **do**
  asd → stop
  if $-0.001 > \omega, f, o > 0.001$ **then**
    asd → calibrate;
    //Perform obstacle detection and avoidance by autism
  end
  if $obst = \Delta$ **then**
    asd = cw OR acw ← asd-asd_{obst};
    else if $obst = d_t$ **then**
      asd = mf ← asd-asd_t
  end
  //Perform object landmark detection thru haptic sensors
  if $asd = f > a \cos \phi$ **then**
    ObjL = e < 1 ← c;
    else if $asd = f > b \sin \phi$ **then**
      ObjL = e < 1 ← c;
  end
  //Reach to targeted object landmark with create haptic vibration feedback towards autism
  if $asd = tObjL$ **then**
    asd←$X_\omega = F_\omega$ x H_ω
    else if $asd = tObjL$ **then**
      asd←ObjL
  end
end

Figure 4.1: Shows the proposed pseudocode of the autonomous of haptic spatial orient-navigate algorithm

4.4 Haptic Sensor Recognition for Autism Spatial Orientation and Navigation Using Landmark Mapping Method

As it was already presented in the pseudocode of the autonomous haptic spatial orient-navigate (AHSON) algorithm, Figure 4.2 shows the process of how the navigation of autistic people occurs through the landmark mapping method with the assistance of their spatial orientation and haptic sensors. This process shows, each of the Obj_{object} (landmark) stores information about the next Obj_{object} (landmark) associated, and also in which direction the autistic people user must navigate.

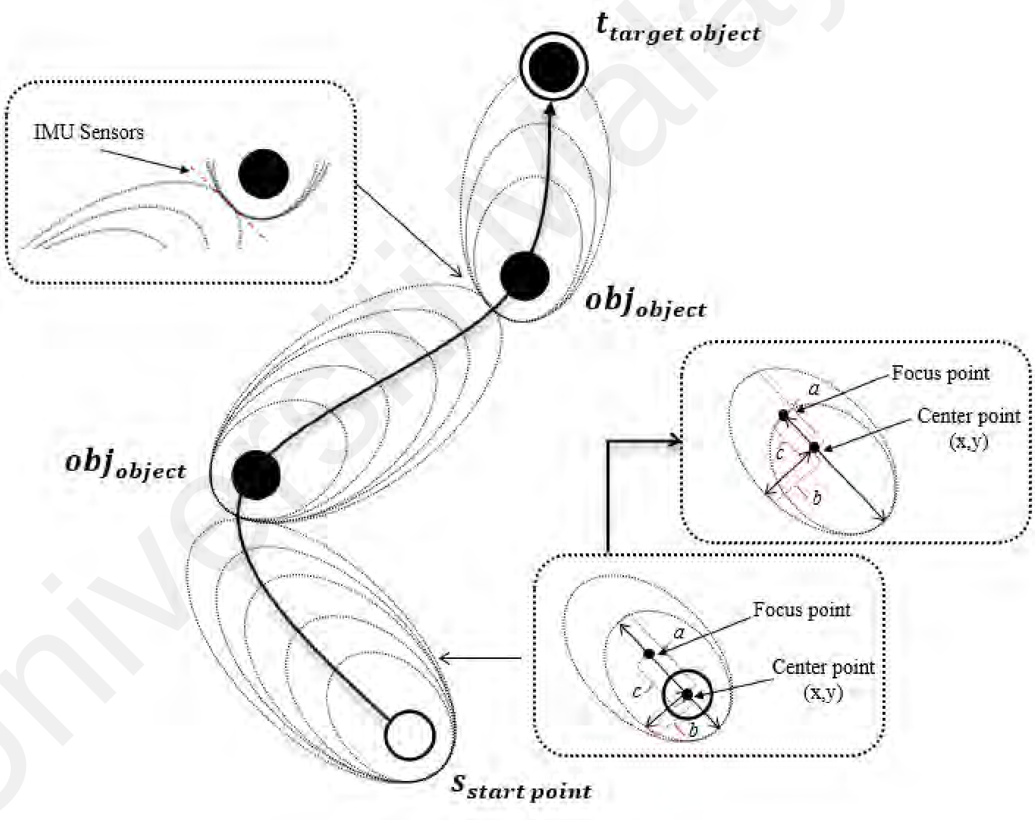


Figure 4.2: Shows the process of navigation of autistic people

The following sub-sections explain the process of haptic sensor recognition and navigation in a virtual environment.

4.4.1 Haptic (Vibrotactile) Sensor Detection and Tracking for Orientation Estimation

Based on Figure 4.3, the following sub-section explains the process involved in the detection of haptic sensors through IMU signals and how autistic people are able to recognise and understand their self-awareness and spatial awareness in a new virtual environment:

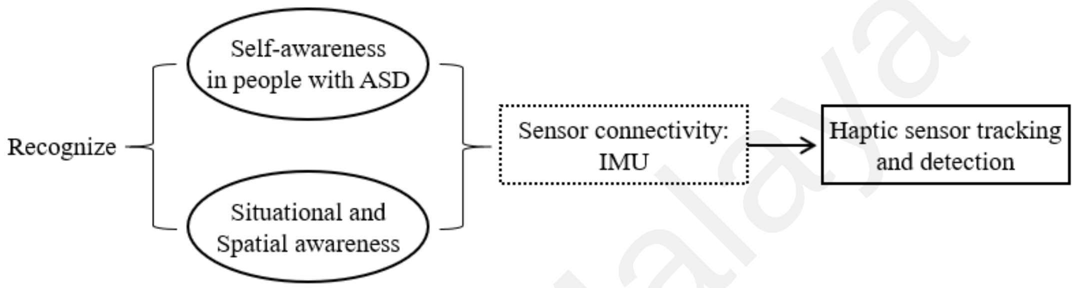


Figure 4.3: Shows the overview of the haptic sensor detection and tracking for orientation estimation

4.4.1.1 Recognition of Self-Awareness in Autistic people

Self-awareness is defined as the ability of a person to recognise themselves as separate from the environment while being aware of their own sensations, perceptions, and behaviors (Feize & Faver, 2019; Morin, 2011). Autistic people mainly refer to a person who has impairments in sensory dysfunction and repetitive behaviors (Hazen et al., 2014; Hodges et al., 2020; Manning-Courtney et al., 2013; Schauder & Bennetto, 2016). Due to these ordinary conditionals, self-awareness can become a unique experience for autistic people. For example, when interacting with any physical objects in their surroundings, they may be unaware of and feel their own sensual. They may have difficulties understanding their surroundings and the relationship between the physical objects, to describe the contrasts between their self or others preferences in common conditions, to involving their self-behaviors to others' actions or environments, and also to understand self and others' feelings (Cheng et al., 2010; Lal & Shahane, 2011).

4.4.1.2 Recognize of Spatial Awareness

Situational awareness refers to a person's ability to know what's happening around them and react when necessary (Koskinen-Kannisto, 2013; Vieweg, 2012). A component of situational awareness can be divided into three categories: perception (where a person can achieve situational awareness through situation assessment using the perception method); comprehension (which refers to the understanding of the situational assessment); and projection (which refers to the person's understanding of how the situation is likely to develop). Situational awareness is an important aspect of decision making in different situations, especially during navigation in virtual environments to recognise and understand the surroundings. Meanwhile, spatial awareness is the ability of the person to understand their environment, and the ability of the person to understand their individual relationships between the objects in their surroundings (Carmichael et al., 2012; Hollett et al., 2016; Stevens-Smith & Dance, 2004; R. Yang et al., 2011). Apart from this, spatial awareness also refers to understanding of the person in terms of the relationship between two objects when a change in position (orientation) has occurred. Spatial awareness allows the person to visualise the objects or locations from different angles and recognise them through the haptic sensor, which is able to process and provide information about the position (orientation data) of the personal interaction and movement and also the details of the object's surface, such as stiffness (de Jesus Oliveira et al., 2017; Luo et al., 2017).

4.4.1.3 Sensor Estimation from Inertial Measurement Units (IMU)

Inertial measurement refers to the combination of accelerometer and gyroscope units (Ahmad et al., 2013; Y.-S. Lee et al., 2015). The accelerometer is used to measure the sensor's angular velocity and its impact on the sensor's orientation (Ahmad et al., 2013; Y.-S. Lee et al., 2015). Meanwhile, the gyroscope is used to measure the specific force acting on the sensor, and this process gives the facts about the orientation of the sensor (Ahmad et al., 2013; Y.-S. Lee et al., 2015). Therefore, this proposed algorithm is intended to use *inertial measurement units* (IMUs) as inertial sensors to estimate the position and orientation of autistic people as users and control the navigation of the user autonomously through the haptic device. For inertial sensors, the estimations of the sensor's position and orientation are fundamentally connected to each other, and this process is defined as "dead reckoning" (refer to Figure 4.4).

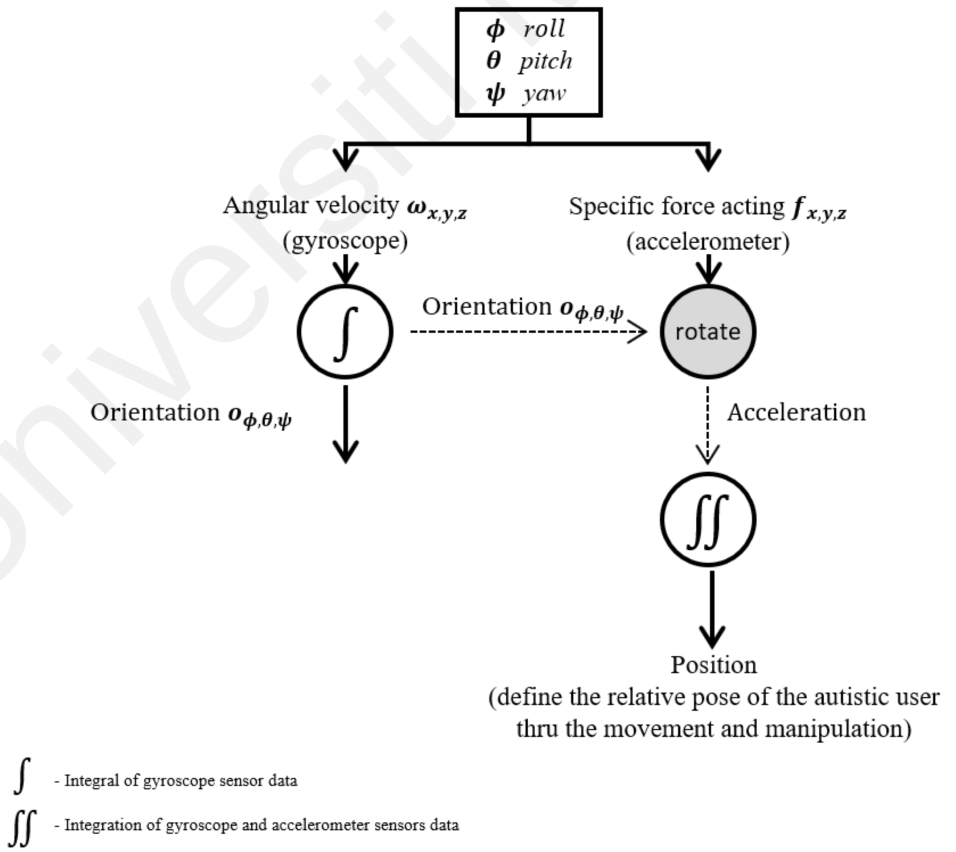


Figure 4.4: The flowchart of dead-reckoning of the haptic sensors' detection through the integration of the accelerometer and gyroscope sensors' data measurements define the user position and orientation for autistic people

4.4.1.4 Formulation of the Orientation Estimation by IMU Sensor

The estimation of the orientation can be defined based on Euler angles: roll ($\boldsymbol{\phi}$), pitch ($\boldsymbol{\theta}$), and yaw ($\boldsymbol{\psi}$) which provide the initial attitude of a rotating data ($\boldsymbol{\omega}_{gyroscope}$) and specific force acting data ($\boldsymbol{f}_{accelerometer}$) (Castro-Toscano et al., 2017; Kang & Park, 2009). The $\boldsymbol{\omega}$ (gyroscope data) with components ($\boldsymbol{\omega}_x$, $\boldsymbol{\omega}_y$, $\boldsymbol{\omega}_z$) can be classified as the rotation rate of angular velocity, while orientation ($\boldsymbol{\phi}, \boldsymbol{\theta}, \boldsymbol{\psi}$) is classified as a product of the Euler angles (Castro-Toscano et al., 2017; Kang & Park, 2009). Therefore, the orientation estimation can be integrated through the orientation ($\boldsymbol{\phi}, \boldsymbol{\theta}, \boldsymbol{\psi}$) from gyroscope measurement ($\boldsymbol{\omega}_x$, $\boldsymbol{\omega}_y$, $\boldsymbol{\omega}_z$). The three-axis gyroscope data presented is based on the products of Euler angles as

$$\boldsymbol{\omega} \text{ (angular velocity vector)} == (\boldsymbol{\omega}_x, \boldsymbol{\omega}_y, \boldsymbol{\omega}_z)$$

$$\text{3 axis gyroscopes} \longrightarrow \int \xrightarrow{(\boldsymbol{\phi}_{gyro}, \boldsymbol{\theta}_{gyro}, \boldsymbol{\psi}_{gyro})}$$

Meanwhile, it will calculate roll ($\boldsymbol{\phi}$) and pitch ($\boldsymbol{\theta}$) as input data of the gyroscope and integrate them with $\boldsymbol{f}$ which represents the accelerometer data with components ($\boldsymbol{f}_x$, $\boldsymbol{f}_y$, $\boldsymbol{f}_z$)(Castro-Toscano et al., 2017; Kang & Park, 2009). The three-axis accelerometer data is presented based on the products of Euler angles as

$$\boldsymbol{f} \text{ (acceleration vector)} = (\boldsymbol{f}_x, \boldsymbol{f}_y, \boldsymbol{f}_z)$$

$$\text{3 axis accelerometers} \longrightarrow f\tan\left[\frac{f_y}{\sqrt{f_x^2+f_z^2}}\right] \xrightarrow{(\boldsymbol{\phi}_{acc})}$$

$$f\tan\left[\frac{f_x}{\sqrt{f_y^2+f_y^2}}\right] \xrightarrow{(\boldsymbol{\theta}_{acc})}$$

4.4.1.5 Haptic Sensor Detection and Tracking

A haptic-based IMU sensor has unique sensors that are integrated to detect and track (automatically) the navigation of an autistic people in a virtual environment (Ahmad et al., 2013; Nair et al., 2018; Ruiz et al., 2011). This type of one-of-a-kind sensor is used to provide orientation and position information so that autistic people can interact and avoid obstacles while navigating virtual environments. Therefore, at this stage of the process, the IMU sensor can provide the accurate orientation data to determine and track the appropriate attitudes (Ahmad et al., 2013; Nair et al., 2018; Ruiz et al., 2011). When navigating in a virtual environment, it's important to have the direction and position of the autistic people towards the objects. Navigating in a slightly wrong direction may put the navigator on the wrong path, which enables him or her to fail to reach the desired target objects (McMahon et al., 2015; Moreno et al., 2019; Moya et al., 2013; Smith, 2015; Urmson et al., 2008). Thus, the IMU sensor is able to detect and track (automatically) the orientation and position changes accurately. As seen in Figure 4.2, the IMU sensor is used to track and detect the position of the autistic user and continuously create an eclipse until they reach the targeted object or landmark.

4.4.2 Object or Landmark Detection and Obstacle Avoidance

In HBVE, the user must avoid obstacles in order to reach the targeted point (G. Lee & Chwa, 2018). The users need to move to the target point using ***t*** from a vibrotactile sensor, but the movement of the users depends on the locations of the target point and the obstacles as well (Lobo et al., 2019; Nair et al., 2018). Thus, users should be able to move in the opposite direction around its boundary by avoiding the obstacle (G. Lee & Chwa, 2018; Nair et al., 2018). This vibrotactile sensor always maintains the distance (***d***) between the autistic people user and the obstacle via moving around the boundary in two different directions either in: clockwise (***cw***) or anticlockwise (***acw***), and this have shown in Figure 4.5.

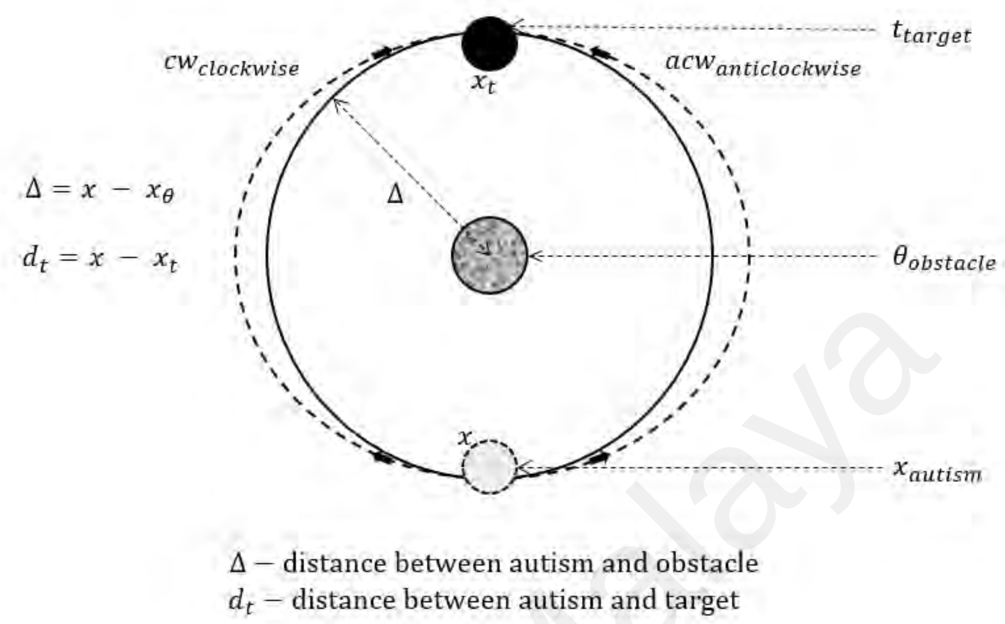


Figure 4.5: Illustration of obstacle avoidance during navigation

4.4.3 Landmark Identification and Navigation via Haptic Sensor

With the continuous haptic sensor detection by autistic users, it enables us to measure the total accelerometer (*f*) applied during the navigation (Iwamoto et al., 2020; Kang & Park, 2009). This total accelerometer verification is based on the following condition: If the total accelerometer detection level is above the focus point, then a new ellipse will be created in both x and y directions from the centre point to detect the targeted object or landmarks.

4.4.4 The Process of Generate Vibration Feedback towards Autism

This process provides a user with vibration as haptic feedback once they reach the targeted object or landmark. The haptic devices will generate a custom vibration as haptic feedback towards users (Dangxiao et al., 2019; Ozioko et al., 2020; C. Salisbury et al., 2009). Furthermore, this process continuously seeks the next target object or landmark.

4.4.5 The Validation of Proposed Algorithm

The validation of the proposed algorithm will be conducted through experimental evaluation in chapter 6, section 6.3, with a focus on these three different aspects: (1) study the overall performance of autistic people participants in terms of wayfinding with and without the AHSON algorithm as assistance, (2) investigate the effectiveness of the AHSON algorithm based on signals generated, and (3) the comparison of the parameters between four different navigation algorithms including the AHSON algorithm. At the conclusion of the evaluation, the overall effectiveness and limitations of the proposed algorithm, as well as future directions, will be discussed.

4.5 Discussion

It is essential for some autistic people to have the ongoing support of their parents or caregiver in the real world, especially when moving from one location to another or looking for any object (Klintwall et al., 2011; D. Li et al., 2019; Qiu et al., 2020). This continuous support cannot be a permanent solution, nor can it determine an individual's capacity for travelling or moving alone in challenging circumstances (Qiu et al., 2020; Melanie Ring et al., 2018; Urmson et al., 2008). Even if a parent or caregiver makes the decision to provide autistic people with training in real-world settings, this may still raise concerns about the autistic individuals' physical safety (Cliburn et al., 2007; Difede & Hoffman, 2002; D. Li et al., 2019). As a result, it is critical or something to consider using virtual environments as learning environments in order for them to become familiar with the process of locating their location, especially in unfamiliar environments (Bliss et al., 1997; S. Y. Chung & H. J. Yoon, 2011; Difede & Hoffman, 2002; Manju et al., 2017; Parsons & Mitchell, 2002; Ramloll & Mowat, 2001; Strickland, 1996; Tatale et al., 2019; Waller et al., 1998; Witmer et al., 1996). However, the findings of this study indicate that autistic people face two challenges when attempting to practice in virtual environments. The first of these challenges is the user's inability to acquire information about the position of a desired location or object through sensory acquisition in a virtual environment (Ahmadpoor & Shahab, 2019; Battaglia et al., 2011; Bozgeyikli et al., 2016; Harrison & Hare, 2004; K.-E. Jung et al., 2006; Lahav & Mioduser, 2008; O'Riordan & Passetti, 2006; Riederer et al., 2014). The second challenge is autistic people's inability to understand their surroundings, particularly when they are in an unfamiliar environment, due to an impairment in their ability to form mental maps (Amon et al., 2018; Carpenter et al., 2002; Melanie Ring et al., 2018; Smith, 2015). Therefore, this research came up with the idea of an autonomous navigation support algorithm that makes use of haptic technology as a haptic sensor provider in order to solve the problem that was mentioned previously. The autonomous algorithm that has been proposed is designed on the basis of its function of assisting users in moving from one location to another while avoiding obstacles and moving towards a desired target location without getting lost while navigating. This proposed algorithm was developed with four different procedures: the detection of haptic sensors, the detection of obstacles and avoidance, the detection of objects or landmarks using haptic sensors, and finally the reaching of the targeted object or landmark using haptic feedback. The detection provided by haptic sensors is utilised in order to formulate an estimate of the user's orientation within a virtual environment (Battaglia et al., 2011; Díaz et al., 2006a). Despite the fact that the majority of research has been developed and investigated with different types of sensors, the IMU is one of the types of sensors that can provide accurate sensor orientation and position for autistic people through the use of accelerometers and gyroscopes (Bouyer et al., 2017; Hamza-Lup et al., 2019; Jia et al., 2013; Pfeiffer & Rohs, 2017; G. S. Ruthenbeck et al., 2016). This orientation data, which can be defined as Euler angles, consists of roll, pitch, and yaw; meanwhile, gyroscope, which can be classified as the rate of rotation of an angular velocity (Castro-Toscano et al., 2017; Kang & Park, 2009). The orientation of autistic people can be estimated using these two measurements (Euler angles and gyroscope) when integrated together (Kang & Park, 2009). In addition, the recognition of self-awareness, which is defined as a person's ability to recognise themselves as separate from their environment while being aware of their own sensations and behaviours, may make it difficult for autistic people to understand their surroundings or the relationship between the objects in their environment (Feize & Faver, 2019; Morin, 2011). In the meantime, situational and spatial awareness refers to the capacity of autistic people to be aware of what is going on around them and to respond appropriately when necessary, as well as the significance of these abilities in terms of decision-making in a variety of situations (Koskinen-Kannisto, 2013; Vieweg, 2012). As the user is navigating or finding the route via the IMU sensor, the sensor is able to track and detect the position of the autistic user and continuously create an eclipse until they reach the targeted virtual object (Ahmad et al., 2013; Nair et al., 2018). The user needs to be capable of avoiding obstacles while navigating and interacting with virtual objects so that they can get to the object or landmark that they are aiming for (G. Lee & Chwa, 2018; Lobo et al., 2019). By employing haptic sensors, users are able to determine the total accelerometer force that was applied while navigating (Iwamoto et al., 2020; Ramos et al., 2019). In addition, once the user has reached the target object, the haptic device will provide them with haptic feedback in the form of a customised vibration (Dangxiao et al., 2019; Ozioko et al., 2020; C. Salisbury et al., 2009). As a result of the development of the autonomous algorithm that was proposed, the haptic sensor now possesses the capability to generate the IMU sensor and successfully perform its function of assisting the user in navigating within a virtual environment.

4.6 Summary

This section proposed an autonomous spatial navigation algorithm, and different methods have been carried out to validate this proposed algorithm, which will be discussed separately in chapter 6. Automatic navigation in a virtual environment is accomplished through the use of inertial measurement units (IMUs) and landmarks from the environment. The current node of a landmark or object in the virtual environment defines the next target position using an IMU sensor, allowing autistic people to navigate and reach the goal more easily. In the course of navigation and landmark detection, this algorithm also performs obstacle detection and avoidance, which is useful for preventing overlap. This algorithm also allows the haptic device to create haptic vibrations for autistic people when they come into contact with the targeted landmark or object, which is a useful feature. It is intended that this proposed algorithm be validated in the following chapters in order to ensure that it meets the main purpose of the study.

CHAPTER 5: STRUCTURING OF HAPTIC-BASED VIRTUAL ENVIRONMENT FRAMEWORK

The purpose of this chapter is to determine the components that are used in designing a haptic-based virtual environment (HBVE) for autistic people, which will be accomplished through spatial learning and cognitive mapping. This chapter's research is based on four elements: a thorough examination of the existing haptic-based virtual environment framework (HBVE-Framework), an investigation of the interaction components of HBVE, an investigation of the spatial cognition ability, and an investigation of the relevant studies component for autistic people.

5.1 Introduction of the Proposed Framework

The design of a HBVE is essential for the development of any HBVE application, particularly for autistic people. Even though technology is growing faster in terms of facilitating autistic people to perform certain activities or tasks, when it comes to designing a HBVE application for autistic people, it is more challenging due to some special considerations such as adoption and familiarisation in a virtual environment as well as differences in the deficiencies of autistic people. Thus, this research intends to propose a HBVE-Framework for researchers or developers to design a HBVE application, as well as to facilitate autistic people in understanding their spatial relationships through cognitive mapping skills. The components related to autistic people, spatial learning and cognitive mapping, and haptic technology were gathered through a literature review (chapter 2), existing HBVE-Frameworks (chapter 3), and the proposed autonomous algorithm as subcomponents. The following sections provide the details of the procedure conducted to recognize and organize the components accordingly.

5.2 Method

In order to achieve the objective of this research, it is necessary to establish the idea of a conceptual and technical framework, which will be used to develop the proposed framework. The conceptual (theoretical) framework is defined as explaining the major aspects to be analyzed and studied, such as the key factors, concepts, and the presumed interrelationship across them graphically (Miles, 1994). Meanwhile, the technical framework is described as having general functionalities that may be enhanced and changed by another type of user-written code, and it can also provide a conventional method for developing an application (Chou, 2003; Othlinghaus-Wulhorst & Hoppe, 2020). The proposed framework was developed in this study using existing theory and prior research, as well as existing software framework components, with the following motives:

(1) To address the existing frameworks that have been introduced for autistic people.

(2) To address the components used across the existing frameworks and the limitations of the existing frameworks.

(3) To address whether the existing frameworks are suitable for HBVE application designs for autistic people to learn and improve their spatial learning and cognitive mapping skills, and also highlight whether the existing framework needs to be improved by adding new components or whether a new framework should be recommended for autistic people to improve their spatial learning and cognitive mapping skills.

(4) To address the existing reusable software framework components by simply modifying the user-written codes or replacing them with new software system components.

Various development processes are used to develop the proposed HBVE-Framework, including the following:

(1) Recognizing the components that require integration into the framework.

(2) It is important to recognise the appropriate frame structure as a guideline for developing the proposed framework.

(3) Components are arranged in accordance with the accepted framework structure.

Implementing the first two processes is accomplished by the review of literature, and implementing the third process is accomplished using the outcomes of the first and second processes, which are used to arrange the components of the framework structure.

5.2.1 Recognize of Components

Systematic reviews (SLRs) and narrative reviews (NLRs) are the two types of literature reviews that are used to recognise the components, as shown in Figure 5.1. The recognition of relevant components for framework development is divided into four stages: (1) SLRs components, (2) NLRs components, (3) recognition of existing components based on NRLs, and (4) gathering all components for the proposed framework development. The arrow between each review source shows the relationship between each source as well as the continuous studies from one source to another. The literature review process takes place with the SLRs as the first stage on "Learning Modalities" and follows with the influence or impact on "Autism Behaviour and Capabilities". Simultaneously, NRLs on "Autism Behaviour and Capabilities" were performed to understand the additional influence and efficiency in the other four review sources ("Spatial Ability," "Spatial Knowledge," "Wayfinding Behaviour," and "Cognitive Mapping"). The review process is being extended to other NRLs in order to reccognize additional components involved in the design of this framework, particularly "environment" and components related to spatial learning, haptic technology, and virtual environments. Based on Figure 5.1, all the components that were recognised through the literature review are presented in Table 5.1, along with the objective and resource citations.

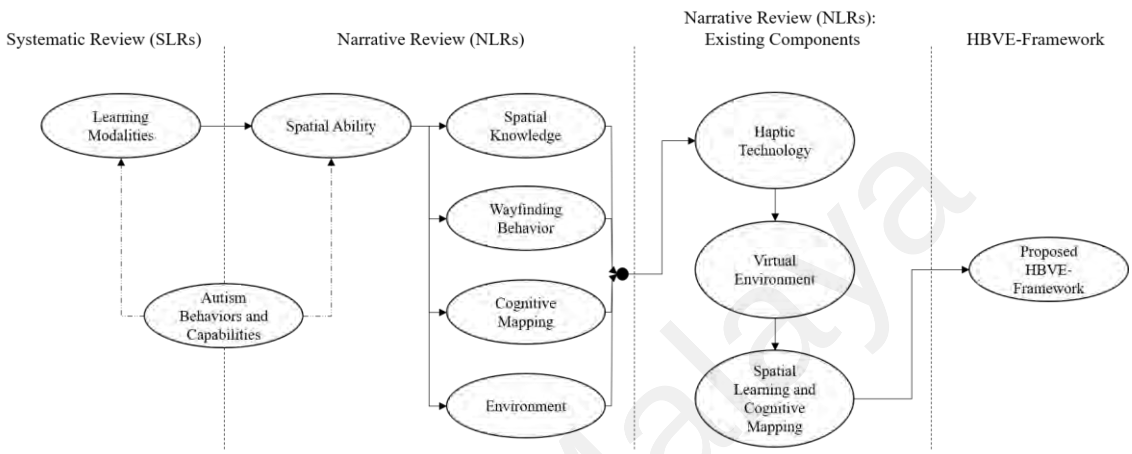


Figure 5.1: It indicates the different types of literature processes conducted to recognize relevant components for framework development

Table 5.1: The details of components, objective of the component and source citations

Component	Objective	Source Citation
Autism Behaviours and Capabilities	To understand the behaviours and capabilities of autistic people before designing a HBVE.	(Filipek et al., 2000)
Learning Modality	To interact with the virtual environment by providing, obtaining, and storing sensory information.	(S. Zhang et al., 2013)
Environment	To determine the concept of environment to be chosen to present as a real environment in a virtual environment.	(Leonard & Villeneuve, 2019)
Spatial Ability	To understand and recall the spatial relationships between objects or their surrounding environments.	(Sarmiento & Collazos, 2012)
Spatial Knowledge	It's a set of knowledge about the spatial relationships between objects in the virtual environment and how the individual can process the knowledge to find the direction in the virtual environment.	(Sarmiento & Collazos, 2012)
Wayfinding Behaviours	It's the process of finding the direction from one location to another location by improving an individual's understanding of their surrounding environment.	(Sarmiento & Collazos, 2012)
Cognitive Map	It is a process of mental demonstration by autistic people in order to acquire, code, store, recall, and decode any information from their spatial environment.	(S. Zhang et al., 2013)
Physical Haptic Interface	It is used as a platform for communicating between humans and machines by creating a sense of touch in response to user interactions and movements.	(MacLean, 2000)
Haptic Rendering	It is a computational model that used to process and converting haptic information such as force and tactile to a haptic interface	(K. Salisbury et al., 2004b)

	which able to send the haptic information as a sense of touch feedback to a user.	
Haptic Collision Detection	To determine whether the collision between the user through a haptic interface and the virtual object distance in the simulation engine has collided or not, and to implement collision prevention.	(Choi et al., 2017)
Haptic Feedback	It's a kind of feedback form, such as vibration or pressure patterns, to process and compile sensitive information for users' sense of touch.	(S. Y. Chung & H. Yoon, 2011)
Control Algorithm	To reduce the error between the future and relevance of haptic's tactile or forces, it's developed position sensors at the haptic interface intersections.	(K. Salisbury et al., 2004b)
Visual Rendering	To generating three-dimensional objects in real-time, which depends on the graphics card and with the assistance of a hardware accelerator for three-dimensional.	(K. Salisbury et al., 2004b)
Virtual Collision Detection	Focused on the simulation engine to detect collisions between objects and autistic people users in the virtual environment.	(Le et al., 2016)
Simulation Engine	To build the real-time virtual environment, this component includes all the valid sub-components to generate the pre-rendered virtual scene through haptic technology for the end-user interaction.	(Eck & Sandor, 2013)
Graphics Scene Activity	It's a process that integrates all the virtual three-dimensional models and graphics content together to allow users to interact and manipulate the virtual objects.	(Choi et al., 2017)
Spatial Processing Coding System	To sense and encode spatial information that is related to a location in a HBVE.	(Buckley & Seery, 2016)
Interaction and Manipulation	To perform a basic interaction in a specific objects' manipulation to achieve high-level tasks such as the spatial learning tasks.	(Sarmiento & Collazos, 2012)
Cognitive Map Navigation	To form a mental model or visualise objects by recalling and decoding information regarding the object attributes and location of the objects.	(S. Jul, 2002)
Wayfinding	To find their route to their desired location or objects based on novel routes, landmarks, directions, paths, or cognitive maps.	(S. Jul, 2002)
Rendering Content	For processing the information from controller and model components to display or create real-time immersion for users.	(Eck & Sandor, 2013)
Sensory Modality	As a feature of stimulation after engaging with the haptic interface, and also, this can be identified during interactions with their environment according to temperature, pressure, sound, light, and smell.	(Jia et al., 2013)
User Achievement	To view their achievements according to the benchmarks of the tasks in a HBVE.	(Choi et al., 2017)
Spatial Representation Information	To enable a user to visualise and imagine the spatial relationship between objects and their surroundings.	(Cho, 2017a)

5.2.2 Recognize of Framework Structure

In the review of existing frameworks, it was discovered that four of the existing frameworks have unique structures that are difficult to adapt to the new design and development of the framework. This is because they are only able to assist in the development of certain types of haptic applications that focus on more hypothetical aspects of haptic technology. The rest of the existing framework structure can be used to design and develop a new virtual environment framework. According to the remaining framework, the model, view, and control (MVC) pattern, which was proposed by (Ackermann, 1994), was used to design and develop the new proposed framework for this research study. This was done for two reasons:

(1) It is important to note that the application of the MVC pattern has a significant impact on the entire development of HBVE since the primary principle of this pattern is to identify the components at three separate stages. These three stages work independently to present the whole architecture of HBVE with clearly defined interfaces. Therefore, the developers are able to separate their implementation processes, which allows them to develop and maintain the HBVE with higher efficiency (D'Andrea et al., 2013; X. Zhang & Lu, 2012). Furthermore, any modifications made during the implementation of a component in the development of the HBVE, such as the use of a new haptic interface, have no effect on the overall structure of the HBVE or the implementation of the other components (Curry & Grace, 2008).

(2) It is even capable of lowering the cost of implementing HBVE components due to the availability of freely available libraries (D'Andrea et al., 2013). As an example, the Model pattern necessitates the simulation of a haptic hand metaphor from the real world in order to build an immersive virtual environment with a haptic interface.

Therefore, this study able to use the existing three-dimensional modelled hand metaphor product from the virtual engine, which allowed us to save a lot on development costs. Developers will be able to use real-time 3D-modelled objects and interact with them using the capabilities of a haptic interface.

5.2.3 Arrangement of Components in Framework Structure

In order to ensure proper synchronisation between the components and the framework structure, all of the components that were identified during the process described in section 5.2.1 were logically placed in the selected MVC pattern. The placement of each component in the MVC pattern is determined by the component's objective, which is discussed in section 5.2.1 of this document. Table 5.2 presents all of the logical components as well as the objective of each component's placement. The input to the controller is made up of seven different components (autistic behaviours and capabilities, learning modalities, environment, spatial ability, spatial knowledge, wayfinding behaviours, and cognitive map). Meanwhile, the controller is made up of five different components (physical haptic interface, haptic rendering, haptic collision detection, haptic feedback, and control algorithm). The model is comprised of eight different parts (visual rendering, visual collision detection, simulation engine, graphics scene activity, spatial processing coding system, interaction and manipulation, cognitive map navigation, and wayfinding). However, there are four components to the view (rendering content, sensory modality, user achievement, and spatial representation information).

Table 5.2: Placement of components in the MVC Pattern

Stage	Objective	Components
Input of Controller	To organize autism behaviors and spatial cognition knowledge and use it during haptic device handling.	autism behaviors and capabilities, learning modalities, environment, spatial ability, spatial knowledge, wayfinding behaviors, and cognitive map
Model	To process the input data (haptic data) and render it along with visual data.	visual rendering, visual collision detection, simulation engine, graphics scene activity, spatial processing coding system, interaction and manipulation, cognitive map navigation, wayfinding
View	To display sensory feedback within the virtual environment application.	rendering content, sensory modality user achievement, and spatial representation information.
Controller	To receiving input data and performing the related task or activity in the model as instructed by the haptic device.	Physical haptic interface, haptic rendering, haptic collision detection, haptic feedback, and control algorithm

5.3 Haptic Based Virtual Environment Framework

This section demonstrates the framework that contains the basic components that are important and required in the development of a HBVE. These components have been compiled and arranged in accordance with the MVC design pattern. This framework can also be divided into two types of components: primary components and secondary components. The main component is comprised of 24 components, while the subcomponents are comprised of 24 components, and this has been shown in Figure 5.2.

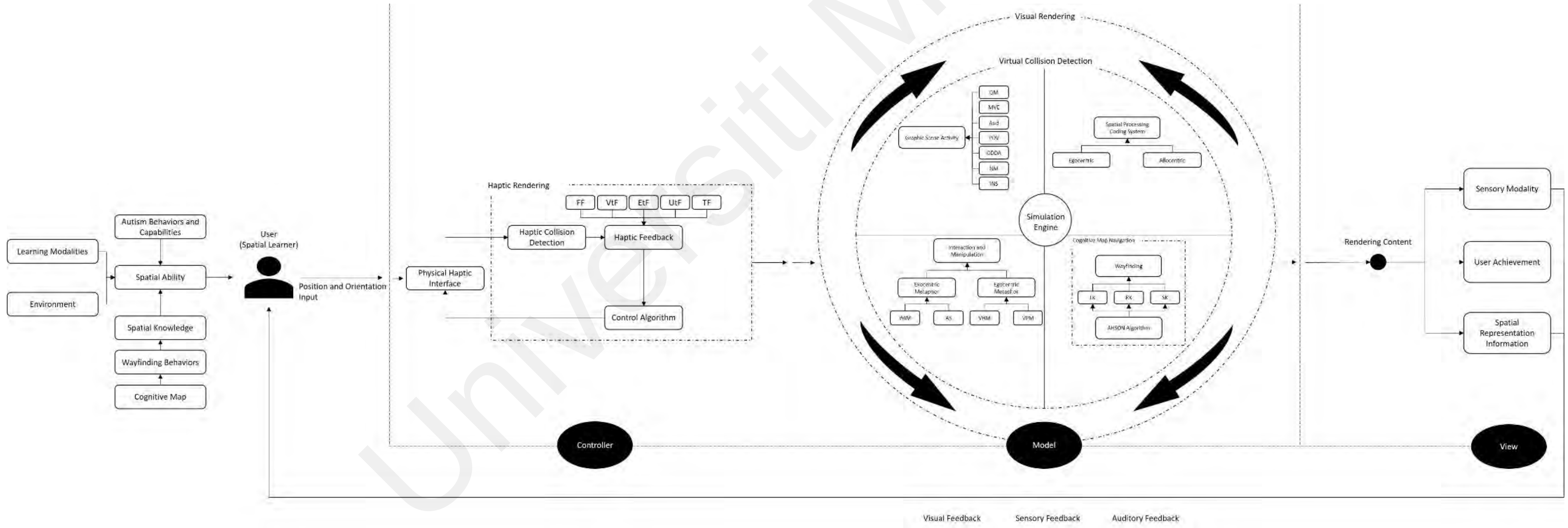


Figure 5.2: The Proposed Haptic-based virtual environment Framework for Autistic people

5.3.1 Input of Controller

The input of the controller is intended to process the data of spatial ability and cognitive ability of autistic people through the haptic modalities, while also identifying their communication behaviour and interaction capabilities in a non-immersive environment. These functions are used to allow the transmission of spatial ability information between autistic people and the haptic device (refer to Figure 5.3).

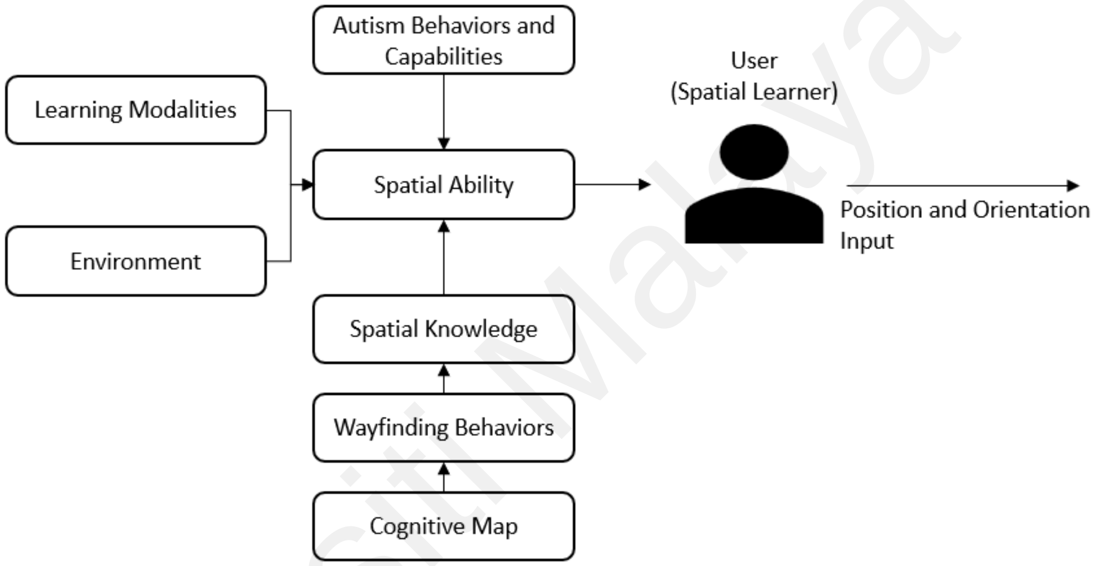


Figure 5.3: The Components of Input of Controller

5.3.1.1 Autism Behaviors and Capabilities

Repetitive patterns of behaviour in terms of communication with their social and environments, as well as a lack of abilities during interaction with their environment, are common in autistic people (Bearss et al., 2018). Before designing a HBVE for autistic people, it is critical to understand their behaviours. Furthermore, this behaviour component is capable of assisting by selecting the most appropriate learning modalities and spatial ability methods for the situation. In contrast, a capability in autistic people refers to the cognitive skills of the individual when interacting with the environment (Bos et al., 2019). A cognitive skill is meaningful to an individual who is able to create the thinking ability by obtaining, programming, accumulating, remembering, and interpreting information related to the location or attributes of the environment (Carpenter et al., 2002).

5.3.1.2 Learning Modalities

Learning modalities refer to sensory channels, which consist of four major modalities: tactile (touching), visual (seeing), kinesthetics (moving), and auditory (hearing). These four modalities enable an individual to interact with the environment through providing, obtaining, and storing information (Akamatsu et al., 1995; Moallem, 2007; O'Riordan & Passetti, 2006). However, while the characteristics of learning modalities may differ for each individual with ASD, an understanding of certain common features can help in the determination of which learning modalities are most appropriate for a particular individual (Klintwall et al., 2011; O'Riordan & Passetti, 2006). For this research, haptic modalities have been selected to understand the capabilities of autistic people in mastering the spatial learning and cognitive mapping skills.

5.3.1.3 Environment

The environment that will be used to represent the real-world scenario in a virtual environment has become an important consideration, particularly when designing a virtual environment for the purpose of training specific communities, such as autistic people, because the learning situation and practise skills will be different and varied from one another (Dalgarno, 2002; Luong et al., 2020; Stansfield et al., 1995; K. Zhang & Liu, 2016).

5.3.1.4 Spatial Ability

Spatial ability, also known as visuo-spatial ability, is the ability of an individual to understand and recall the spatial relationships between objects and their surrounding environment (Coxon et al., 2016; H. Lin, 2016; Y. Yang et al., 2014). Especially for autistic people, these types of abilities are widely used in their daily activities to solve a wide range of tasks, such as navigation and estimating distances between objects or from one location to another in an environment (Ramloll & Mowat, 2001; Youngstrom & Strowbridge, 2012). For instance, the use of directional clues as a guide for autistic people during navigation in a new environment. That means, during navigation, autistic people are able to mentally generate and transform a visual object that is surrounded in the new environment and try to understand and recall the relationship between the objects they imagine and the real-time environment. There are a few sub-components that are detectable, as per below in sub-sections:

(a) ***Spatial Knowledge***

Spatial knowledge in autistic people refers to the capability of the person to identify objects in their surroundings by pointing in the direction of the object and being able to move within the paths specified with the knowledge of the objects and their location (Wen et al., 2011). The spatial knowledge is coded based on the user's perception, visualisation, and imagination through their short-term sensory memory (Picinali et al., 2014; Wen et al., 2011). For better understanding, once the user has developed their spatial knowledge, the knowledge is organised in a way that is more logical to them for future benefits. Usually, spatial knowledge is organised into any form of recall in order to be recalled while the user navigates around the environment. Spatial knowledge can be classified into three types of methods: landmark knowledge, route knowledge, and survey knowledge (Wen et al., 2011).

(b) ***Wayfinding Behaviors***

In accordance with theoretical perception, wayfinding is classified as the process between two aspects: the cognitive skills of an individual and their surroundings, by determining and following a route between a starting point and desired locations (Khan & Kolay, 2017; Y. Yang et al., 2018). Wayfinding behaviour focuses on the influence of different levels of spatial knowledge that are processed and stored as the user navigates in the environment (Ramloll & Mowat, 2001; Vaez et al., 2016). Wayfinding may contribute to solving issues with getting lost during the navigation process. The success of wayfinding is dependent on the modalities that are used to interact. Wayfinding is directly accessible to the user's sensory system, and it is believed that this could be an influence on the wayfinding in an environment (Chang & Wang, 2010).

(c) ***Cognitve Map***

Cognitive mapping can be well-defined as a process of mental demonstration by autistic people in order to acquire, code, store, recall, and decode any information from their spatial environment in terms of relative location, attributes, or objects surrounding them (Johns, 2003; H. Zhang et al., 2014a). It is important for autistic people to have this knowledge skill to define and process their route or way in order to reach their desired target locations or objects.

5.3.2 Controller

The *Controller* serves as a platform for gathering feedback from the requests or actions of autistic people. This is used for controlling the HBVE application logic and acting as a mediator between the input of the *Controller*, *Model*, and *View*. In other words, the *Controller* receives an input (spatial ability-input of the controller) from the autistic people as users through the *View*, processes the input data with the support of the *Model*, and at the end is able to provide feedback to the autistic people users through the *View*. This phase has been explained in more detail with the following components as in sub-sections (refer to Figure 5.4).

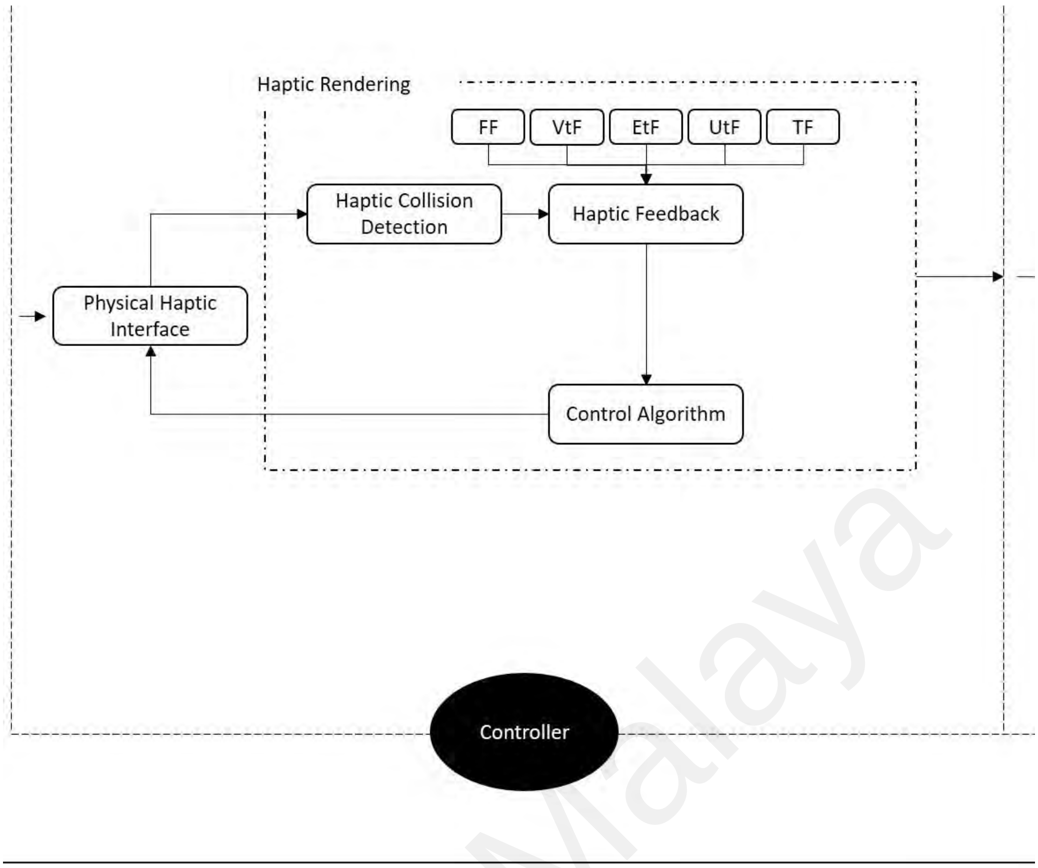


Figure 5.4: The Components of Controller

5.3.2.1 Physical Haptic Interface

The haptic interface (also known as the device) is used as a platform for communicating between humans and machines by creating a sense of touch in response to user interactions and movements (Jafari et al., 2016). The haptic interface is usually built or designed based on sensory and motor modules to detect and insert electrical signals into virtual environments based on interaction and manipulation. Meanwhile, electrical signals have been coded and transformed into meaningful information (action) by the virtual environment and also by the haptic interface, transferring signals in response to the user's muscles (Pfeiffer & Rohs, 2017). Tactile sensation and force (kinesthetic) sensations are the two common types of sensations that a haptic interface encompasses, and this will be discussed in more detail in the haptic feedback section

(Hamam et al., 2013b). Haptic interfaces are generally applied and implemented in a virtual environment for the user to interact with virtual objects.

5.3.2.2 Haptic Rendering

Haptic rendering is a computational model that is used to process and convert haptic information such as force and tactile information into a haptic interface that is able to send the haptic information as a sense of touch feedback to a user, and this can only be achieved by combining both hardware and software components in a virtual environment (Rüdel et al., 2018; Sagardia et al., 2015). Hardware limitations can prevent any haptic interface from implementing the actual force or tactile feedback that is measured as a haptic sensation to the user. This major component can be divided into three different typical components: haptic collision detection; haptic feedback; and control algorithm, which is required for the haptic interface to be able to render and provide haptic feedback to the users (Sagardia et al., 2015). These three typical components will be explained in more detail in the following section.

5.3.2.3 Haptic Collision Detection

Haptic collision detection is the process of algorithmically measuring and computing all the relevant collision information within a HBVE by detecting the intersection between two or more virtual objects and characters. The main objective of this component is to determine whether the collision between the user through a haptic interface and the virtual object distance in the simulation engine has collided or collision prevention (Díaz et al., 2006b). Haptic collision detection usually requires the concepts of linear algebra or computational geometry, and also includes a few different methods such as vector usage, plane detection, and physical simulators to solve the haptic collision detection issues (MacLean, 2000).

5.3.2.4 Haptic Feedback

Haptic feedback commonly applies to advanced feedback forms such as vibration or pressure patterns to process and compile sensitive information for users as a sense of touch. Haptic feedback provides two basic benefits to the user that can improve the user experience while interacting with virtual objects, and haptic feedback can also improve the user's performance, especially in the field of medicine to treat rehabilitation patients (Manju et al., 2017). This is achieved by using vibration patterns as haptic feedback, allowing the user to focus on the task at hand while controlling the hand movements in a virtual environment. Somatosensory system processes include haptic feedback information (vibration and pressure) to the brain as part of user interaction and action feedback (Y. Song et al., 2021).

(a) Force Feedback

Force feedback is the most studied haptic feedback in haptic technology. Muscles and ligaments are the two segments that define the force feedback into the human musculoskeletal system through the skin. Force feedback-based haptic devices are able to provide high sensitivity to impact and pressure on a large scale to the human body(Dennerlein & Yang, 2001). These kinds of haptic feedback devices are also able to give autistic people sufficient freedom of interaction and movement in a virtual environment, since force feedback devices enable the user to move in line with their body reactions (Bouyer et al., 2017; Pérusseau-Lambert, 2016). There are two types of force feedback devices that are currently used and studied widely: biomimetic and non-biometic devices. Biomimetic force feedback devices are designed based on human limb movement capability, and the variability of these devices varies for each user since they are ideally focused on the functionality of the user's body. Non-biomimetic force feedback devices are usually not focused on the user's body. Apart from this, force feedback appliances are classified into two categories: active force feedback devices and resistive force feedback devices. Active force feedback devices are limited to motor control (Dennerlein & Yang, 2001). Meanwhile, resistive force feedback devices limit the interaction and movements of autistic people with brake control assistance (Tsai et al., 2019).

(b) ***Vibrotactile Feedback***

In the field of haptic effective computing, the most widely explored haptic feedback is vibrotactile. The vibrotactile-based haptic interface mainly generates pressure to detect and define user skin receptors (C. Salisbury et al., 2009). Studies identified that skin receptors are able to receive and detect vibration, pressure up to 1000 hertz and 80 to 250 hertz, or the user's speech frequency, which makes the user's skin feel the sense of touch and sounds (Alahakone & Senanayake, 2009). Autistic people can easily control vibrotactile feedback, and it only requires a minimal level of tracking parameters; however, in terms of tactile sensitivity, vibrotactile feedback cannot provide the depth level of sensations required.

(c) ***Electrotactile Feedback***

Electrotactile feedback commonly shares the same features as vibrotactile feedback, but in addition, this type of feedback can affect the user's nerve system by producing electrical impulses. This means that by using electrotactile feedback based on a haptic device or interface, the person is able to feel and have the sense of virtual object texture (MacLean, 2000). The pattern and form of this haptic feedback to an individual's skin depends on the frequency and intensity of the haptic interface, and also the user's sensory sensitivity is influenced based on the electrode size, material, contact force, voltage, hydration, and the type of the person's skin. Because electrotactile feedback can generate a wide variety of patterns and forms of feedback, most current research trends are centred on electrotactile feedback as a haptic sensation for interaction and manipulation tasks in a virtual environment (Pamungkas & Ward, 2016; Vizcay et al., 2021). Furthermore, in terms of electrical impulses, electrotactile feedback can define and provide a wide range of tactile sensations compared to other types of haptic feedback. Electrical muscle stimulation (EMS) is one of the types of electrotactile feedback which is widely used in the field of medicine, especially for treating rehabilitation and cognitive impairments.

(d) ***Ultrasound Tactile Feedback***

Ultrasound tactile feedback is a type of haptic feedback based on the high frequency of sound waves. This type of haptic feedback depends on one or more emitters, which are centred in any one of the parts of the body to exchange and transfer the sensory signal between the body parts, and this concept is defined as acoustic time reversal (Jones & Tan, 2012). In order to develop and create the impact of feedback on a larger scale, it's required to have a field of haptic feedback and also require a combination of multiple emitters to form powerful haptic feedback. As a result, this can develop a haptic interface that is invisible to the user (Hasegawa & Shinoda, 2018; Rakkolainen et al., 2020). Autistic people can feel and have sensory sensitivity through their skin to the turbulence as haptic feedback generated by the ultrasound waves. This kind of haptic technology is the most preferable technology for this implementation since it does not require participants to wear any haptic accessories, but it's quite expensive and less perceptible when compared to the other two feedbacks (electrotactile and vibrotactile feedback).

(e) ***Thermal Feedback***

Thermal feedback is classified as highly sensory towards autistic people since it requires direct contact with the person's skin. This thermal feedback is formed based on the grid of actuators. Thermal feedback devices are easy to design and can also be easily used compared with other haptic feedback devices (vibrotactile and ultrasound tactile) for two reasons: this kind of feedback does not require a larger scale of actuators to design and develop temperature (heat) feedback, and each actuator does not require to be located or centred very close to each other actuator in the grid (Fleury et al., 2020; Giri et al., 2021). Furthermore, this haptic feedback is only able to be migrated from one location to another location, and this should be completed as fast as possible to have a real-time sensation and feel (Robles-De-La-Torre, 2006). Therefore, a high level of energy is required to have a haptic device or interface based on thermal feedback.

5.3.2.5 Control Algorithm

This type of algorithm is programmed into a controller phase in order to reduce the error between the future and relevant haptic forces or tactiles. The control algorithm is required to command haptic interfaces. This control algorithm iterates through the preferred tactile or force vectors and outputs values as a real tactile or force vector that will be commanded to the haptic interface (K. Salisbury et al., 2004a; Su et al., 2012). The control algorithms develop the position sensors at the haptic interface intersections. The autistic people user's position in the virtual environment is determined by the position of the haptic interface in Cartesian virtual environments, and this process is based on the control algorithm, where this algorithm is able to integrate the information gathered from each sensor to acquire the position of the haptic interface in the Cartesian virtual environment (Shao et al., 2019).

5.3.3 Model

The *Model* phase functions as an intermediate platform for managing the input data from the autistic people user via *View* and also provides feedback to instructions (haptic rendering information) from the controller to update the haptic interface and the *Model* phase itself. The main objective of this phase is to manage and process the HBVE and spatial learning and cognitive mapping components together in the application to provide feedback to the *View* and *Controller*. The following sub-sections provide more details about the components that are involved in this phase (refer to Figure 5.5).

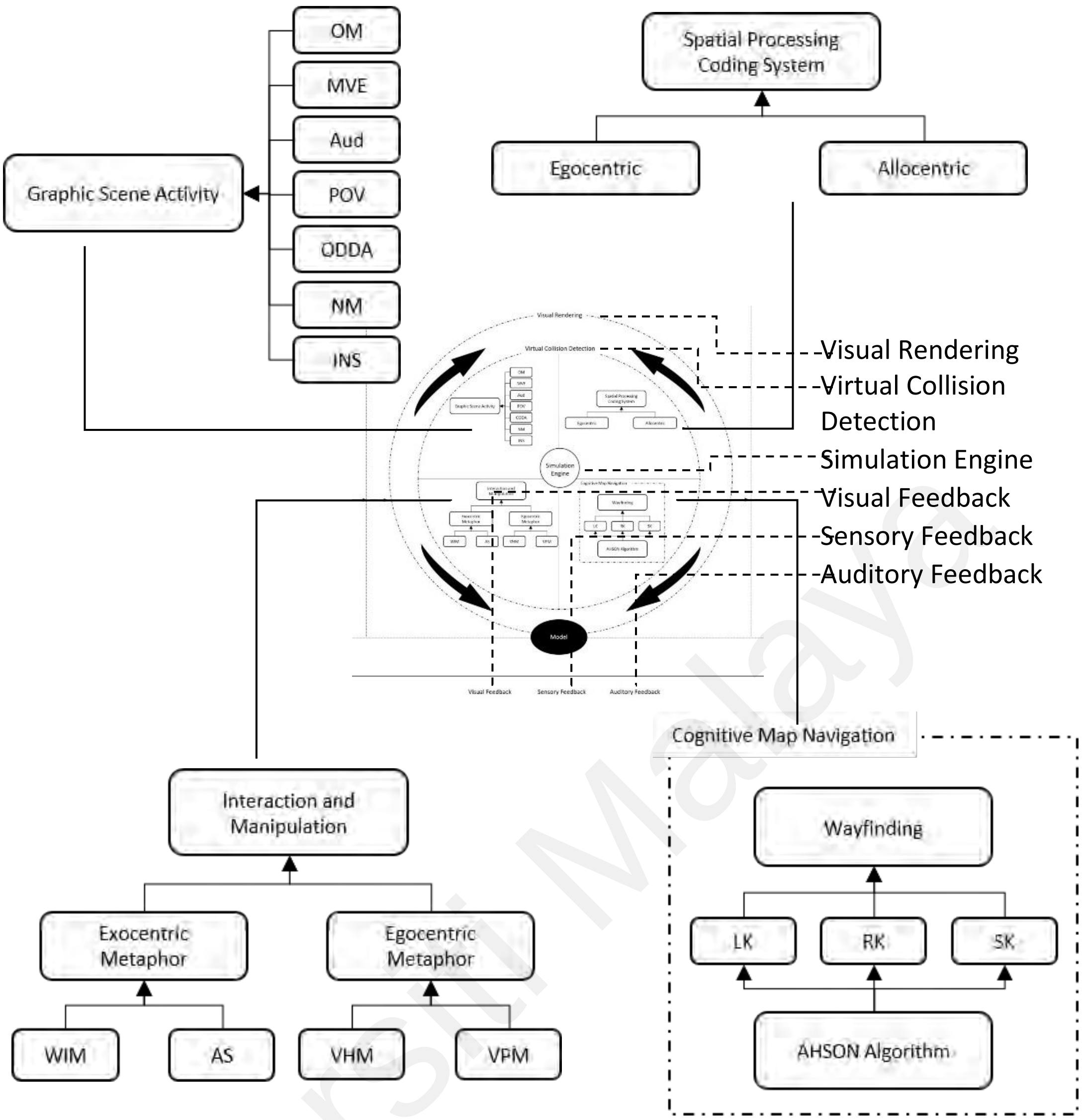


Figure 5.5: The Components of Model

5.3.3.1 Visual Rendering

Visual rendering is the process of generating three-dimensional objects in real time, which depends on the graphics card with the assistance of a 3D hardware accelerator (Choi et al., 2017). Visual rendering is becoming the most important area that needs to be focused on in the development of virtual environments in real-time. There are a few important features in terms of visual rendering, such as texture mapping, indirect illumination, motion blur reflection, shadows, transparency (graphic) and others as well (P. Christensen et al., 2018). Meanwhile, there are some techniques and algorithms that have been used to render virtual objects in real-time, such as rasterization, scanline rendering, radiosity, object order algorithm, and others (P. Christensen et al., 2018; Lawlor, 2017).

5.3.3.2 Visual Collision Detection

As discussed in the previous section, 5.3.2.3. In parallel, this component focused on the simulation engine to detect collisions between objects and autistic people users in the virtual environment by providing information about what level or point collisions have occurred (Changeon et al., 2012). Both components of haptic collision detection in the haptic interface and the collision detection algorithm in the simulation engine were aligned and integrated together to be responsible for the detection of collisions between objects and autistic people users during the interaction in a virtual environment through the haptic interface (W. Wu et al., 2017).

5.3.3.3 Simulation Engine

The simulation engine is the process of gathering all the related components, functions, and features for the implementation of the HBVE application. This component assists in building the real-time HBVE application, including validating subcomponents to generate the pre-rendered virtual scene through haptic technology for the end-user interaction (K. Salisbury et al., 2004b). This component is designed to receive all the relevant information from the input and controller components, and construct and execute the sub-components of the virtual environment modelling, spatial processing coding system, interaction and manipulation, and cognitive map-navigation into a single engine process to develop a virtual scene (Richard et al., 2021).

5.3.3.4 Graphics Scene Activity

A graphics scene activity is a computer-based simulated three-dimensional environment where 3D objects and graphic content are integrated together to allow users to interact with and manipulate the virtual objects (Izard et al., 2017). This component allows the developer to create 3D virtual models and objects and complex terrain environments for visual interpretation. The subcomponents of virtual modelling, such as audio, motion animation, and visual effects, are used to create a realistic situation (real-time effects)(Hamam et al., 2013a). Meanwhile, other sub-components such as point of view (POV), object detection and object avoidance (ODOA), navigation map (NM), and instruction and navigation support (INS) are mapped together in their main component to develop an effective virtual (immersive) environment. The following section will go into more detail about the sub-components of the graphics scene activity.

(a) ***Object Modelling (OM)***

Object modelling is a sub-component that allows the developer to develop and produce a three-dimensional (3D) digital representation of any surface of an object (Rosenman et al., 2007). This process can be done through the use of any specialised software by collecting and manipulating points (such as vertices) or via various geometric entities (such as cubes, lines, spheres, triangles, or curved surfaces) in virtual space to create 3D objects (Bowman & Hodges, 1997). The 3D object modelling process consists of three different methods: polygonal modelling, curve modelling, and digital sculpting. Meanwhile, 3D objects modelling also has three different types of modelling techniques: constructive solid geometry, implicit surfaces, and subdivision surfaces (Keeter, 2020). Part of modelling, the 3D objects are also defined with texture mapping on their surfaces to give them a real-world texture sense.

(b) ***Motion and Visual Effects (MVE)***

Motion (also known as motion graphics) and visual effects are the two different aspects in terms of virtual environment development. Motion graphics are animated graphic designs that bring an object or character to life rather than static images or objects

(Bozgeyikli et al., 2016). Motion is usually used to develop an interactive virtual interface, such as title sequences, text (spin around), navigation buttons, and simple character animations (jumping and walking), especially for virtual agent characters in the virtual environment (Bowman et al., 1998). Meanwhile, visual effects are defined as the process of integration to create real-time scene effects through the combination of existing footage and computer-generated imagery (Newbutt et al., 2017; Y. D. Yang et al., 2017). This subcomponent is usually used for creating real-time world atmosphere effects such as fire, smoke, rain, shadows, and lighting. There are a number of varieties of lighting effects, such as point, dynamic, fog, spotlights, wavering, shimmering, coronas, and omnilighting, which the developer is able to use to create real-time lighting effects.

(c) ***Audio Effects (Aud)***

In order to bring the real world and natural atmosphere into the HBVE, the audio effects (foreground and background) become an important aspect since they can represent some action or meaning for the 3D objects or the environment itself (Ying et al., 2003). The most common sound effects used are footsteps during the autistic people users' walk-through the environment. The audio effects from the environment (ambient) in the virtual environment bring a sense of presence to autistic people users (Johnston et al., 2019). In addition, the audio effects also become one of the supportive aspects of autistic people users' navigation by enhancing their cognitive skills through the recall and recognition of 3D objects and spatial knowledge within the virtual environment.

(d) ***Point of View (POV)***

The user perspective of autistic people is an important design aspect in the development of a haptic-based virtual environment application. A Point-of-View (POV) perspective is how an autistic people (user) is able to see or experience (by observing) a virtual environment via a haptic interface (Hamza-Lup et al., 2019). POV can be classified into two types in HBVE application development: first-person POV and third-person POV (Bos et al., 2019). First-person POV refers to the ability of the user to view the environment through the eyes of the person themselves (user), and by observing their surroundings in a virtual environment up close, it is also believed that this type of POV provides a more immersive feel for the user (Shareef & Farivarsadri, 2019). Meanwhile, third-person POV provides the ability for users to observe the main character's movement in a virtual environment. This becomes bound to the users' sense that they are directly involved in the virtual environment. Also, it's very difficult for users to accurately measure their focus of interest even though the third person POV provides a wider field of view of the virtual environment (Amon et al., 2018). In order to know and control their movement and position towards the targeted object, the character's visual focus (first person POV) is very important.

(e) ***Object Detection and Object Avoidance (ODOA)***

One of the most challenging processes in HBVE development is the design of a continuation/robust object detection and object avoidance system within a real-time application. Object detection describes the ability of the haptic interface's camera (stereo or monocular) to recognise the shape of objects and their current position in a virtual environment (Choi et al., 2017). Meanwhile, object avoidance (obstacle avoidance) is the process of detecting virtual objects (obstacles) and avoiding collisions during wayfinding to their desired or targeted object. The object avoidance in a virtual environment uses a type of collision avoidance/obstacle avoidance algorithm as a sensor for its navigation (Dautenhahn, 2000). Object detection and object avoidance are the two inseparable aspects in the study of a virtual object's avoidance ability.

(f) ***Navigation Map (NM)***

A navigation map is an important aspect of providing effective wayfinding assistance for users in virtual environments through haptic feedback. This navigation map is developed based on the user's orientation within the virtual environment and is usually located at the corner of the screen in a virtual environment with common features such as the current position of the user, virtual objects (obstacles), and objectives of the virtual environment (Qiu et al., 2020; Thorndyke & Hayes-Roth, 1982). This navigation map generally renders the current user position based on the direction being faced through the camera point of view (García-Catalá et al., 2020).

(g) ***Instruction and Navigation Support (INS)***

The basic objective of an instruction and navigation support sub-component in a HBVE is to explain to autistic people users the goal of the application and basic control of the virtual environment with haptic interfaces (Parsons & Mitchell, 2002). It's very important to provide a set of instructions and navigation support details to assist autistic people users in learning how to navigate and operate in HBVE, since understanding a new HBVE, especially for novice users with autism, is not always easy. Therefore, it's important to include this component to describe the objective of the HBVE and how it works. This set of instruction and navigation support materials is divided into three forms of descriptions: 1) provides an overview of the objective of the HBVE and the spatial learning and cognitive mapping tasks involved; 2) provides details about how to use a haptic interface to communicate and navigate in virtual environments; and 3) provides details about the features that are involved in the virtual interface and virtual environment (space).

5.3.3.5 Spatial Processing Coding System

The spatial processing coding system (known as visual-spatial processing) is the ability of autistic people to express and recognise objects in a HBVE and also evaluate how far the objects are from themselves and from each other as well (Chabani & Hommel, 2014). In general, it is the ability of autistic people to sense and encode spatial information that is related to a location in HBVE. This spatial processing usually used for navigation purposes in HBVEs is a cognitive map, and through this, the user attempts to figure out the relation to the initial point and then orients themselves in the right direction to reach their desired location in the HBVE (Bertone et al., 2005a). Spatial processing coding systems can be divided into two types of spatial imagery transformation: egocentric and allocentric, and these are discussed in more detail in the following sub-sections.

(a) ***Egocentric***

Egocentric refers to perspective transformations that involve the self (autistic people) and their relationship to objects in the HBVE (Cai et al., 2013; Ke & Im, 2013). Users try to describe the location of objects in HBVE relative to their body axis, whether as up-down (vertical), left-right (horizontal), or front-back perspective.

(b) ***Allocentric***

Allocentric contrasts with that egocentric perspective and is a form of spatial transformation that involves an object-to-object-based relationship within the HBVE (Miniaci & De Leonibus, 2018). This type of spatial imagery transformation is an attempt to encode spatial information about the location of an object or its attributes with respect to other objects in the HBVE.

5.3.3.6 Interaction and Manipulation

The haptic based virtual environment (HBVE) requires a basic interaction in a specific objects' manipulation so autistic people are able to focused on those high-level tasks such as the spatial learning tasks (Amon et al., 2018). A broad range of research has been carried out in the field, looking at what interaction metaphors and manipulation interfaces should be developed to improve autistic people users' performance in virtual environments through a haptic interface. There have been two types of generic interaction metaphors involved in haptic technologies for object selection and manipulation in virtual environments: the exocentric metaphor and the egocentric metaphor (De Boeck et al., 2005). The following sub-sections provide the details of the interaction and manipulation metaphor:

*(a) **Exocentric Metaphors***

Exocentric metaphors are well known for outside-in-world scenarios where the user is able to interact with the virtual object from an outside (external) viewpoint (De Boeck et al., 2005). These types of metaphors generally very useful for large-distance manipulation tasks in the HBVE (De Boeck et al., 2005). However, these types of metaphors are considered very difficult in terms of interaction since they require very detailed interaction, especially for HBVE. Exocentric metaphors can be divided into different types of metaphors as presented below in the sub-sections:

i World-In-Miniature

Through the World-in-Miniature technique, the user is able to interact and manipulate with the life-world size of a virtual environment through the representation of a small scull-size virtual environment (Stoakley et al., 1995). That means changing or interacting with mini virtual objects in terms of orientation or position, directly representing the virtual objects in a life-size world (VE). It is always referred to as easy and fast for handling large scale or distance-based haptic environment tasks. This metaphor can be used for selection and manipulation of objects apart from being used for navigation, and this metaphor can also improve the interaction performance based on force feedback of haptic technologies.

ii Automatic Scaling

Automatic scaling, also known as the scaled-world grab metaphor (Mine et al., 1997), enables the user to bring the immersive of virtual objects through a haptic interface closer to the autistic people arm extension and also makes the changes dramatically to the distance to the virtual object. Studies also claimed that by the use of this type of metaphor, the interactions in HBVE are almost similar to a virtual pointer or virtual hand interaction once the environment has been scaled. Other studies supported that this metaphor will be very intuitive, especially for autistic people.

(b) ***Egocentric Metaphors***

The egocentric metaphor is known for interaction through the inside world (De Boeck et al., 2005). Virtual hand and virtual pointer metaphors are the two types of common sub-metaphors under the egocentric approach to HBVE. An egocentric metaphor usually enables autistic people to directly interact with the interior of the virtual environment. Most studies show that these types of metaphors are usually not the primary preference for those manipulation tasks on a large scale in HBVE. Instead, users prefer more precise options for manipulation of objects. This egocentric metaphor can be divided into two different metaphors for HBVE:

i Virtual Hand Metaphor

The virtual hand metaphor allows users to manipulate the virtual objects by grabbing and changing the position of objects in the VE. For example, the classical-simple virtual hand technique is used to perform basic selection or manipulation tasks by interacting directly with the virtual objects to create tactile-based interaction, and this process is classified as a one-to-one mapping method since it involves interaction between the virtual hand and the physical hand (Pietroszek & Lee, 2019). However, when compared to the Go-Go technique, also known as the arm-extension technique (Bowman & Hodges, 1997), it's preferable to use a non-one-to-one linear mapping method as the process of interaction between the virtual hand and the user's physical hand. Even though these both classical-simple virtual hand and Go-Go techniques are used to perform selection and manipulation tasks with virtual objects, they are very difficult to implement for those tasks that involve remote manipulation or feature small objects.

ii Virtual Pointer Metaphor

The virtual pointer metaphor is used to select and manipulate a virtual object by pointing in the direction of the object with the virtual pointer. This technique can be distinguished from others in terms of the direction of the virtual pointer, the selection of volume, and the method used for the purpose of disambiguating the selected virtual object by the user as desired. This means the direction of this technique can determine the orientation and position of the virtual hand (LaViola Jr et al., 2017). The direction of this technique is also classified into two types of pointers: the user's eye position and the manipulation of tracker location. *The ray-casting technique* is one of the types of techniques under the virtual pointer that uses the laser pointer (ray) to point and select the virtual object (Steinicke et al., 2006). Meanwhile, the *flashlight technique* uses the same method as the *ray-casting technique* but differs in terms of how it is applied. The *flashlight technique* uses an infinite cone rather than a laser pointer (Liang & Green, 1994). Also, this technique is limited in terms of selection tasks where the selection of any close virtual objects is required, even though it is able to perform the basic selection tasks such as remote control or selection of small objects.

5.3.3.7 Cognitive Map Navigation

This component is required to enhance the ability of autistic people to use spatial knowledge (landmark knowledge, route knowledge, and survey knowledge) in order for autistic people to be able to form mental models or visualise objects by recalling and decoding information regarding the object attributes and location of the objects (H. Zhang et al., 2014b). Wayfinding is one of the techniques that are used to create the mental model (cognitive mapping) during navigation in virtual environments via a haptic interface, and this has been explained in more detail in the following section (Golledge, 1999).

5.3.3.8 Wayfinding

As pointed out in the results section, wayfinding is an important component for autistic people who can easily get lost on their route (Yingying et al., 2021). Therefore, this component is selected to help autistic people find their route to their desired location or objects based on novel routes, landmarks, directions, paths, or cognitive maps (Ariel overview) (Arthur & Passini, 1992; Ramloll & Mowat, 2001). This can be implemented through the following subcomponents in the HBVE:

(a) ***Landmark Knowledge***

The landmark knowledge subcomponent can be implemented through 3D objects in the virtual environment by providing the visual features such as 3D shapes, size of objects, texture, and motion of the animation to the autistic people users' viewpoint (Lindsay & Lamptey, 2019).

(b) ***Route Knowledge***

The route knowledge subcomponent can be implemented by incorporating relational terms (signs) such as "in front of," "behind," "beside," "go toward," "turn," and "go" into the virtual environment to provide spatial information to autistic people (Caron et al., 2004).

(c) ***Survey Knowledge***

The survey knowledge sub-component can be applied based on the implementation of the complete map of the virtual environment (such as a mini-map) for autistic people users to view the environment as a third-person controller/perspective (Caron et al., 2004).

5.3.3.9 Autonomous Haptic Orient-Navigate Algorithm

An autonomous haptic spatial orientation and navigating algorithm is proposed and developed for autistic people to learn their spatial skills and to navigate in a virtual environment without depending on their caregiver or parent's guidance. This algorithm is also proposed to find the nearest emergency exit during navigation by the use of existing emergency direction signs in the virtual environment if the user loses their way or in any emergency situation. This algorithm is comprised of four sections: orientation, localization, mapping, and controller. This orientation provides the natural ability or awareness to maintain the individual's body orientation in relation to the virtual environment and also provides the ability to read and use simple cognitive maps for navigation. Localization is used to determine the position accurately in the virtual environment during navigation (M. C. Lin & Otaduy, 2008). Meanwhile, mapping is the process or activity that is used to extract the virtual objects or path characteristics and map them accordingly to enable the person (autistic people) to navigate or move from one position to another position until they reach their goal. The controller is used to perform a smooth path during navigation in virtual environments. The algorithm is combined with haptic sensors; the navigation and orientation of the user determine the path of the user in the virtual environment.

5.3.4 View

The view component is a means of representation of the haptic and spatial information from the *model* to autistic people in the form of haptic feedback (sensors) and spatial knowledge. The following sub-sections provide the details of the sub-components that are involved in this pattern (refer to Figure 5.6).

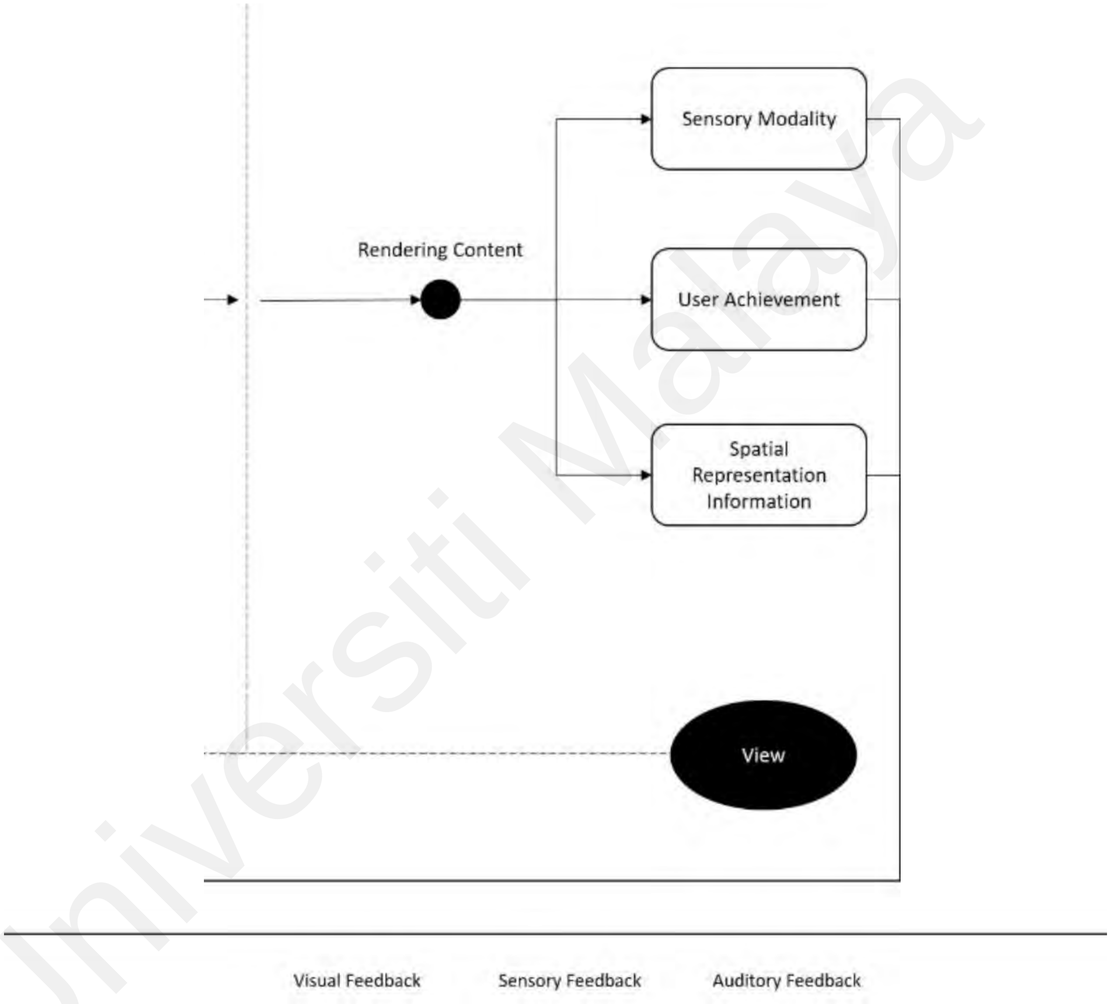


Figure 5.6: The Components of View

5.3.4.1 Rendering Contents

Rendering content is an important component in the development of HBVE where it is responsible for processing the information from controller and model components to display or create real-time immersion for users (Manju et al., 2017). These activities are completed through the processing of each element of the haptic and spatial environment, such as: virtual objects, text, audio, animation, spatial orientation data, and haptic feedback.

5.3.4.2 Sensory Modality

Sensory modality is also known as stimulus modality, and can be referred to as a feature of stimulation after engaging with a haptic interface (Minogue & Jones, 2006). These sensory modalities can be identified in autistic people's interactions with their environment according to temperature, pressure, sound, light, and smell. Users can recognise the sensation when the sensory receptor is activated during the interaction with the haptic interface. This study decided to concentrate on the pressure modality. Pressure (via vibration) modality is defined as a sense of touch or haptic perception in which the user can feel the surroundings or object through interaction and manipulation activities with direct skin contact via the haptic interface. This process will provide a sense of what is being identified or grasped by giving sensation information such as temperature, weight, size, shape, and the material of the object. The sensory modalities can be classified into three types of feedback: haptic feedback (sensory feedback), visual feedback, and auditory feedback (Sigrist et al., 2013), and this will be discussed in more detail in the following sub-sections.

5.3.4.3 User Achievement

The user achievement component provides autistic people with the ability to set up their own profile with basic information (Whitby & Mancil, 2009). Their profile will always update accordingly with their progress in terms of the completion of their assigned spatial learning and cognitive mapping tasks. Therefore, at the end of each of the tasks, the autistic people users are able to view their achievements according to the total scores, time taken to complete each of the tasks, and spatial cognition learning metrics (such as the number of object/landmark detections, distance, and number of directions used). This allows autistic people to apply their previously learned spatial knowledge to their current task by improving their spatial learning skills.

5.3.4.4 Spatial Representation Information

The spatial representation information component is the process of gathering spatial cognition memory information (spatial knowledge: landmarks, routes, and surveys), which is developed through the cognitive mental model from the interaction with virtual environments through a haptic interface, and the spatial knowledge gained will be transmitted to the real-time environment (to autistic people users) (Ahmadpoor & Shahab, 2019). This means that this component provides the amount of spatial knowledge received by autistic people users, how well the spatial awareness reaches them, and how well it improves in terms of their spatial learning skills (Bertone et al., 2005b).

5.3.4.5 Haptic Feedback

Haptic feedback is defined as the ability of autistic people to touch and experience the objects in their surroundings. Haptics allow users to experience the sensations required to simulate feeling a firm object. Haptic feedback is deployed based on vibration (also pressure and temperature), which provides the sense of touch during engaging with haptic interfaces (Pfeiffer & Rohs, 2017). These types of sensory feedback can allow users to perform activities that they were not capable of previously due to impairments in social interaction, repetitive behaviours, and activities (H. Zhao et al., 2017). In this way, haptic feedback in the virtual environment increases the effectiveness of learning processes such as spatial learning. This haptic feedback is used to explore the relative spatial information from the surrounded object through the haptic interface during navigation in a virtual environment.

5.3.4.6 Visual Feedback

Visual feedback is also known as vision, and is the most important aspect of sensory modality during interaction with a virtual environment, including for perceiving spatial information through spatial learning for autistic people (Hailpern et al., 2009). Without visual feedback, it's completely impossible to interact in a virtual environment, especially for autistic people in activities such as walking on virtual and uneven terrain, grasping virtual objects, and finding the direction of a targeted object or landmark. According to several researchers, the visual feedback required depends on the types of spatial learning tasks and spatial learning skills, and these also indirectly provide impacts on sensation (haptic feedback) for autistic people (Andreasen et al., 2019; Dong et al., 2017; Hailpern et al., 2009; Sigrist et al., 2013).

5.3.4.7 Auditory Feedback

Auditory feedback is commonly used to control and navigate in the virtual environment, especially for autistic people and visual impairments. This type of feedback is used to fully understand the subjective experience of any virtual object sounds with real-time effects. Thus, in terms of navigation tasks in a virtual environment, autistic people are able to find the direction of the targeted object by moving towards it through the use of object-generated sounds (Andreasen et al., 2019). For instance, by using echolocation in a virtual environment for navigation, it allows autistic people to acquire spatial information about the object or landmarks through sensing echoes (Dong et al., 2017). Echolocation has been observed in many forms of ultrasound in terms of humans, animals, and physical objects, such as stomping feet, snapping fingers, bat sounds from the mouth, and hitting an object like a car.

5.4 Evaluation of the Proposed Framework

The evaluation of the proposed framework begins with different types of evaluation methods, such as expert review and a case study, and is followed by a standard confirmation of the expert's satisfaction survey of the framework. The process of the evaluation method of the proposed framework is shown in Figure 5.7. An expert review was conducted based on the perceptions of academicians, researchers, designers, and developers who were contributing to HBVE. The expert review begins with academicians, followed by researchers, and finally, designers and developers. The initial version of the proposed framework was improved by integrating the changes suggested by the academicians. Based on the first modified version of the framework, the second expert review was conducted with researchers. After the expert reviews was conducted, the following tests, such as a case study test and a standards confirmation of expert's satisfaction survey, were conducted to review the proposed framework and provide feedback regarding the acceptance of the framework. As mentioned earlier, the modified version framework that was created after the first and second assessment of expert group suggestions was integrated, and this modified version of the framework was used to carry out the case study and standard confirmation of the expert's satisfaction survey. At the end of the evaluation, the new version of the proposed framework was established based on feedback collected from the third group of experts.

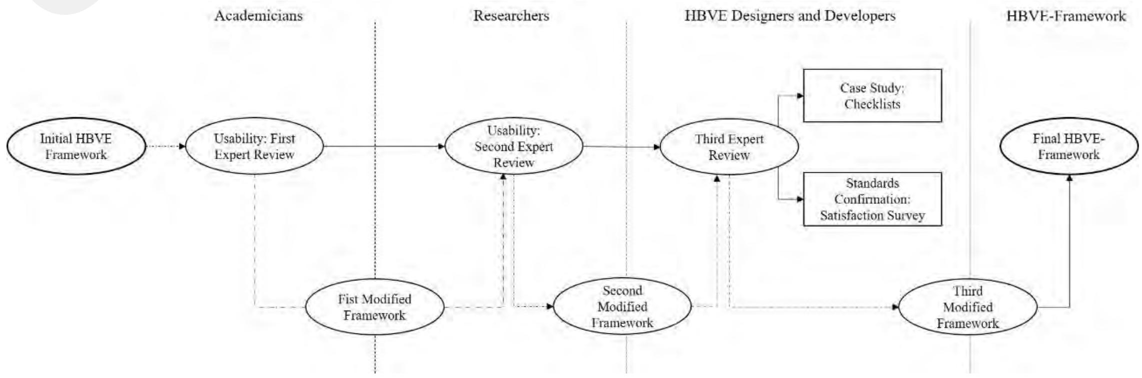


Figure 5.7: The Process of Evaluation Method of the Proposed Framework

5.5 First Expert Evaluation: Academicians

This expert review study was conducted to evaluate the perspective of academicians on the proposed framework and to find violations of usability standards and best practice. This begins with describing the recruitment process of participants, the instruments used to evaluate, the data analysis method used, and finally reviewing the results for the improvement of the proposed framework.

5.5.1 Participants and Recruitment

In selecting the participants, this study recruited academicians from several platforms (*ResearchGate*, *Google Scholar*, *LinkedIn*, and *Google* search engine) that are well-versed in the area of haptic technologies and spatial cognition. In addition, the experts were recruited on the basis of their knowledge and experiences in the five subtypes of autism that fall under the "umbrella" of autism spectrum disorder (ASD): autistic disorder, asperger syndrome, childhood disintegrative disorder, rett syndrome, and pervasive developmental disorder (Al-Mosawi, 2020; Mehra et al., 2019). The evaluation was made up of 14 experts (11 males and 3 females) and the demographics of all the participating experts are shown in Table 5.3.

Table 5.3: Demographic Information of Academic Experts

Experts	Value (n = 14)
Gender, mean ± SD	1.21 ± .426
Male, n (%)	11 (78.6)
Female, n (%)	3 (21.4)
Research Area of Interest, mean ± SD	3.64 ± 1.549
"Umbrella" of Autism Spectrum Disorder (ASD) n (mean ± SD)	5 (.36 ± .497)
Haptic Rendering and Interaction, n (mean ± SD)	12 (.86 ± .363)
Virtual Reality/ Environment, n (mean ± SD)	8 (.57 ± .514)
Spatial Learning, n (mean ± SD)	7 (.50 ± .519)
Cognitive Mapping, n (mean ± SD)	3 (.21 ± .426)
Wayfinding and Navigation, n (mean ± SD)	3 (.21 ± .426)
Human Computer Interaction (HCI), n (mean ± SD)	6 (.43 ± .514)
Others (User Centred Design (UCI), Robotics, Computer Based Learning, Artificial Intelligence, etc.), n (mean ± SD)	12 (.86 ± .363)
Research Experience, mean ± SD	2.79 ± .802
≤ 5 years, n (%)	1 (7.1)
6 – 10 years, n (%)	3 (21.4)

11 – 15 years, n (%)	8 (57.1)
≥ 16 years, n (%)	2 (14.3)
Location, n (%)	2.07 ± .9.17
Asia, Africa and Oceania, mean ± SD	5 (35.7)
America, n (%)	3 (21.4)
Europe, n (%)	6 (42.9)

5.5.2 Instruments Used

Instruments are created with a combination of open-end and close-end questions. The questionnaire consists of four dimensions. Each dimension has its own emptiness, and this has been shown in Table 5.4. The close-ended questions are measured based on the eleven-level Likert scale: "High agrees," "Considerably high agree," Moderate agree," "Considerably disagree agree," "Disagree agree," "No usability," "Low disagree," "Considerably high disagree," "Moderate disagree," "Considerably agree disagree," and "Agree disagree".

Table 5.4: Details of Dimensions and Types of Questions in Questionnaire

Dimensions	Objective	Types and Numbers of Questions
Part A	Expert Demographics: The fundamental characteristics information, the expert's research field, and the number of years of involvement.	Question type: Close-end and open-end. Number of questions: dEQ1, dEQ2, dEQ3, dEQ4
Part B	Perception of each of the individual components: To understand the expert's perception in terms of each of the main and sub-components in the proposed framework will determine whether the proposed components meet the goal of the framework, eliminating all unnecessary components and defining their importance.	Question type: Close-end and comments/suggestion. Number of questions (Main Components): mEQ5, mEQ6, mEQ7, mEQ8, mEQ9, mEQ10, mEQ10, mEQ11, mEQ12, mEQ13, mEQ14, mEQ15, mEQ16, mEQ17, mEQ18, mEQ19, mEQ20, mEQ21, mEQ22, mEQ23, mEQ24, mEQ25, mEQ26, mEQ27, mEQ28 Number of questions (Sub-Components): sEQ29, sEQ30, sEQ31, sEQ32, sEQ33, sEQ34, sEQ35, sEQ36, sEQ37, sEQ38, sEQ39, sEQ40, sEQ41, sEQ42, sEQ43, sEQ44, sEQ45, sEQ46, sEQ47, sEQ48, sEQ49, sEQ50, sEQ51, sEQ52

Part C	Perception of the structure of the framework: To understand experts' perception in terms of the selection of a framework structure and to ensure whether the components are placed and grouped in the right or clear directions.	Question type: Close-end and comments/suggestion. Number of questions (Main Structure): msEQ53, msEQ54, msEQ55, msEQ56 Number of questions (Sub-Structure): ssEQ57, ssEQ58, ssEQ59, ssEQ60, ssEQ61
Part D	Perception of the relationship between components: To understand the expert's perception in terms of defining the relationship between the components in the proposed framework, and how this will be configured based on general and specific levels of relations.	Question type: Close-end and comments/suggestion. Number of questions (Main Relationship): mrEQ62, mrEQ63, mrEQ64, mrEQ65 Number of questions (Sub-Relationship): srEQ66, srEQ67, srEQ68, srEQ69, srEQ70, srEQ71, srEQ72
Part E	Perception of the overall framework: To understand the expert's perception in terms of their overall perception of the proposed framework in both positive and negative viewpoints.	Question type: Open-end and comments/suggestion Number of questions: oQ73

5.5.3 Data Analysis

This section consists of two types of analysis methods that have been used, namely quantitative and qualitative analysis, to analyse the subjective value of the use.

5.5.3.1 Quantitative Analysis Method

A quantitative analysis was performed to analyse the close-ended questions and data, and this was measured based on the average of the respondents.

5.5.3.2 Qualitative Analysis Method

The qualitative analysis method was used to review the subjective suggestions or opinions of the expert respondents on the components of the framework. The subjective questions are analysed based on the following three types of opinions: positive, negative, attention, and recommendations. The positive opinion meant the acceptance of the components by the expert, who did not require any additional changes to the proposed component in the framework. Meanwhile, negative opinion meant those components that failed to satisfy the experts and required immediate attention. Recommendations indicate that some attention or improvement is required.

5.5.4 Results

This section presents the results from the expert responses, and these were measured based on the subjective value of usability. The questions in Part B show each of the responses from the respondents about the components in the framework according to model, view, and controller phases. The results are shown for each component based on the following assessment levels (refer to Table 5.5):

Table 5.5: Details of Dimensions and Types of Questions in the Questionnaire

Usability Assessments Level	Values
High agrees	>1.00
Considerably high agree	0.80
Moderate agree	0.60
Considerably disagree agree	0.40
Disagree agree	0.20
No usability	0.00
Low disagree	-0.20
Considerably high disagree	-0.40
Moderate disagree	-0.60
Considerably agree disagree	-0.80
Agree disagree	-1.00<

The results shown in the following figures are based on lines or with square markers. The average value of usability can indicate the levels of expert perception of the component in a framework through agree, neither agree nor disagree, nor disagree.

5.5.4.1 Usability Rating: Perception of the Experts Group Based on Individual Components

Figure 5.8 shows results based on all seven components in the user phase, where it refers to the importance and use of these components in the framework. Based on the usability assessment level, all seven components may be agreed upon by experts as long as the average value is greater than "0.01". Also, most of the experts claim "Autism

Behavior and Capability" and "Spatial Ability" are most needed compared to other components, with a high average value of "1.18" and "0.86".

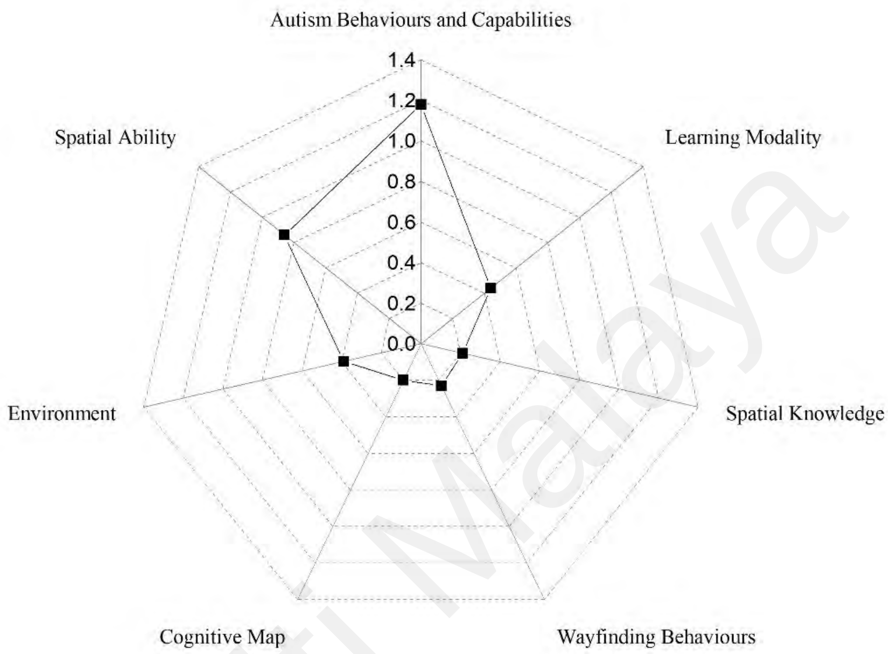


Figure 5.8: Average Values of Usability of Experts for Components in the User

Meanwhile, Figure 5.9 shows that all components are in the controller phase. According to this figure, the major four components ("Physical Haptic Interface," "Haptic Rendering," "Haptic Collision Detection," and "Haptic Feedback") of the controller phase show high average values among experts, as this is the more important process and requires attention in terms of designing and interacting with both haptic technology and virtual environments. Meanwhile, the average value of other components is too low compared to the four major components, and this is due to the fact that the average value of these components is influenced by "Components Weight" and "Usability Rating" values. This means that, according to expert views, these components are still required in the development of any haptic-based design.

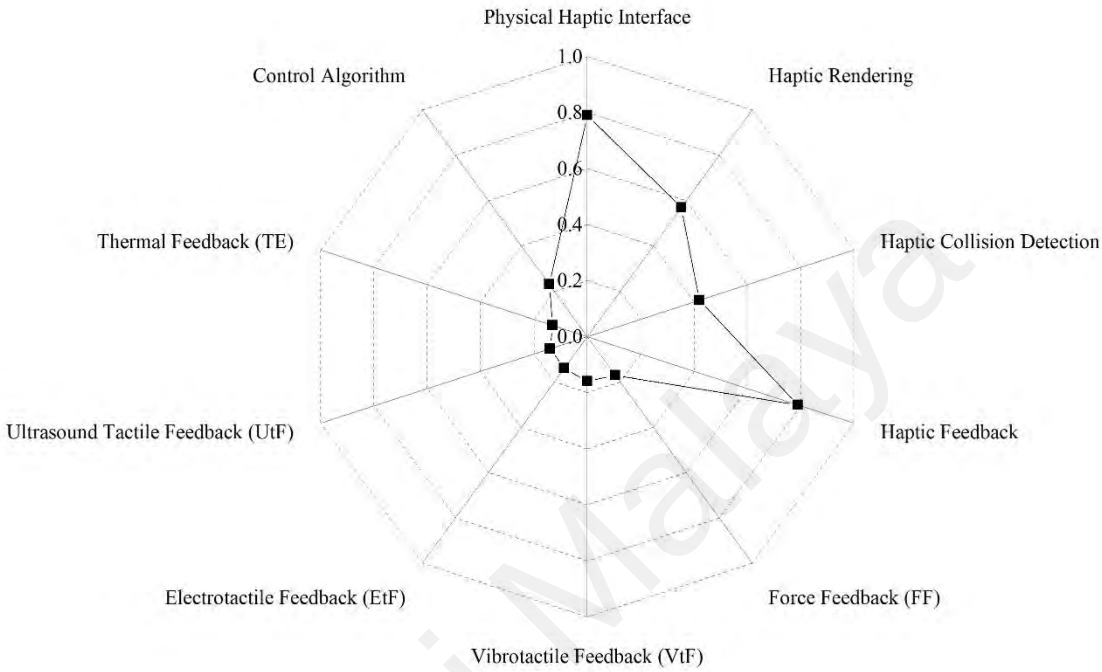


Figure 5.9: Average Values of Usability of Experts for Components in the

Figure 5.10 shows all the components in the model phase. From the model phase, most experts agreed on the components, and this can be seen in this picture with an average value greater than "0.01", where according to the "Usability Assessment Level," average values greater than or equal to 0.01 are acceptable components from the perspective of expert views.

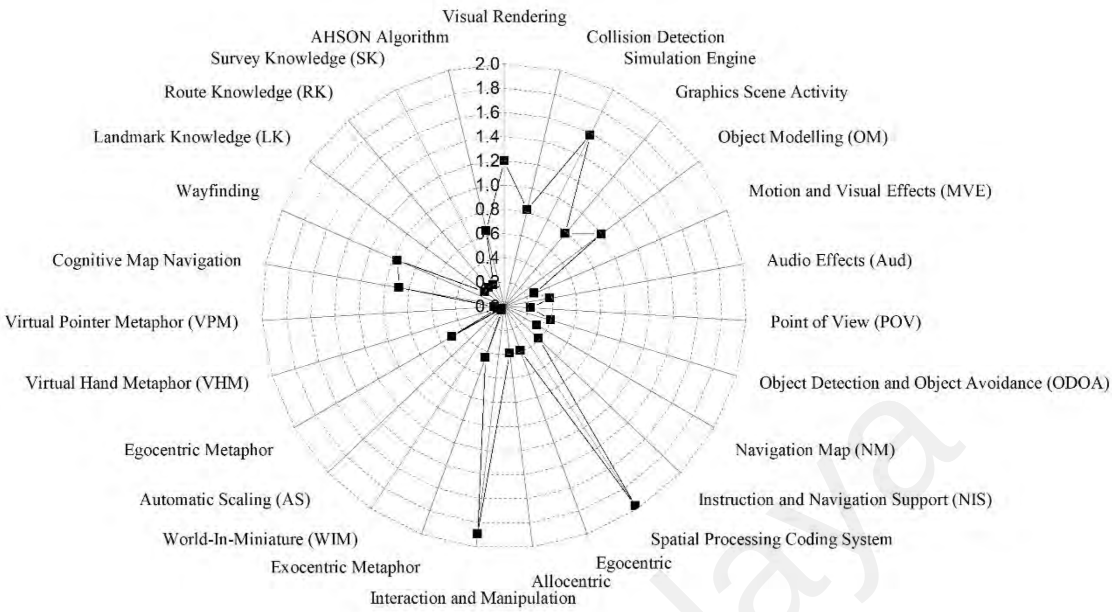


Figure 5.10: Average Values of Usability of Experts for Components in the Model

Figure 5.11 shows that all components are in the view phase. As this model impacts the interaction between user and haptic feedback, the average value is very high among the experts, as can be seen from the following figure, with an average value of "0.96" and above.

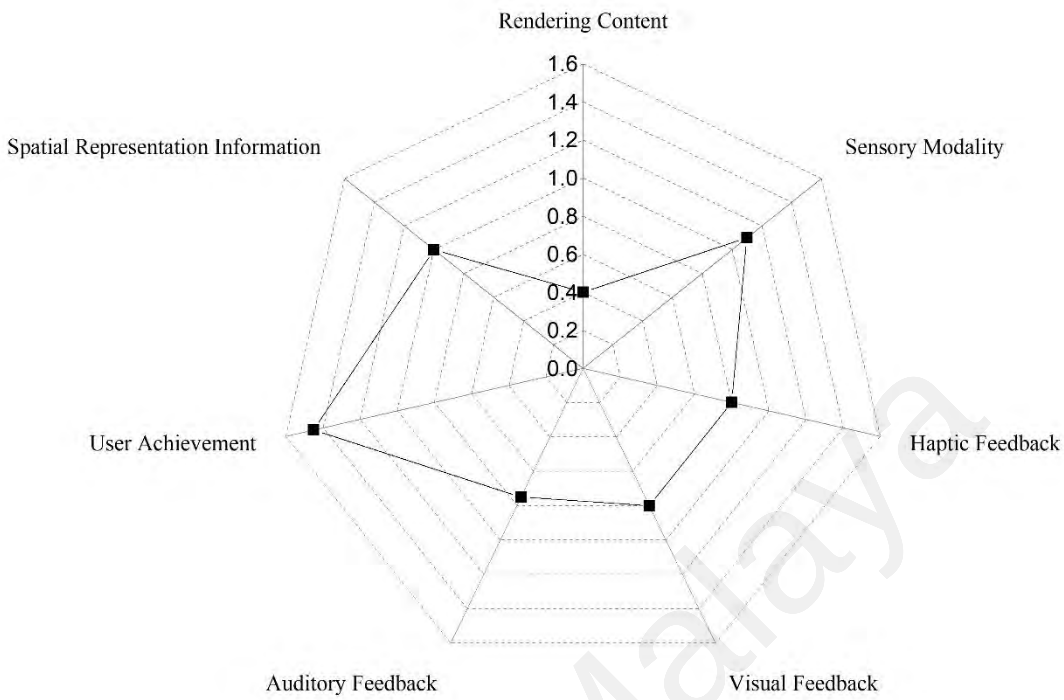


Figure 5.11: Average Values of Usability of Experts for Components in the View

5.5.4.2 Usability Rating: Perception of the Experts Group Based on the Arrangement of Components in the Phase and Overall MVC Pattern

Figure 5.12 shows the average values of responses for the MVC pattern of the HBVE-Framework. The figure output is divided and presented into two different evaluation stages. The first stage studied the overall MVC pattern of the framework (User (components in the Controller phase), Model, View, and Controller). Experts believe that the MVC pattern-based framework is easier to adapt and understand, and also that it can see the relations between the MVC pattern and HBVE. Meanwhile, the second stage of evaluation studied the average values from the sub-components of the model phase. Most experts claim that they can see and evaluate the relationship between virtual engine components and space cognition components.

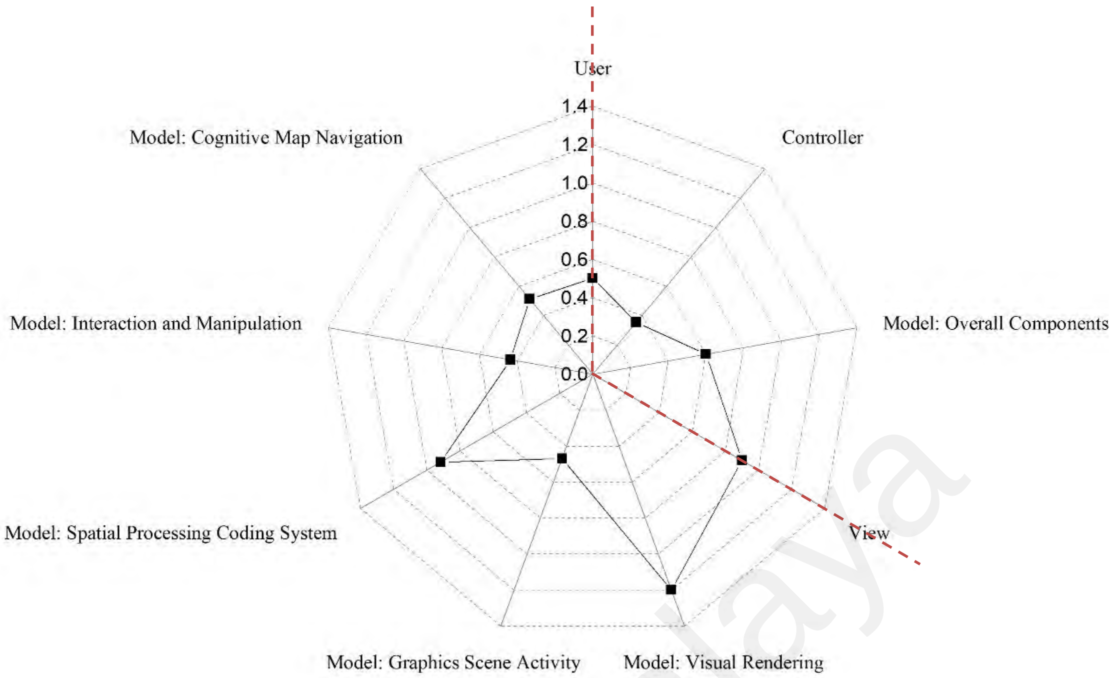


Figure 5.12: Average Values of Usability of Experts for the MVC Structure of

5.5.4.3 Usability Rating: Perception of the Experts Group on the Relationship between Components

Figure 5.13 shows the correlation of the reaction to the relationship between the components. Based on the analysis results, it is found that most experts agree that there is a proper relationship between the components.

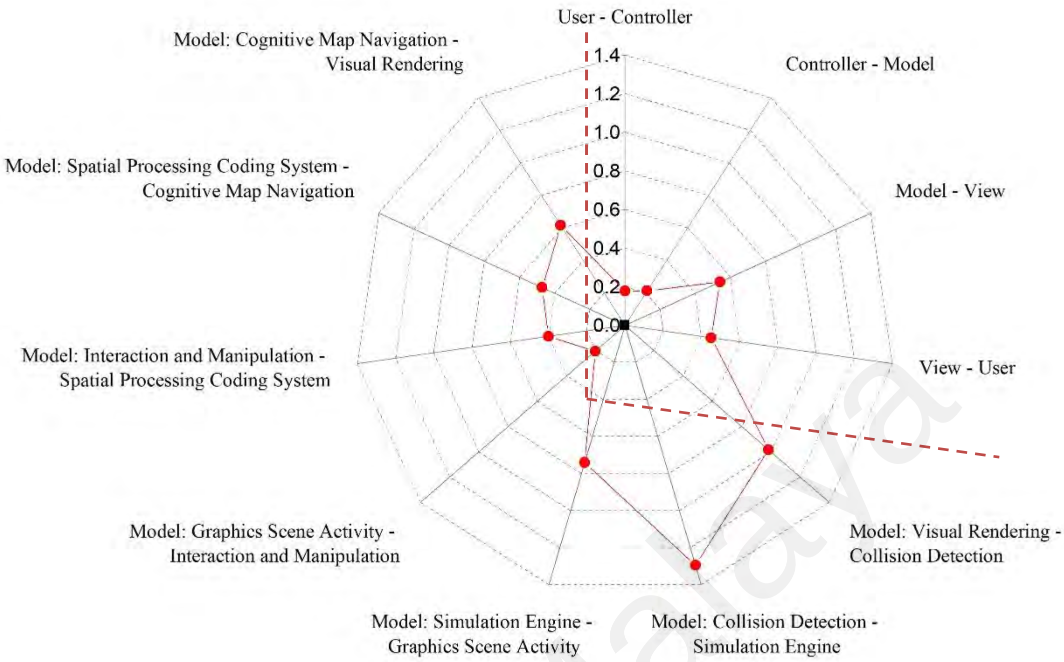


Figure 5.13: Correlation Relationship between Components for the

5.5.4.4 Usability Rating: Perception of the Experts Group Based on the Descriptive Responses

Table 5.6 shows the descriptive statistical responses by experts from Parts B to E, with four different levels of descriptive response: positive, negative, attention, and recommendation. A total of 1022 descriptive responses from expert responses have been collected and analyzed. The collected data was presented based on the mean and the standard deviation. Most of the respondents provided positive feedback by accepting (67.1%) the components, and these show the importance, effectiveness, and existence of relationships between components in the framework. In contrast, (0.6%) respondents showed negative reactions by rejecting the components due to a lack of component naming, the details in the components' descriptions, and as well the relationship between the components. For example, the "environment" component should be named "training environment" since the scope of this component is related to the environmental scenario. In addition, there were (22%) respondents showing their attention to the components by highlighting the issues such as the description of the component not being clearly stated or showing the actual direction of the component. For example, the "user achievement" component does not provide clearer information about what kind of user achievement information will be shared with the end-user and how it will be helpful at the end of the session. Meanwhile, (10.3%) of the respondents shared their opinion by pointing out some recommendations to increase the effectiveness of the framework and to view the framework as a whole in terms of its contributions to the design and development of HBVE applications, such as providing more details about the components with relevant examples.

Table 5.6: The descriptive statistical responses by academic experts were considered according to four categories based on different dimensions

Dimensions	Positive			Negative			Attention			Recommendation			Total		
	n	***mean***	***SD***	***n***	***Mean***	***SD***	***n***	***Mean***	***SD***	***n***	***mean***	***SD***	***n***	***mean***	***SD***
Part B	417	29.79	5.886	6	.43	1.158	197	14.07	5.240	94	6.71	2.867	714	51.00	.001
Part C	114	8.14	.864	0	.00	.000	10	.71	.914	2	.14	.363	126	9.00	.001
Part D	133	9.50	1.225	0	.00	.000	14	1.00	.961	7	.50	.650	154	11.00	.001
Part E	13	.93	.267	0	.00	.000	0	.00	.000	1	.07	.267	14	1.00	.001
Total	677	48.35	6.913	6	.43	1.158	221	15.79	5.833	104	7.43	3.131			

5.5.5 Revised According to Expert Perceptions

According to expert perceptions, only a few aspects needed to be revised in the initial framework to produce a better version of the framework. The revision takes place based on the following aspects: 1) facts about the components 2) highlight and add the new component if it exists, and 3) provide the relationship between the components.

5.5.5.1 Facts about the Components:

The following aspects were revised and integrated into the components:

(1) The description of the "Learning Modality" component has been added.

(2) An example of spatial ability information related to cognitive learning has been included in the component's description.

(3) Provided more details about the "User Achievement" component.

(4) The name of the "Environment" component is changed to "Training Environment."

5.5.5.2 Adding New Component

Based on feedback from the expert group, the data repository component has been added as a new component as well:

Data Repository: This component is designed to collect, store, and deliver haptic feedback, virtual environment (VRE), and spatial visualisation content for end-user and developer perception. This component can manage both real-time and archived data sets in the VRE simulation engine's memory processing. The haptic feedback data is extracted using a haptic device and preserved in the form of an IMU and EMG signal data set in a data repository. In addition to time and VRE motion content data, this component also processes and stores navigation, selection, interaction, and manipulation as user achievements in a data repository.

5.5.5.3 The Relationship between Components

The relationship between "Spatial Ability" and the "Autism Behavior and Capability" components should be in two-way communication rather than "Autism Behavior and Capability" to the "Spatial Ability" component since the knowledge of spatial is different for each individual and the impact of spatial learning indirectly impacts the capability of the individual as well.

5.6 Expert Evaluation: Researchers

This assessment is conducted according to researchers who explore the design and development of HBVE. This evaluation used the same concepts as presented in Section 5.6, such as the recruitment process of participants, the instruments used to evaluate, and the data analysis method used. Therefore, this evaluation excluded those aspects that were already discussed and presented in the previous section 5.5. This evaluation section focuses on the components of the model, view, and controller to improve the initial version of the framework.

5.6.1 Participants and Recruitment

As previously stated, participants in this study are researchers who are well-versed in and involved in the design of HBVE, particularly for autistic people and spatial cognition. They have been recruited and contacted via social network platform such as *LinkedIn* and *ResearchGate* related to the area of HBVE design, and eventually six participants have been identified for participation. This is presented in Table 5.7 as demographic information about experts.

Table 5.7: Demographic Information of Researcher

Experts	Value (n = 6)
Gender, mean ± SD	1.33 ± .516
Male, n (%)	4 (66.7)
Female, n (%)	2 (33.3)
Research Area of Interest, mean ± SD	.48 ± .229
"Umbrella" of Autism Spectrum Disorder (ASD) n (mean ± SD)	3 (.50 ± .548)
Haptic Rendering and Interaction, n (mean ± SD)	4 (.67 ± .516)
Virtual Reality/ Environment, n (mean ± SD)	3 (.50 ± .548)
Spatial Learning, n (mean ± SD)	2 (.33 ± .516)
Cognitive Mapping, n (mean ± SD)	3 (.50 ± .548)
Wayfinding and Navigation, n (mean ± SD)	2 (.33 ± .516)
Human Computer Interaction (HCI), n (mean ± SD)	5 (.83 ± .408)
Others (User Centred Design (UCI), Robotics, Computer Based Learning, Artificial Intelligence, etc.), n (mean ± SD)	6 (1.00 ± .001)
Research Experience, mean ± SD	2.67 ± 1.033
≤ 5 years, n (mean ± SD)	1 (16.7)
6 – 10 years, n (mean ± SD)	1 (16.7)
11 – 15 years, n (mean ± SD)	3 (50.0)
≥ 16 years, n (mean ± SD)	1 (16.7)

5.6.2 Results

This section presents the perceptions of the experts towards the modified version of the initial framework according to model, view, and controller phases.

5.6.2.1 Usability Rating: Perception of the Researchers and HBVE Designers

This section presents the average values of the responses of the MVC pattern (model, view, controller, and including user of controller) based of the framework, as shown in the figures: Figure 5.14 (user of controller), Figure 5.15 (controller), Figure 5.16 (model), and Figure 5.17 (view). The results were extracted and analysed based on six experts' responses to all the components in the model, view, controller, and user of the controller. According to the figures for all phases, most experts have agreed to accept the inclusion of all components. This is because the average value is greater than 0.60, indicating that designers and researchers recognise the significance of these components.

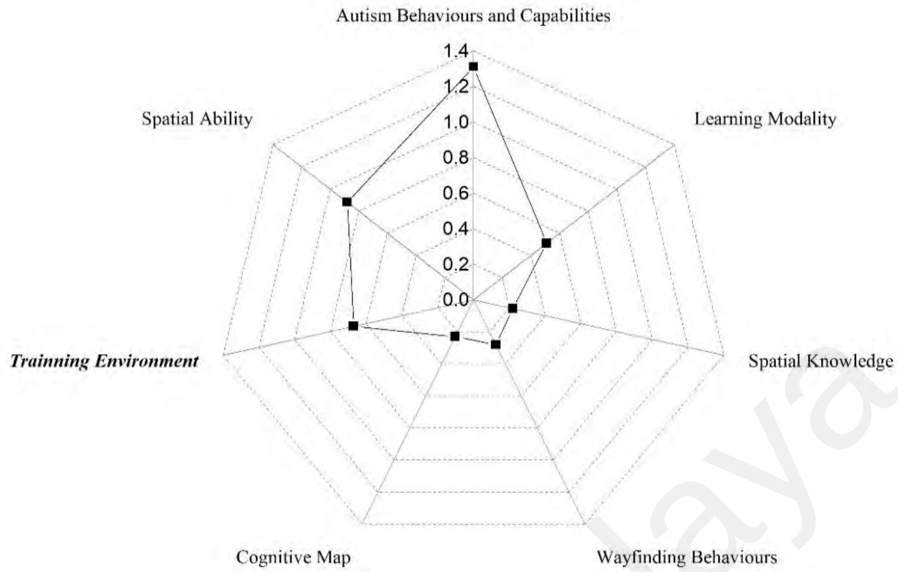


Figure 5.14: Average Values of Usability by Researchers for Components in the User Phase

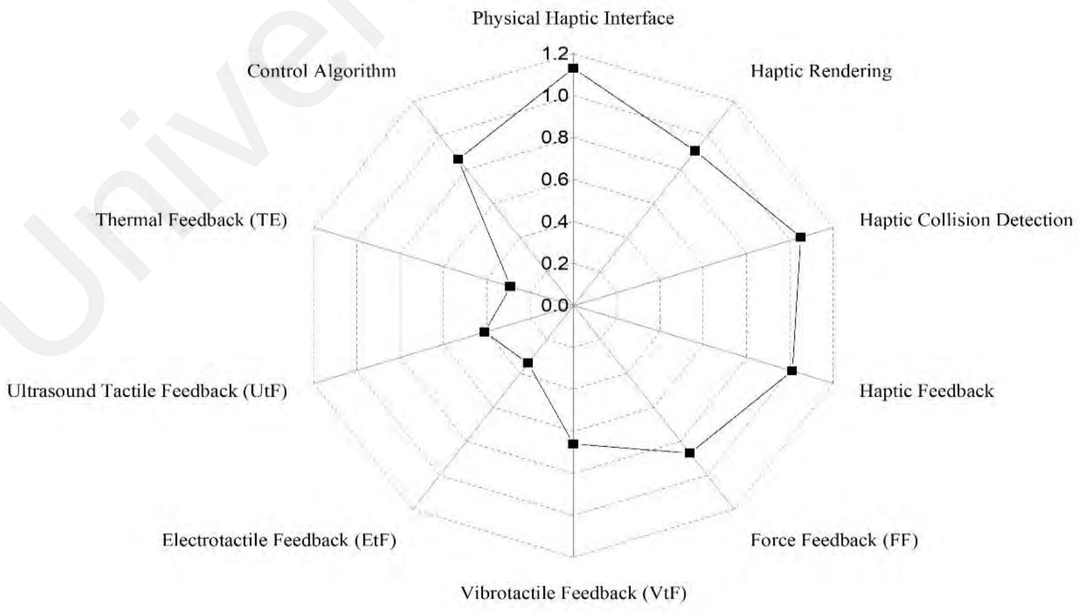


Figure 5.15: Average Values of Usability by Researchers for Components in the Controller Phase

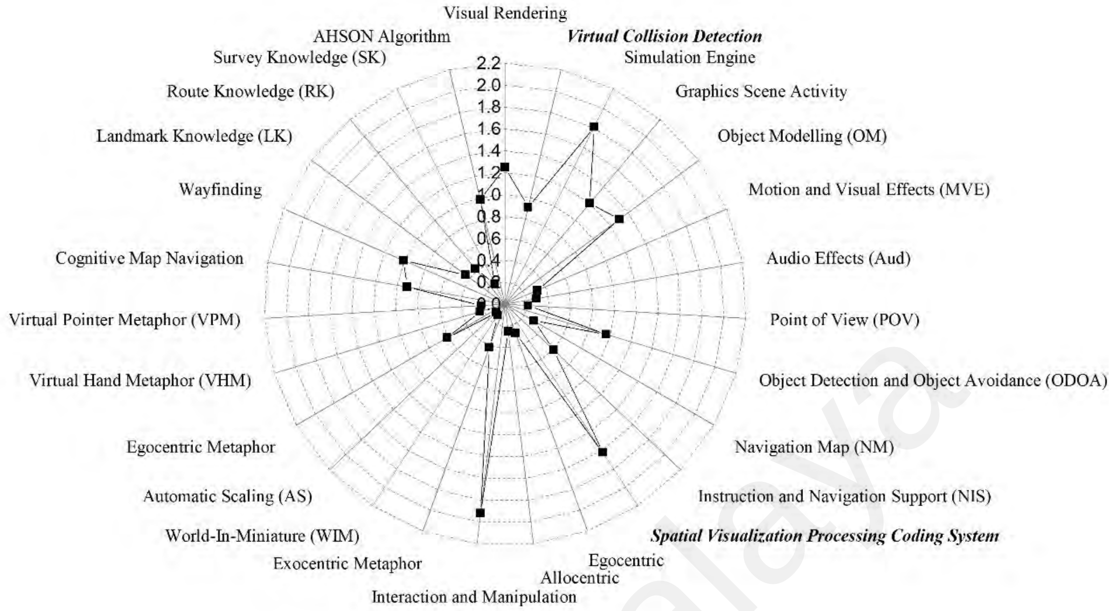


Figure 5.16: Average Values of Usability by Researchers for Components in the Model Phase

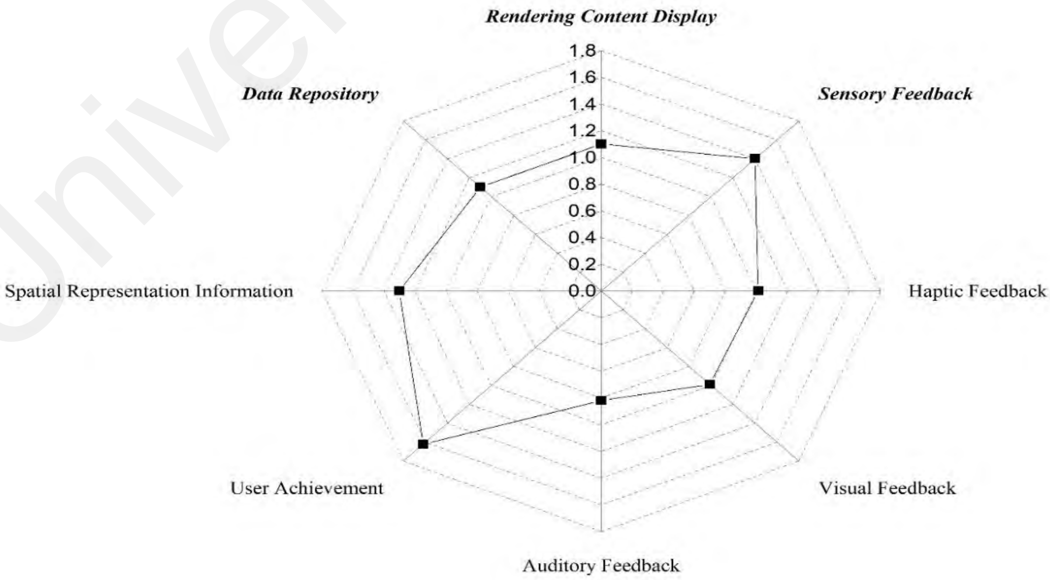


Figure 5.17: Average Values of Usability by Researchers for Components in the View Phase

5.6.2.2 Usability Rating: Perception of the Researchers Based on the Descriptive Responses

Table 5.8 shows the descriptive responses by researchers from Part B to E, with four different levels of descriptive response: positive, negative, attention, and recommendation. A total of 432 descriptive responses from expert responses have been collected and analyzed. Overall, the respondents accepted (65%) all the components, and this shows the contents of the components were presented well with sufficient descriptive information. Meanwhile, there were (23%) respondents showing their attention to the components by requiring more details and facts on the autism and spatial learning-related components (autism behaviour and capability, spatial ability, wayfinding behavior, spatial knowledge, training environment, cognitive map, and learning modality). In addition, (11%) of the respondents shared their opinion by highlighting that it was required to merge some of the components by reducing the total number of components and also standardising the component names. For instance, spatial ability and spatial knowledge can merge together as one component since most of the significance is shared.

Table 5.8: The descriptive statistical responses by the researchers were considered according to four categories based on different dimensions

Dimensions	Positive			Negative			Attention			Recommendation			Total		
	n	*mean*	*SD*	*n*	*Mean*	*SD*	*n*	*Mean*	*SD*	*n*	*mean*	*SD*	*n*	*mean*	*SD*
Part B	173	28.83	4.875	4	.67	1.633	89	14.83	5.456	40	6.67	1.966	306	51.00	.001
Part C	48	800	.894	0	.00	.000	5	.83	.983	1	.17	.408	54	9.00	.001
Part D	55	9.17	1.472	0	.00	.000	6	1.00	.894	5	.83	.753	66	11.00	.001
Part E	5	.83	.408	0	.00	.000	0	.00	.000	1	.17	.408	6	1.00	.001
Total	281	46.83	5.492	4	.66	1.632	100	16.66	5.785	47	7.83	2.401			

5.6.3 Revised According to Expert Perceptions

The following aspects were revised and integrated into the components according to the analysis of the quantitative and qualitative responses:

(1) An example of autism behaviour and capability information related to spatial learning and cognitive learning has been included in the description of the component.

(2) Examples of spatial knowledge, wayfinding behavior, and cognitive maps, learning modality, and training environment information have been included in the description of the component to give more clarification on those components.

5.7 Expert Evaluation of Haptic-Based Virtual Environment Framework: Standards Evaluation by Case Study: Designers and Developers

Simply stated, standard evaluation is the process of determining whether the components in a proposed framework meet the quality, purpose, and standards established by the majority of designers or developers from an industry perspective for any HBVE. Therefore, this evaluation was carried out with the help of two types of expert groups: HBVE designers and developers who contribute to the development of haptic-based applications, with the appropriate documentation, such as details of the instruments used and processes followed. An analysis has been carried out at the end of this section in order to validate the HBVE design framework. The quantitative and qualitative methods, which were used in the previous expert evaluations (sections 5.5 and 5.6), were used to perform the analysis of the findings of this part, respectively.

5.7.1 Instrument Used

The following aspects provide the details of the instruments used to conduct this evaluation:

Proposed Framework Specification Document: This document provides the details of the revised version of the framework after the second expert evaluation.

Case Study Document: The case study presented in this document is based on a real-world scenario. This case study scenario is described in the following section. 5.7.3. This document describes the underlying issues and is expected to provide a better solution by thoroughly defining the highlighted issue or requirement and finding the best and most relevant components from the proposed framework as a solution for this case study. The experts (HBVE designer and developer) who participated in this case study evaluation were responsible for providing information about HBVE application design and development. In addition, the purpose of this document is to provide not only the details of the case study, but also a set of checklists of the components proposed in the HBVE-Framework. Even though there are different sets of checklists from various industries, each with their own format, this checklist itself is prepared based on an industry standard format (industry practise) to list out the necessary components to design and develop an HBVE application. Therefore, according to the standard format, the following information is shared with the expert's group in two different parts:

(1) Part A: Provide an overview of the case study for the design or development of HBVE applications (such as: title of the case study, the scenario of the case study, and the targeted age range of autistic people).

(2) Part B: Provide the checklists with the details of the HBVE application components according to the three major phases in the pattern (control, model, and view) and the "input of controller" from the initial pattern of the proposed framework.

Standards confirmation of expert satisfaction survey: This inspection was conducted based on the questionnaire which adopted the software product quality model by ISO/IEC 25010:2011-Systems and Software Quality Requirements and Evaluation (SQuaRE) (Estdale & Georgiadou, 2018). Table 5.9 shows the details of the selected characteristics and sub-characteristics derived from the software product quality model with short notes and the number of questions attempted in the questionnaire.

Table 5.9: It shows the characteristics derived from the quality model by ISO/IEC 25010: 2011 – SQuaRE with notes and survey questions used in the questionnaire

Characteristics	Notes	Survey Question
Appropriateness recognizability	The designer is capable of identifying the required components as well as the framework pattern.	Did you find the components and framework structure that were presented to be relevant to your development process?
Learnability	The designer will be able to learn the framework's structure as well as the component patterns that make up the framework.	Do you believe this framework is straightforward and clear to understand in terms of its components and framework structure?
Portability	The designer was able to use this framework to transfer haptic signals to the HBVE application through the haptic interface.	Do you believe that by applying this framework to HBVE development, it will be able to support the application in terms of transferring haptic signals via a haptic interface?
Usability	The designer can use this framework and its components to construct an HBVE application.	Do you believe that this framework can be utilised as a guideline for the development of HBVE applications?
User error protection	The designer is able to construct an HBVE application while reducing the likelihood of risk or errors.	Do you believe that by utilising this framework, the developed application will be able to reduce potential errors during haptic interface and virtual object interaction?
Accessibility	The designer can use this framework and its components to develop an HBVE application for autistic people to learn and improve their spatial learning and cognitive mapping skills.	Do you believe this framework can assist the developer in developing an HBVE application that enables autistic people to improve their spatial learning and cognitive mapping skills?
Modularity	The designer can utilise this framework to change components in order to accommodate people with autistic spectrum disorders, spatial abilities, and haptic feedback, all with minimal influence on the other components.	Do you believe that by utilising this framework, a developer will be able to easily switch from one component to another with minimal influence on the overall performance of the haptic application?
Functional Appropriateness	This framework only contains the components that are absolutely necessary.	Do you believe that this framework is only presented with components that are relevant to the development of HBVE applications?
Co-existence	This framework enables the developed HBVE application to function efficiently while integrating with the haptic interface.	Do you believe that by utilising this framework, the developed HBVE application will be able to function effectively with the use of a haptic interface?

5.7.2 Case Study Protocol

Expert review is conducted on the basis of the instruments indicated earlier in section 5.7.1 (the revised version of the proposed framework specification document, a case study document with the checklists and standards confirmation of expert satisfaction survey form). The experts are expected to review the provided instruments and identify and indicate in the checklists which components should be used to construct the HBVE application in accordance with the case study that has been provided. After finishing the case study, the experts were asked to provide feedback based on their perceptions of their experience with the case study as well as their opinions on how the HBVE application should be designed and implemented in the standards confirmation survey instrument.

5.7.3 Data Analysis

This section, similar to the previous two expert evaluations, includes two types of analysis methods that were used, namely quantitative and qualitative analysis.

5.7.3.1 Quantitative Analysis Method

The close-ended questions and data from the expert's checklists, as well as the standards of confirmation from the expert satisfaction survey, were subjected to quantitative analysis, which was quantified by the mean and standard deviation of the respondents.

5.7.3.2 Qualitative Analysis Method

The qualitative analysis method was used to examine the expert respondents' subjective opinions or justifications for selecting or rejecting components from the case study checklist document. Where the subjective responses are analysed based on their unique remarks. The positive opinion signified the expert's acceptance of the components without requiring any further changes to the framework's proposed components.

Meanwhile, negative opinion refers to those components that did not meet the experts' standards and hence required rapid attention.

5.7.4 Case Study: Relevant Components for Autistic people to Learn Spatial and Cognitive Mapping Skills Through Haptic Interface

The purpose of this section is to determine whether the revised HBVE-Framework is applicable to the development of an HBVE application that will allow autistic people to improve their spatial knowledge and cognitive mapping skills through the use of a haptic interface. This evaluation was based on the following real-life case study, which used haptic technology as a development solution:

"*According to M. Zhang et al. (2020), children with autism have difficulties with cognition tasks, particularly those requiring spatial awareness in an urban environment. There are a variety of difficulties that these children experience, including difficulty finding directions and prepositions, placing an object in the appropriate position, using a map as guidance, and remembering and recalling the direction or objects. There are numerous activities or tasks that can allow children to improve their spatial awareness, but most parents or caregivers choose not to allow their children to practise in a real environment owing to worries about their safety. Therefore, it is necessary to develop a virtual environment to let the children practise and improve their spatial knowledge and cognitive mapping skills. Furthermore, because there is no sense of touch during interaction with a virtual object in a virtual environment, the development should incorporate a haptic interface as an input modality into the virtual environment.* "

In this case study, the expert was expected to apply their knowledge and real-life haptic application development experience to identify and determine the necessary components from the revised HBVE-Framework that were suitable for development in the application.

5.7.4.1 Result: Summarization of the Selected Components

Table 5.10 shows the components that were selected as development solutions for this particular case study by each of the experts who participated in it. The findings are analysed and presented in accordance with each component of the HBVE-Framework. While most experts have selected the same components for each other for the majority of the components in this particular case study, there are still differences of opinion on some of the components, such as the types of haptic feedback, audio effects (Aud), navigation map (NM), and techniques of interaction and manipulation. This is most likely due to the use of various forms of haptic interfaces as well as the availability of other navigation support (for example, the AHSON algorithm).

Table 5.10: Selected Relevant Components by Experts for the Case Study

C.No.	Main Component	Sub Component	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	N	mean	SD
1	Autism Behaviours and Capabilities		✓	✓	✓	✓	✓	✓	6	1.00	.00
2	Learning Modality		✓	✓	✓	✓	✓	✓	6	1.00	.00
3	Training Environment		✓	✓	✓	✓	✓	✓	6	1.00	.00
4	Spatial Ability		✓	✓	✓	✓	✓	✓	6	1.00	.00
5	Spatial Knowledge		✓	✓	✓	✓	✓	✓	6	1.00	.00
6	Wayfinding Behaviours		✓	✓	✓	✓	✓	✓	6	1.00	.00
7	Cognitive Map		✓	✓	✓	✓	✓	✓	6	1.00	.00
8	Physical Haptic Interface		✓	✓	✓	✓	✓	✓	6	1.00	.00
9	Haptic Rendering		✓	✓	✓	✓	✓	✓	6	1.00	.00
10	Haptic Collision Detection		✓	✓	✓	✓	✓	✓	6	1.00	.00
11	Haptic Feedback	Force Feedback (FF)		✓	✓		✓		3	.50	.55
		Vibrotactile Feedback (VtF)	✓			✓			2	.33	.52
		Electrotactile Feedback (EtF)							0	.00	.00
		Ultrasound Tactile Feedback (UtF)						✓	1	.17	.41
		Thermal Feedback (TE)							0	.00	.00
12	Control Algorithm		✓	✓	✓	✓	✓	✓	6	1.00	.00
13	Visual Rendering		✓	✓	✓	✓	✓	✓	6	1.00	.00
14	Virtual Collision Detection		✓	✓	✓	✓	✓	✓	6	1.00	.00
15	Simulation Engine		✓	✓	✓	✓	✓	✓	6	1.00	.00
16	Graphics Scene Activity	Object Modelling (OM)	✓	✓	✓	✓	✓	✓	6	1.00	.00
		Motion and Visual Effects (MVE)	✓	✓		✓	✓		4	.67	.52
		Audio Effects (Aud)	✓			✓		✓	3	.50	.55
		Point of View (POV)	✓	✓	✓	✓	✓	✓	6	1.00	.00
		Object Detection and Object Avoidance (ODOA)	✓		✓	✓		✓	4	.67	.52
		Navigation Map (NM)	✓			✓			2	.33	.52
		Instruction and Navigation Support (NIS)	✓	✓	✓	✓	✓	✓	6	1.00	.00
17		Egocentric	✓	✓		✓	✓		4	.67	.52

	Spatial Visualization Processing Coding System	Allocentric	✓		✓		✓	✓	4	.67	.52
18	Interaction and Manipulation	Ecocentric Metaphor		✓		✓	✓	✓	4	.67	.52
		World-In-Miniature (WIM)							0	.00	.00
		Automatic Scaling (AS)							0	.00	.00
		Egocentric Metaphor	✓	✓		✓	✓		4	.67	.52
		Virtual Hand Metaphor (VHM)	✓	✓	✓			✓	4	.67	.52
		Virtual Pointer Metaphor (VPM)	✓			✓	✓		3	.50	.55
19	Cognitive Map Navigation		✓		✓	✓		✓	4	.67	.52
20	Wayfinding	Landmark Knowledge (LK)	✓	✓	✓	✓	✓		5	.83	.41
		Route Knowledge (RK)	✓	✓		✓	✓	✓	5	.83	.41
		Survey Knowledge (SK)			✓	✓		✓	3	.50	.55
		AHSON Algorithm	✓	✓	✓	✓	✓	✓	6	1.00	.00
21	Rendering Content Display		✓	✓	✓	✓	✓	✓	6	1.00	.00
22	Sensory Feedback	Haptic Feedback	✓	✓	✓	✓	✓	✓	6	1.00	.00
		Visual Feedback	✓	✓	✓	✓	✓	✓	6	1.00	.00
		Auditory Feedback	✓			✓		✓	3	.50	.55
23	User Achievement		✓	✓	✓		✓		4	.67	.52
24	Spatial Representation Information		✓	✓	✓	✓	✓	✓	6	1.00	.00
25	Data Repository		✓	✓	✓		✓		4	.67	.52
Total Selection:			38	32	31	36	33	32			

5.7.4.2 Result: Detailed Information of the Selected Components

This section covers additional in-depth information about the feedback that has been gathered from the experts. Following the feedback that has been collected, the structural design of the HBVE-Framework will be explained in four stages. These stages are as follows: input of controller, controller, model, and view. A summary of the collected feedback based on each of the components to be selected or rejected was made, and experts were also required to provide their remarks (opinions) on why those particular components should be selected or rejected in each case. The remark was required to explain that they were determining and justifying their decision on that specific component for the future development of HBVE applications through this similar type of case study. Based on the expert’s selection in Table 5.10 from the proposed HBVE-Framework, the following details show one of the expert's selections and decisions for this particular case study (refer to Table 5.11):

Table 5.11: Remarks by One of the Experts for the Case Study

C.No.	Main Component	Sub Component	Selected	Rejected	Remarks
1	Autism Behaviours and Capabilities		✓		Getting to know the person with autism's behaviour and abilities is important because each person has a different set of characteristics, symptoms, and abilities. So, the proposed application should meet their needs by providing the right method for communication and interaction with haptic technology.
2	Learning Modality		✓		Use this component to figure out what learning modalities are best for autistic people to learn about their spatial awareness.
3	Training Environment		✓		There is a chance that autistic people might need spatial knowledge in different kinds of places. So, this component is needed to choose the right environment to build a virtual world that can give the person real-world knowledge.
4	Spatial Ability		✓		This component of an application is needed in order to be able to learn about how locations and things are connected in the first place.
5	Spatial Knowledge		✓		Because spatial knowledge is good at finding the direction or where things are, this component is important. For example, this could be knowledge of routes or landmarks as a way to get to a goal.
6	Wayfinding Behaviours		✓		This component is needed to understand how all the spatial information about the object is used to figure out its direction and where it is in the environment.
7	Cognitive Map		✓		This component is needed to understand how autistic people learn, store, and recall spatial knowledge.
8	Physical Haptic Interface		✓		The user can select the type of haptic interface they want to use to interact with the virtual world, and they can also see how their sense of touch changes as they interact.
9	Haptic Rendering		✓		This component is needed to process the haptic information that the user sends through the haptic interface.
10	Haptic Collision Detection		✓		There must be this component in order to process and check for collisions when someone is using a haptic interface in a virtual world.
11	Haptic Feedback	Force Feedback (FF)		✓	This kind of feedback isn't very convincing about how well an autistic person can control their bodies and how much information they can process.
		Vibrotactile Feedback (VtF)	✓		For this type of case study, the vibration method was preferred as feedback to an autistic person, and this was due to the pattern and personalization of vibrotactile effects.
		Electrotactile Feedback (EtF)		✓	This kind of feedback is usually associated to skin problems like skin irritation, which can make it hard for an autistic person to control the interaction.

		Ultrasound Tactile Feedback (UtF)		✓	This kind of feedback costs a lot and isn't as noticeable as the other kinds of feedback.
		Thermal Feedback (TE)		✓	This kind of feedback requires a lot of energy when the user uses a haptic interface.
12	Control Algorithm		✓		To take control of the position sensors when the haptic interface is used and to deal with haptic communication problems.
13	Visual Rendering		✓		It is used for processing and displaying virtual objects and visual effects in real time.
14	Virtual Collision Detection		✓		It is used to find out if people and virtual objects collide in a virtual environment.
15	Simulation Engine		✓		To combine all the necessary inputs to make a virtual environment for autistic people.
16	Graphics Scene Activity	Object Modelling (OM)	✓		To create and model the virtual object as well as the scene's situational environment.
		Motion and Visual Effects (MVE)	✓		This component is in charge of the virtual object's movement and visual effects, as well as the characters themselves.
		Audio Effects (Aud)	✓		This produces the sound effect, for example, when the first-person or third-person controller walks around the screen.
		Point of View (POV)	✓		To figure out how the autistic person sees things, whether they are a first-person or third-person controller.
		Object Detection and Object Avoidance (ODOA)	✓		This component is needed for the object to be able to see and avoid objects when it is near other objects.
		Navigation Map (NM)	✓		This component is intended to assist autistic people in determining how to get around and allows the user to evaluate distance and view the entire environment from a single perspective.
		Instruction and Navigation Support (NIS)	✓		This component is needed to help autistic people who should get the right instruction to move around in a virtual world.
17	Spatial Visualization Processing Coding System	Egocentric	✓		This component helps autistic people by letting them interact with things in a virtual world.
		Allocentric	✓		This component helps with the processing of spatial information as it moves between different objects.
18	Interaction and Manipulation	Exocentric Metaphor		✓	It necessitates very accurate interaction and manipulation, including the deformation of a virtual object, which autistic people will find more difficult to control with this type of metaphor.
		World-In-Miniature (WIM)		✓	The precise control of virtual object by autistic people is challenging and they are required to spend more time struggling with fine grained navigation.

		Automatic Scaling (AS)		✓	This is not suitable for those with autism, as the automated scaling aspects make it difficult to regulate discomfort and suffering during interactive activities, as when dealing with a haptic interface in a complex virtual environment.
		Egocentric Metaphor	✓		It needed to interact with virtual objects.
		Virtual Hand Metaphor (VHM)	✓		Large virtual objects can be grabbed or moved with this method.
		Virtual Pointer Metaphor (VPM)	✓		Useful for picking out virtual objects on a small scale.
19	Cognitive Map Navigation		✓		It helps the user visualise the location or objects by remembering their information.
20	Wayfinding	Landmark Knowledge (LK)	✓		To figure out the direction by using landmark information.
		Route Knowledge (RK)	✓		To figure out the direction by using route information.
		Survey Knowledge (SK)		✓	Even though this component is effective when using cognitive mapping skills, it takes a long time for autistic people to use this type of knowledge.
		AHSON Algorithm	✓		Useful as navigational support in a virtual world to help find the way to an object or location.
21	Rendering Content Display		✓		Used to process the information received in between controller and model stages for autistic users.
22	Sensory Feedback	Haptic Feedback	✓		This component provides vibrations that autistic people can feel as a sense of touch when they interact with virtual objects.
		Visual Feedback	✓		This component provides visual feedback for autistic users, such as virtual objects and the effects they have on the content itself.
		Auditory Feedback	✓		This component provides auditory feedback to autistic users, such as footsteps sounding during walking in a virtual environment.
23	User Achievement		✓		To show how many points were earned during practise with the application.
24	Spatial Representation Information		✓		To process spatial information such as landmarks or route information.
25	Data Repository		✓		To keep track of and update the information of people who are autistic, especially their scores when they practise with an application.

5.7.5 Standards Confirmation According to Expert Perceptive

This section provides the average values of all expert responses in terms of their perspective and experience of the revised framework based on each characteristic from the standards inspection or confirmation (refer to Figure 5.18). The findings revealed that all of the experts were in agreement with the inclusion of all of the components and the structure of the framework, which fulfilled the requirements of ISO/IEC 25010 and the expectations of the criteria. More than four experts, with an average value greater than 0.9, demonstrated that the developers can easily use this framework to change any of the components according to the characteristics or needs of autistic people, particularly in terms of their modalities, spatial learning elements, and the mode of sensory feedback, with minimal impact on the other components. Furthermore, the experts agreed ("User error protection" overall average value: > 0.5) that this framework has the ability to develop an HBVE application that can reduce the potential for risk or errors during the interaction with a haptic interface, despite the fact that the rest of the experts partially agreed that there is a possibility to increase the potential for risk or errors due to the use of different sets of haptic interfaces and the degree of freedom (DOF). The experts admitted that this proposed framework can be used as a guideline to develop an HBVE application because it is easier to understand and it only presents the required components for the HBVE application development with a special focus on autistic people to learn and improve their spatial knowledge and cognitive mapping skills (with an overall average value of > 0.9 for "Usability," "Functional Appropriateness," and "Learnability").

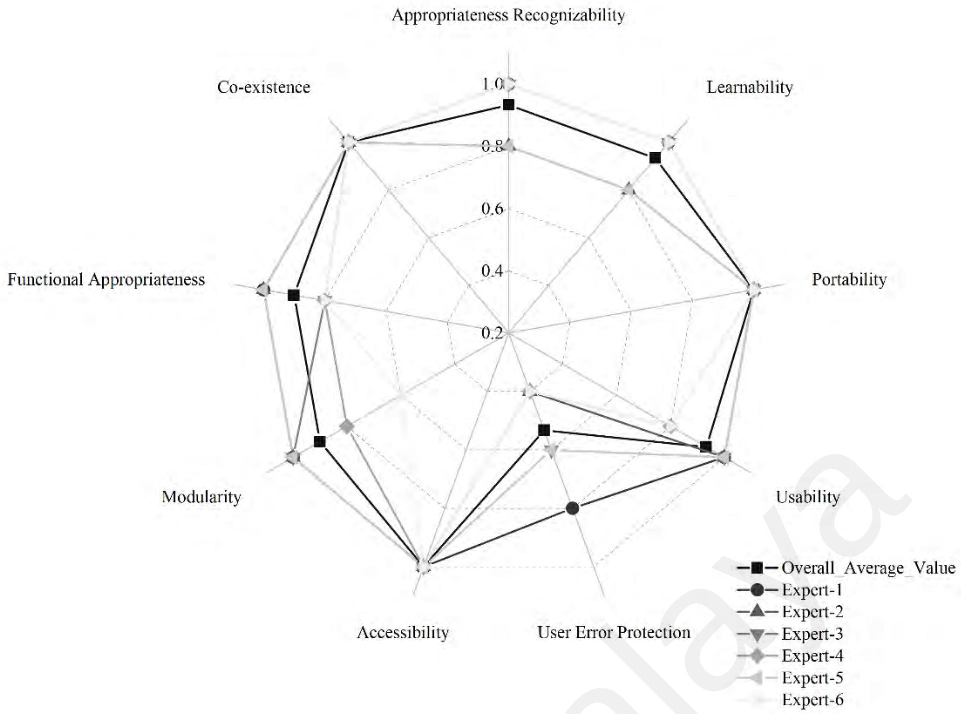


Figure 5.18: Overall Average Values of Standard Confirmation Responses for Revised Version of HBVE-Framework

5.7.6 Revised According to Expert Perceptions

The final version of the proposed framework for this research was revised and reproduced after the changes were made to the components or after the addition of a new component based on expert suggestion and opinion (refer to Figure 5.19). The framework's final version shows the changes made to the existing components since the initial version, as well as the newly introduced component. This final version of the framework will be used to construct an HBVE application that will develop and improve spatial knowledge and cognitive mapping skills in autistic people.

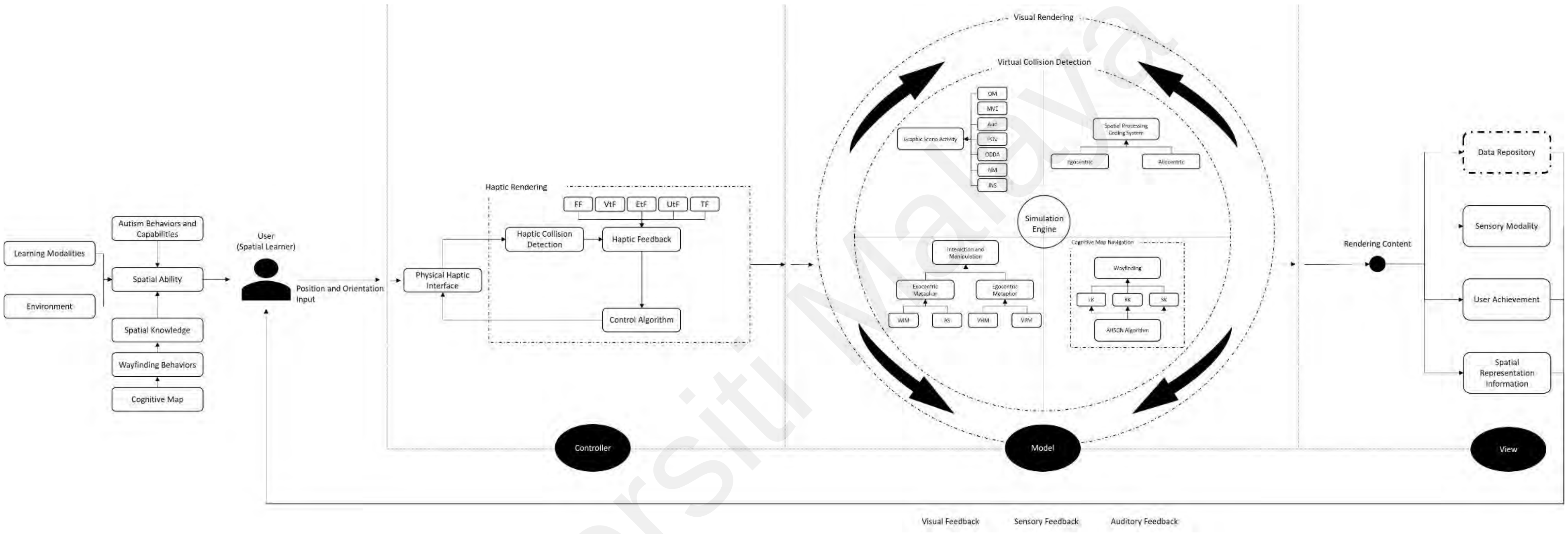


Figure 5.19: The Final Version of Haptic-Based Virtual Environment Framework for Autistic people

5.8 Summary

A new HBVE-Framework for autistic people was proposed in this chapter, which emphasizes the development and improvement of autistic people's spatial leaning and cognitive mapping skills. An expert evaluation was carried out in order to determine and confirm that the proposed framework can be used to achieve the study goal. Initially, academicians were asked to evaluate it based on their indubitable opinions regarding the components, the structure of the framework, and the relationships that existed between those components within the framework. The second stage of this evaluation will be focused on another set of expert groups (researchers and developers) who will provide their opinions and suggestions (based on the case study that aligns with this research objective) on the revised version of this framework based on their experience and skills with the development or research in the fields of haptic technology and spatial cognition. Finally, all of the suggestions and recommendations were taken into consideration and incorporated into the final version of the HBVE-Framework, which is expected to achieve the goals of this research.

CHAPTER 6: REAL-TIME HAPTIC RENDERING INTERACTION SIMULATION DEVELOPMENT AND EVALUATION

This chapter presents the development of a simulation of the haptic-based virtual environment (HBVE) to demonstrate the logical and process view of the proposed HBVE-Framework. The choice of hardware, software, and the implementation of the visual user interface through haptics will be highlighted. At the end of the section, the evaluation of the HBVE simulation conducted with ASD and the outcome of the evaluation were discussed.

6.1 Development of Haptic Based Virtual Environment Simulation

The development of the HBVE simulation is based on concepts and suggestions given by one of the experts from the case study conducted with the HBVE-Framework, which has been presented in chapter 5. The development of the simulation is discussed in greater detail in the following sections.

6.1.1 Software and Hardware Requirements

This section provides an overview of the software and hardware requirements required for the development of the simulation.

6.1.1.1 Autodesk 3Ds Max

This software is used to create 3D models with the help of "x," "y," and "z" coordinates. Polygon group meshes techniques will be used to minimise the number of polygons so that they can smooth the user's movements in virtual environments as well as for the purpose of expediting the rendering process. Meanwhile, the spline and mesh line methods will be used to make 3D object modelling easier (Inventor & Tooling, 2002).

6.1.1.2 Unity 3D with C Sharp (#) Constructor

Generally, this software is used for creating the walk-through function so the user can navigate through the simulation. The "Collision Detection" schema will be applied in order to avoid collision problems between other objects and to create a smooth navigation experience. Apart from this, this software also used to create a communication between the three common interfaces in HBVE, development: haptic interface, user interface (UI) and virtual interface (S. L. Kim et al., 2014). The C# constructor was used to form specific functions or features in the HBVE simulation.

6.1.1.3 MATLAB Compiler SDK

The MATLAB analytical software used plotting functions to produce two-dimensional and three-dimensional graphics based on the haptic feedback signal data from the performance of autistic people in a HBVE. The MATLAB Complier SDK is also used to integrate the C/C++ shared libraries from MATLAB with the haptic device for reading real-time data (Matlab, 2012).

6.1.1.4 MYO Gesture Control Armband

The MYO gesture control armband is a wearable sensor gesture recognition device that is used to detect and read the haptic or tactile (vibrotactile) signals via the user's muscle activities. The haptic/tactile signals are divided into two different types of sensors: (1) electromyography (EMG) sensors to measure the user's electrical impulses from the user's muscles; and (2) highly sensitive nine-axis inertial measurement units (IMU) to measure the user's force, velocity, and orientation during the interaction with a HBVE (Javaid et al., 2021). This haptic device can control virtual objects in a HBVE wirelessly with *Bluetooth* smart signals and can also be compatible with the following operating systems: Windows, Mac, iOS, and Android. The haptic feedback generated from this device can be classified into three different vibration groups: short, medium, and long.

6.1.2 Interface Option for Haptic Interaction

This section provides an overview of available interface options for haptic interaction.

6.1.2.1 Haptic Interface

A haptic interface is used to allow a user to communicate with a virtual environment via their interactions and sensations. Haptics are generally referred to as types of human-computer interaction technology that enable us to process tactile or kinesthetic feedback as a sensation to control the user's gestures or actions on a haptic device (Kirkpatrick & Douglas, 2002). A haptic interface is built with a sensor system to process and generate electrical signals through different sensory interactions in virtual environments (non-immersive environments). Every haptic signal on the haptic interface processes different information, either by sending or receiving signals during interactions with virtual environments, with the goal of providing the user with a sensation feeling in the form of a vibration.

6.1.2.2 Audio Interface

An audio interface in the HBVE may not have a technically complex aspect compared to the other two interfaces; however, it's still an important aspect of creating the user's sensations and achieving full immersion. Usually, an audio interface in the HBVE process through positional audio (multi-speaker audio) enables us to provide a real-time environment illusion. Positional audio is completely a platform for users to view the virtual environment through their ears because it's able to draw the user's attention through the provided cues (Andreasen et al., 2019).

6.1.2.3 Visual Interface

The sight sensory system is an important aspect for users during the interaction with virtual environments because it provides meaningful information that allows the users to visualise and see the virtual objects in real time. Thus, visual interfaces can be classified into two types in a HBVE: stereoscopic and monoscopic visual interfaces (Akamatsu et al., 1995). The stereoscopic visual interface is usually formed based on two aspects: a visual interface with two projection screens (such as head-mounted displays (HMDs), binocular monitors (omni'), and video glasses); and a visual interface with one projection screen (such as stereoscopic screens and shutter glasses) (Choi et al., 2017). Meanwhile, the monoscopic visual interfaces are formed based on head-up displays or see-through HMDs.

6.1.2.4 Graphical Interface

A graphical interface is a platform which enables a user to interact with haptic devices as pointing in a virtual environment. This interface usually uses any form of graphic elements such as icons or menus instead of text characters to display meaningful information to user to communicate with HBVE (Greg S Ruthenbeck & Reynolds, 2015).

6.1.3 Simulation of Virtual Environment

A Virtual Environment (VE) is defined as a user's imagination of non-immersion in a computer-based environment, and it depends on many real-time factors such as texture, lighting, and real-world sound effects. It's filled with 3D objects and animated behaviours that can be seen as virtual objects inside the computer screen to create a real-time visual effect for users (Johns, 2003). Figure 6.1 shows the simulation of the virtual environment based on the HBVE case study outcome from the previous chapter (Chapter 5) with different types of virtual screens. The entire main and sub components (refer to Table 6.1) are mapped and presented accordingly in the virtual screens. Section 6.1.4 and 6.1.5 provides the description of each virtual screen in this simulation.

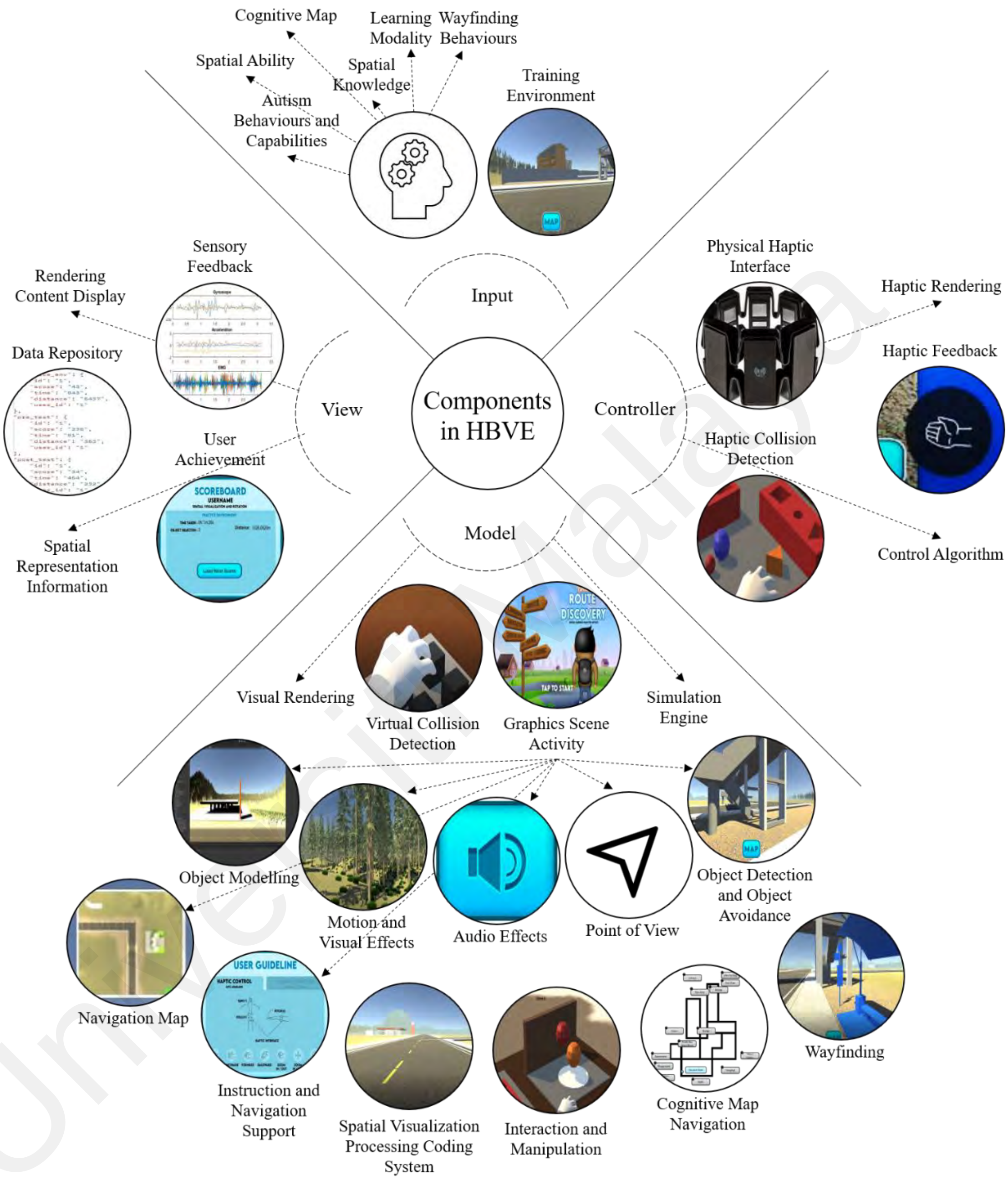


Figure 6.1: The representation of components in virtual environment

Table 6.1: Components of proposed haptic-based virtual environment framework

MC. No.	Main Component	SC. No.	Sub Component
1	Autism Behaviours and Capabilities		
2	Learning Modality		
3	Training Environment		
4	Spatial Ability		
5	Spatial Knowledge		
6	Wayfinding Behaviours		
7	Cognitive Map		
8	Physical Haptic Interface		
9	Haptic Rendering		
10	Haptic Collision Detection		
11	Haptic Feedback	10.2	Vibrotactile Feedback (VtF)
12	Control Algorithm		
13	Visual Rendering		
14	Virtual Collision Detection		
15	Simulation Engine		
16	Graphics Scene Activity	15.1	Object Modelling (OM)
		15.2	Motion and Visual Effects (MVE)
		15.3	Audio Effects (Aud)
		15.4	Point of View (POV)
		15.5	Object Detection and Object Avoidance (ODOA)
		15.6	Navigation Map (NM)
		15.7	Instruction and Navigation Support (NIS)
17	Spatial Visualization Processing Coding System	16.1	Egocentric
		16.2	Allocentric
18	Interaction and Manipulation	17.1	Ecocentric Metaphor
		17.1.1	World-In-Miniature (WIM)
		17.1.2	Automatic Scaling (AS)
		17.2	Egocentric Metaphor
		17.2.1	Virtual Hand Metaphor (VHM)
		17.2.1	Virtual Pointer Metaphor (VPM)
19	Cognitive Map Navigation		
20	Wayfinding	19.1	Landmark Knowledge (LK)
		19.2	Route Knowledge (RK)
		19.3	Survey Knowledge (SK)
21	Rendering Content Display		
22	Sensory Feedback	21.1	Haptic Feedback
		21.2	Visual Feedback
		21.3	Auditory Feedback
23	User Achievement		
24	Spatial Representation Information		
25	Data Repository		

6.1.4 Specifications of Component Development

In accordance with the information presented in the preceding section (Section 6.1.3), this section will provide the detailed information or specification of the development of the simulation of a haptic-based virtual environment based on the components that were selected. In addition, it will be aligned with Section 6.1.1, which will show how the software and hardware were utilized and supported for the development and integration of each of the components in order to make and finish the final product or simulation as expected. This comprehensive description of the development of the component will be separated into three distinct modules, namely the pattern of the controller, the pattern of the view, and the pattern of the model.

6.1.4.1 Pattern of the Controller

In this section, the configuration of the haptic device as a controller for the virtual environment will be presented. This configuration is comprised of a number of distinct steps, the first of which is the use of a collision detection algorithm for haptic devices, followed by the use of a control algorithm, and finally the implementation of a vibration algorithm through haptic devices.

(a) Collision Detecction for Haptic Device

A user needs a device that gives him or her the ability to feel the virtual object in order to manipulate or interact with it in a computer-based virtual environment. Using a collision detection algorithm, this is something that can be accomplished through the haptic device. During the interaction, the surfaces of the virtual object should not become interpenetrating; therefore, the purpose of this algorithm is to prevent that from happening (Choi et al., 2017). This algorithm is able to stop the surfaces at the point of any penetration when the user attempts to interpenetrate two surfaces in the virtual environment. Additionally, it will send haptic feedback information to the haptic device, which, in turn, will produce simulated resistant feedback for the user to indicate that the activity or operation is not permitted. The following algorithm (refer to Figure 6.2) provides an illustration of how the code functions and the actions that are taken into consideration during interaction between a haptic device and a virtual object.

```
void Start()
{
    _lastFramePosition = transform.position;
    XRDevice.SetTrackingSpaceType(TrackingSpaceType.RoomScale);
    _currentGrabObject = null;
    _isGrabbing = false;
}
void Update()
{
    transform.localPosition = InputTracking.GetLocalPosition(NodeType)+ ObjectGrabOffset;
    transform.localRotation = InputTracking.GetLocalRotation(NodeType);
    if (_currentGrabObject == null)
    {
        Collider[] colliders = Physics.OverlapSphere(transform.position, GrabDistance);
        if (colliders.Length > 0)
        {
            if (Input.GetAxis(InputName) >= 0.01f && colliders[0].transform.CompareTag(GrabTag))
            {
                if(_isGrabbing)
                {
                    return;
                }
                _isGrabbing = true;
                colliders[0].transform.SetParent(transform);
                if(colliders[0].GetComponent<Rigidbody>() == null)
                {
                    colliders[0].gameObject.AddComponent<Rigidbody>();
                }
                colliders[0].GetComponent<Rigidbody>().isKinematic = true;
                _currentGrabObject = colliders[0].transform;
                if (OtherHandReference.CurrentGrabObject != null)
                {
                    OtherHandReference.CurrentGrabObject = null;
                }
```

Figure 6.2: Shows an algorithm's logic for a haptic based Collision Detection

(b) Use of Control Algorithm (Component: Control Algorithm)

As previously stated, Figure 6.3 depicts the control algorithm that instructed the haptic device (MYO Armband) to minimize error during haptic device handling. These control algorithms combine the information collected from each IMU sensor, such as accelerometer, gyroscope, and quaternion, to obtain the position of the MYO Armband in 3-dimensional space, which means the user's position within the virtual environment (Sathiyanarayanan & Rajan, 2016). The position of MYO is accessible via *transform.localRotation* and other properties. The *myo_OnArmSynced* variable was used to maintain continuous synchronization on the MYO hub and position, as well as to notify the MYO Armband when a user action was detected.

```
void Update() {
    lock (_lock) {
        armSynced = _myoArmSynced;
        arm = _myoArm;
        xDirection = _myoXDirection;
        if (_myoQuaternion != null) {
            transform.localRotation = new Quaternion(_myoQuaternion.Y, _myoQuaternion.Z, -_myoQuaternion.X, -_myoQuaternion.W);
        }
        if (_myoAccelerometer != null) {
            accelerometer = new Vector3(_myoAccelerometer.Y, _myoAccelerometer.Z, -_myoAccelerometer.X);
        }
        if (_myoGyroscope != null) {
            gyroscope = new Vector3(_myoGyroscope.Y, _myoGyroscope.Z, -_myoGyroscope.X);
        }
        pose = _myoPose;
        unlocked = _myoUnlocked;
    }
}

void myo_OnArmSync(object sender, Thalmic.Myo.ArmSyncedEventArgs e) {
    lock (_lock) {
        _myoArmSynced = true;
        _myoArm = e.Arm;
        _myoXDirection = e.XDirection;
    }
}
```

Figure 6.3: Shows an algorithm's logic for a haptic based Control Algorithm

(c) Calibration of Haptic Device (Component: Haptic Rendering)

This element's actions are determined by the interaction of all of the subsidiary processes, which include haptic collision detection, a control algorithm, and haptic feedback. This combination can also be thought of as a haptic rendering framework. The generation of haptic feedback is one of the functions of this framework. During the course of an interaction with a virtual object, the simulation engine will make use of this framework to control the haptic device. This framework provides assistance in applying the forces, which can be generated or defined based on vibration and transmitted to the user through haptic devices. Figure 6.4 depicts the logic of an algorithm that is connected to or synced with the MYO Armband in order to generate the vibration that acts as either a force or haptic feedback for the user.

```
}
public void Vibrate (VibrationType type) {
    _myo.Vibrate (type);
}
```

Figure 6.4: Shows an algorithm's logic for haptic feedback via haptic rendering

(d) *Vibration Detecion via Haptic Device (Component: Haptic Feedback)*

This component is made possible through the connection between the haptic device and the interaction with the virtual object. The haptic feedback, also known as the impulse of force, will be received and generated based on these two parameters, which are the "Rigidbody" that is present in the virtual environment and the "accelerometer" that is detected from the haptic device. The use of both "Rigidbody" and "Accelerometer" values can form the force as a feedback interaction. Figure 6.5 depicts the logic of the algorithm for receiving and generating haptic feed

```
if (other.tag == "hand")
{
    if (count <= 2)
        count++;
    m_Rigidbody.isKinematic = false;
    m_Rigidbody.AddForce(m_NewForce, ForceMode.Impulse);
    intialAVector = thalmicMyo.accelerometer;

    StartCoroutine(calculateForceAfter2Seconds());
}
if (other.tag == "Finish")
{
    m_ObjectCollider.isTrigger = false;
    m_Rigidbody.isKinematic = true;
    m_Rigidbody.velocity = new Vector3(0, 0, 0);
}
```

Figure 6.5: Shows an algorithm's logic for the haptic feedback

6.1.4.2 Pattern of the Model

The configuration of the virtual interface as a model for the virtual environment will be presented in this section. This configuration is made up of a number of separate steps, the first of which is the number of scenes formed in the simulation engine, followed by the use of a graphical scene activity such as modelling virtual objects, motion, and visual effects, and finally the implementation of navigation maps, instructions, and navigation support.

(a) ***Development and Configuration of Main Menu and Scene Switch (Component: Simulation Engine)***

This activity eventually led to the generation of pre-rendered virtual scenes using a haptic device. This activity is managed by the "SceneManager" parameter, which has the ability to retrieve and load the scene for the user's view after it has been rendered. This activity will be activated when the user interacts with the haptic device. The logic of the algorithm for the processing of the scene rendering and loading is depicted in Figure 6.6.

```
public class ChangeSceneNextLevel : MonoBehaviour
{
    public void BtnNext(string scene_name)
    {
        SceneManager.LoadScene(scene_name);
    }
}
```

Figure 6.6: Shows an algorithm's logic for the scene rendering and loading

(b) ***Design and Implmentation of Virtual Objects and Elements (Component: Graphic Scene Activity)***

In the following subsection, it will discuss the implementation of virtual objects and their constituent parts based on the subcomponents that already emerge in graphic scene activity. It will concentrate and develop based on the configuration activities, such as modelling virtual objects, setting motion and visual or audio effects, creating a navigational map, and creating instructions and navigation support for the user.

Component: Configuration of Object Modelling

This procedure was carried out using both the SketchUp and Unity applications. After creating prototypes of each scenario or virtual environment with low and high fidelity, the process progressed to the next stage, which included five steps: setting up the precise task, building up with the available basic geometry as needed for each 3D model, adjusting the polygons and topology for a better rendering process and output, choosing the right materials and textures for natural effects, and finally mapping and applying lighting. The following figures (Figures 6.7 and 6.8) show an example of model development and configurations.

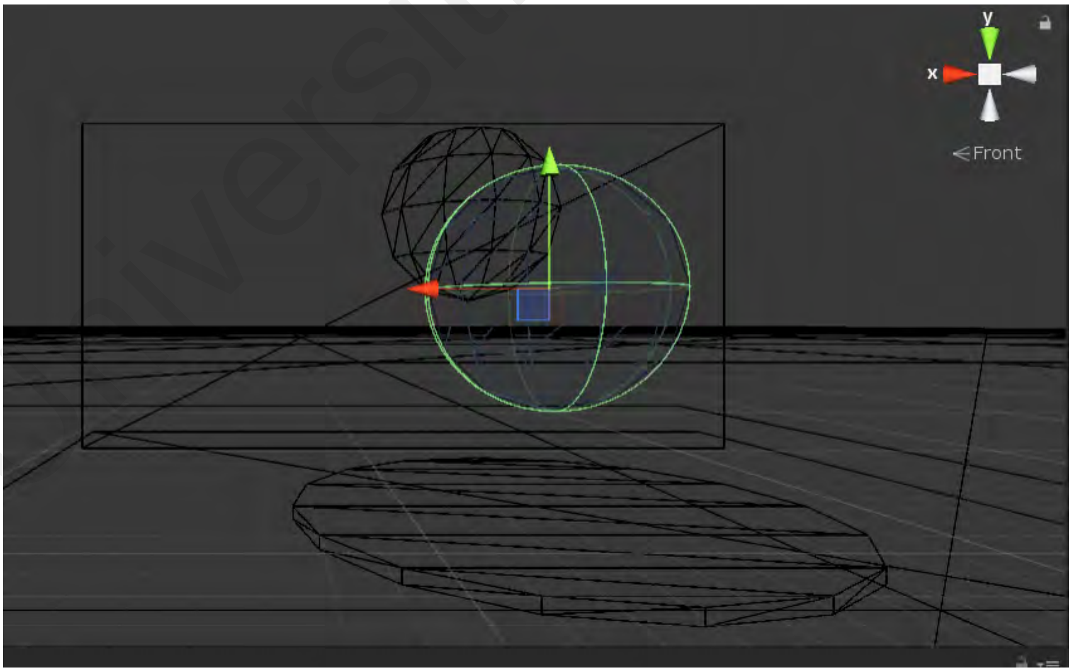


Figure 6.7: Shows an example of a geometry-based 3D model being developed

Appling Lighting Texturing Mapping

Figure 6.8: Shows an example of a 3D model applied with lighting and colour-based texture mapping

Component: Configuration of Motion and Visual Effects

The virtual hand, which was designed to "grab" and "release" a virtual object, necessitated the use of motion effects in order to have a powerful set of controls for adding realistic transitions and animation to the virtual object and virtual environment. Figure 6.9 depicts a hand-grabbing motion configuration that instructs how virtual objects should react in animated concepts when being grabbed and released. This is accomplished by combining the motion transitions *GrabAnimation* and *IdleAnimation*, which work together to provide realistic motion effects to the virtual object.

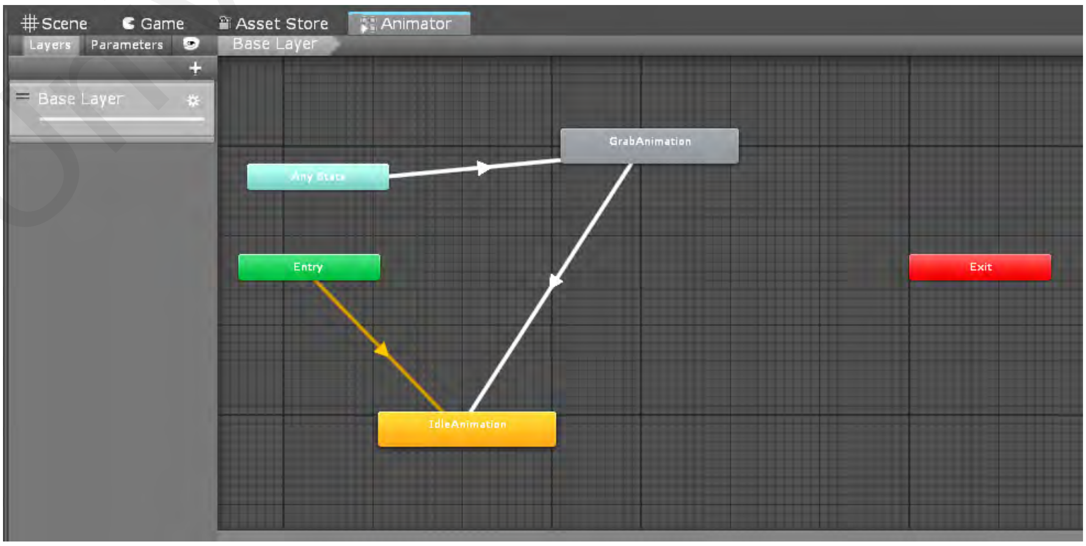


Figure 6.9: Shows an example of a hand-grabbing motion configuration

Component: Configuration of Audio Effects

The wind and footstep sound effects were implemented in the environment to simulate the real world and natural atmospheres. This was accomplished in the same manner as the settings shown in Figure 6.10 by making use of the assets that are already built into the Unity tools themselves. Meanwhile, Figure 6.11 shows an algorithm's logic for footstep audio effects.

Figure 6.10: Demonstrates an audio effect setting for a footstep

```
private void PlayFootStepAudio()
{
    if (!m_CharacterController.isGrounded)
    {
        return;
    }
    int n = Random.Range(1, m_FootstepSounds.Length);
    m_AudioSource.clip = m_FootstepSounds[n];
    m_AudioSource.PlayOneShot(m_AudioSource.clip);
    m_FootstepSounds[n] = m_FootstepSounds[0];
    m_FootstepSounds[0] = m_AudioSource.clip;
}
```

Figure 6.11: Shows an algorithm's logic for footstep audio effects

Component: Configuration of Object Detection and Object Avoidance

The Unity application is utilised in the configuration of this process. This procedure required working with the logic of the algorithm as well as the collider settings in the Unity platform itself. The "Capsule Collider" is what is used to trigger events, and this configuration is basically applied under the "Character Controller" (refer to Figure 6.12). During this time, the "Controller Colliders" parameter is automatically connected to the "Rigidbody" that is attached to the virtual object in the environment. This "Rigidbody" object will be pulled downward by gravity, and it will react to collisions with approaching virtual objects if the appropriate "Collider" elements are also present, and this will be done in order to avoid obstacles. Figure 6.13 depicts the logic behind a collision-based algorithm for obstacle detection and avoidance.

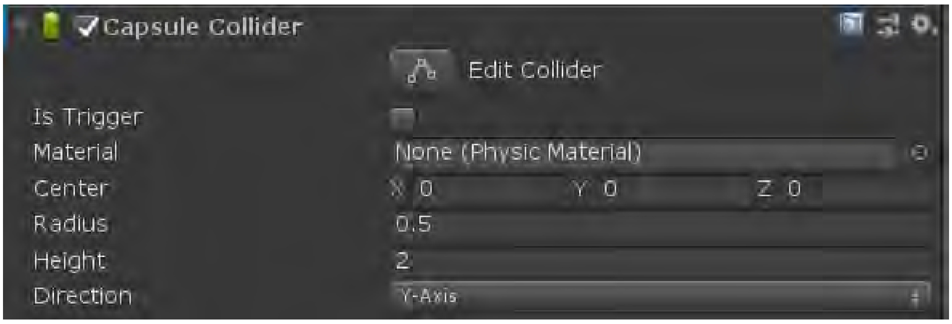


Figure 6.12: Demonstrates a collider setting for an obstacle avoidance

```
private void OnControllerColliderHit(ControllerColliderHit hit)
{
    Rigidbody body = hit.collider.attachedRigidbody;
    if (m_CollisionFlags == CollisionFlags.Below)
    {
        return;
    }

    if (body == null || body.isKinematic)
    {
        return;
    }
    body.AddForceAtPosition(m_CharacterController.velocity*0.1f, hit.point, ForceMode.Impulse);
}
```

Figure 6.13: Shows a collision-based algorithm's logic for obstacle detection and avoidance

Component: Configuration of Navigation Map

This component's features were implemented in the Unity environment. Figure 6.14 depicts the logic of the algorithm for implementing the navigation map. This logic is divided into two parts: one for applying the position of the user coordinate, and another for applying the rotation of the user's direction. In relation to the algorithm, this implementation used the UI (user interface) canvas model. This UI canvas is designed with "Mask" elements for the "Mask Image" which is built with "Raw Image" and "Render Texture". To display the map without any dynamic objects, such as the First Control Player (user), a "Quad" is created beneath the map. This configuration is displayed in Figure 6.15.

```
void LateUpdate()
{

        Vector3 newPosition = player.position;
        newPosition.y = transform.position.y;
        transform.position = newPosition;
        transform.rotation = Quaternion.Euler(90f, player.transform.eulerAngles.y, 0f);
    }
```

Figure 6.14: Shows an algorithm's logic for the transformation of coordinates and direction

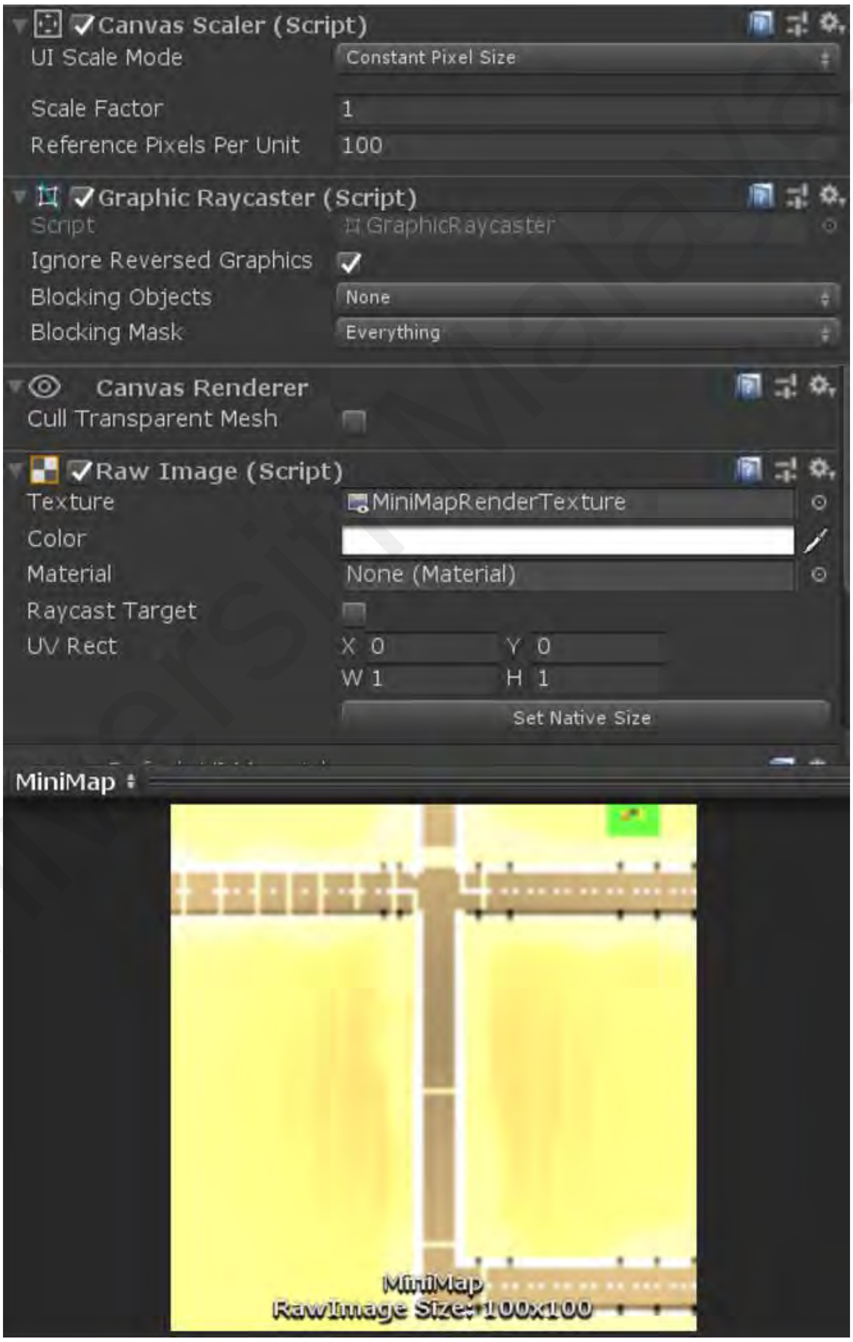


Figure 6.15: Shows a configuration of UI canvas for built navigation map

Component: Configuration of Spatial Visualization Processing Coding System

This method involves mapping the locations of the virtual objects in relation to ourselves. In a nutshell, this should be accomplished using standard coordinate systems. This process is carried out in an egocentric way by mapping virtual objects relative to ourselves. This indicates that in order for this process to work, it will be necessary for the user's brain to continually update the spatial relations that exist between the user and the objects as a result of the user's movement. Meanwhile, in the allocentric case, this is accomplished by mapping the virtual objects in relation to other objects or landmarks. Figure 6.16 illustrates how this procedure was transformed and mapped in a virtual-environment setting. The blue arrow line shows the mapping of the virtual objects in relation to other objects.

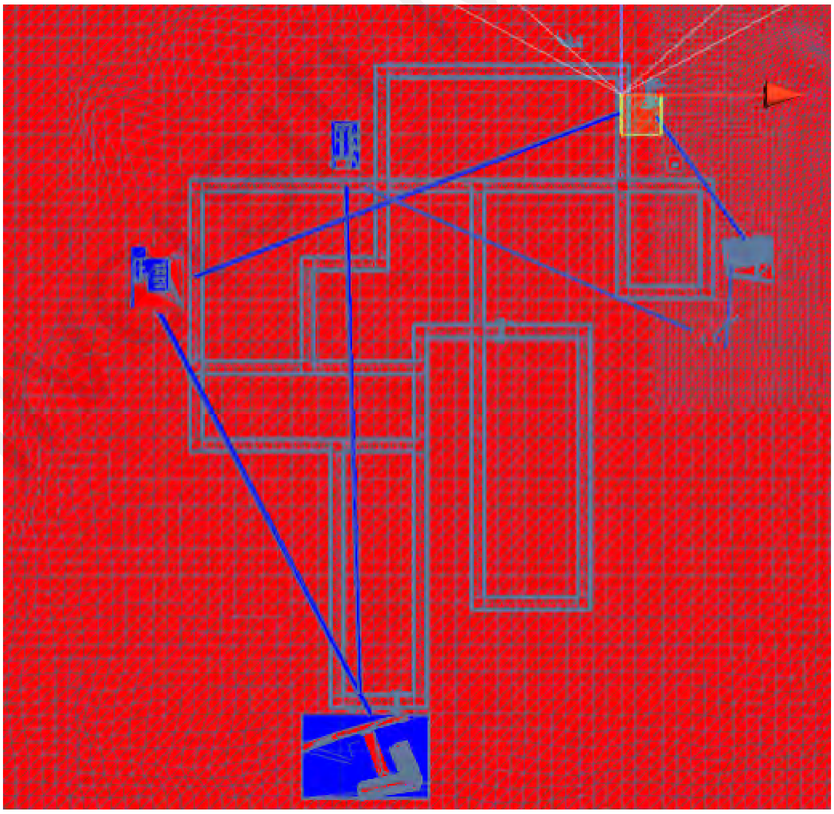


Figure 6.16: Shows a mapping of virtual objects in relation to other objects or landmarks

*(c) **Configuration: Object Selection***

This element is a significant task in virtual environments, and it is one of the activities that occurs most frequently during user interaction in a virtual environment. This implementation is carried out with the assistance of a virtual hand, which has the parameter tagged as "hand." After the user has triggered the object by selecting it, the object's colour will transform into a bright yellow. These two parameters, "rend.material.color" and "OnTriggerEnter," provide a window into the action that is being performed (refer to Figure 6.17).

```
private void OnTriggerEnter(Collider other)
{
    if (other.tag == "hand" && rend.material.color == Color.yellow)
    {
        GameManager.instance.scoreTb.text = "Score:1";
        GameManager.instance.timeCtrl.time = false;
```

Figure 6.17: Shows an algorithm's logic for an object selection

*(d) **Configuration: Object Manipulation and Interaction (Component: Interaction and Manipulation)***

In a virtual environment, the most common manipulation and interaction activities are translation and rotation. This activity must be translated into a simpler logic form as "grabbing" (selection) and "releasing" (movement, translation, or rotation) in order for the virtual hand to act as needed to manipulate a virtual object. Figure 6.18 depicts a hand controller algorithm that is used to instruct the virtual hand to grab and release the virtual object using a haptic device. This is accomplished by combining the variables _anim and _handGrab, as well as the virtual hand orientation algorithm (Figure 6.19) to control the spread of the fingers and the rotation algorithm (Figure 6.20) to reflect the arm's orientation via a haptic device. This rotation algorithm is based on the coordinate system of the haptic device (MYO Armband).

```
void Start ()
{
    _anim = GetComponentInChildren<Animator>();
    _handGrab = GetComponent<HandGrabbing>();
}

// Per-frame update
void Update ()
{
    //Set animator bool IsGrabbing to true if we are pressing grab
    if (Input.GetAxis(_handGrab.InputName) >= 0.01f)
    {
        if (!_anim.GetBool("IsGrabbing"))
        {
            _anim.SetBool("IsGrabbing", true);
        }
    }
    else
    {
        //If we release, set IsGrabbing to false
        if (_anim.GetBool("IsGrabbing"))
        {
            _anim.SetBool("IsGrabbing", false);
        }
    }
```

Figure 6.18: Shows an algorithm's logic for a hand controller

```
bool updateReference = false;
if (thalmicMyo.pose != _lastPose) {
    _lastPose = thalmicMyo.pose;

    if (thalmicMyo.pose == Pose.FingersSpread) {
        updateReference = true;

        ExtendUnlockAndNotifyUserAction(thalmicMyo);
    }
}
if (Input.GetKeyDown ("r")) {
    updateReference = true;
}
```

Figure 6.19: Shows an algorithm's logic for a virtual hand orientation

```
transform.rotation = new Quaternion(transform.localRotation.x,
                                    -transform.localRotation.y,
                                    transform.localRotation.z,
                                    -transform.localRotation.w);
```

Figure 6.20: Shows an algorithm's logic for a virtual hand rotation

(e) ***Configuration: Object Identification/Wayfinding (Component: Wayfinding)***

The Unity platform was utilised to develop this activity. The purpose of the wayfinding feature in a virtual environment is to give the user the ability to move around and locate the route that leads from their current location to their intended destination. This is accomplished through the use of the waypoint algorithm, which is depicted in Figure 6.21. The functionality of this algorithm logic was dependent on the waypoints being set up in the Unity platform as destination marks. In the meantime, the algorithm logic that was applied in order to provide the user with instructions or common information before beginning each of the wayfinding tasks is depicted in Figure 6.22. This function was performed in accordance with the parameter "sentences [taskNo - 1]". In addition, the setting for the waypoint dialogue manager in the Unity platform (refer to Figure 6.23) is required in order for it to be able to support both of the wayfinding algorithms (Figures 6.21 and 6.22) in the appropriate manner.

```
void CheckDistanceToWaypoint(float currentDistance)
{
    if(currentDistance <= minDistance+10f)
    {
        targetWaypointIndex++;
        UpdateTargetWaypoint();
    }
}
```

Figure 6.21: Shows an algorithm's logic for finding the nearest target object or location during wayfinding

```
void Start () {
    player.SetActive(false);
    Camera.SetActive(true);
    continueBtn.onClick.AddListener(hideDialouge);
    dialogueText.text = sentences[taskNo - 1] + "";

public void hideDialouge()
{
    Debug.Log("hide called");
    player.SetActive(true);
    Camera.SetActive(false);
    DialogueBox.SetActive(false);
    player.GetComponent<TimerController>().BeginTimer();
}
public void setTask()
{
    dialogueText.text = sentences[taskNo-1]+"";
}
```

Figure 6.22: Shows an algorithm's logic for a wayfinding with dialogue task instruction

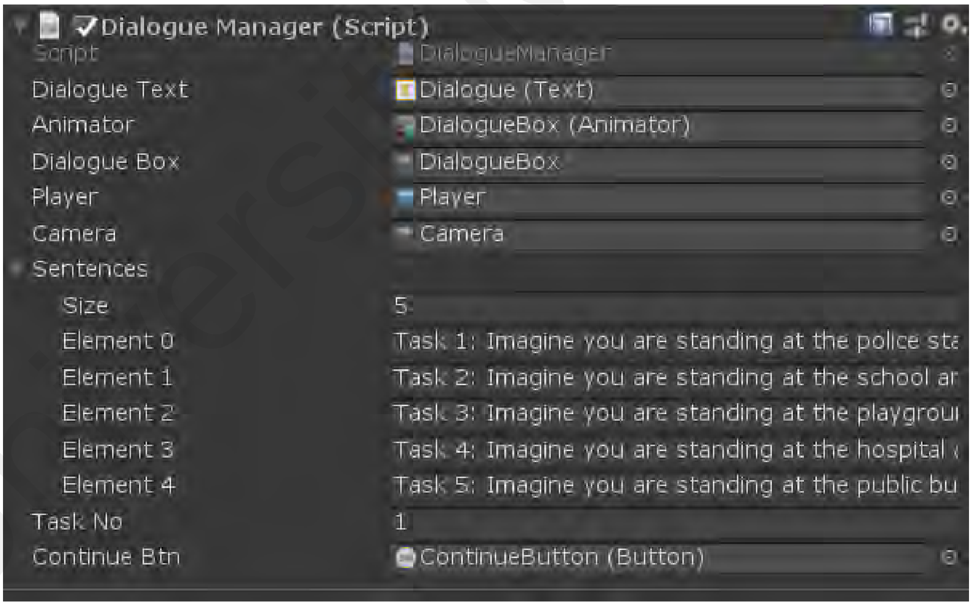


Figure 6.23: Shows a wayfinding configuration setting with dialogue task instruction in Unity

6.1.4.3 Pattern of the View

In this section, the configuration of the haptic device as a controller for the virtual environment will be presented. This configuration is comprised of a number of distinct steps, the first of which is the use of a collision detection algorithm for haptic devices, followed by the use of a control algorithm, and finally the implementation of a vibration algorithm through haptic devices.

(a) Configuration: Score Board Development (User Achievement)

This component was developed in Unity with Visual Studio in order to collect user scores, calculate them, and display them to the users. The value that is captured and calculated at various sets, such as the amount of time spent, the distance travelled, and the objects that are chosen or acquired, and the logic behind the algorithm are depicted in the following figures (Figures 6.24, 6.25, 6.26 and 6.27), which detail each of the different types of scores that can be calculated. In the meantime, the logic that was used to display the results or scores to users is depicted in Figures 6.28, 6.29, 6.30.

```
private void OnTriggerEnter(Collider other)
{
    if (other.tag == "Player")
    {
        other.GetComponent<ScoreCollection>().points++;
        dialogueManager.taskNo++;
        waypntCtrl = other.GetComponent<WaypointController>();
        if (isLastTask)
        {
            waypntCtrl.enabled = false;
            other.GetComponent<PlayerMove>().isGameOver = true;
            switch (MainGameManager.Maininstance.GameType)
            {
```

Figure 6.24: Shows an algorithm's logic for a trigger the player to score collection

```
private void OnGUI()
{
   GUI.Label(new Rect(30, 10, 200, 40), "<size=16>Score: </size>" + points);
    if (points >= 5)
    {
        FullText.text = "Congratulations! By completing the tasks";
    }
}
```

Figure 6.25: Shows an algorithm's logic for a score collection

```
public void UpdateTimerUI()
{
    secondsCount += Time.deltaTime;
    timeCounter.text = hourCount + "h:" + minuteCount + "m:" + (int)secondsCount + "s";
    if (secondsCount >= 60)
    {
        minuteCount++;
        secondsCount = 0;
    }
    else if (minuteCount >= 60)
    {
        hourCount++;
        minuteCount = 0;
    }
}
```

Figure 6.26: Shows an algorithm's logic for an update or count time travelled

```
private void Update()
{
    distance = (checkpoint.transform.position - transform.position).magnitude;
    distanceText.text = "Distance: " + distance.ToString("F1") + " meters";
}
```

Figure 6.27: Shows an algorithm's logic for calculate distance value between user and destiny

```
waypntCtrl.enabled = false;
other.GetComponent<PlayerMove>().isGameOver = true;
switch (MainGameManager.Maininstance.GameType)
{
    case MainGameManager.gameType.Practice:
        prac.SetActive(true);
        pre.SetActive(false);
        post.SetActive(false);
        PlayerScoreBoard_sc.practice_env.score.text = other.GetComponent<ScoreCollection>().points + "";
        PlayerScoreBoard_sc.practice_env.distance.text = distanceCp.distance + "0m";
        PlayerScoreBoard_sc.practice_env.time.text = time.text;
        break;
    case MainGameManager.gameType.Pre_test:
        prac.SetActive(false);
        pre.SetActive(true);
        post.SetActive(false);
        PlayerScoreBoard_sc.pre_test.score.text = other.GetComponent<ScoreCollection>().points + "";
        PlayerScoreBoard_sc.pre_test.distance.text = distanceCp.distance + "0m";
        PlayerScoreBoard_sc.pre_test.time.text = time.text;
        break;
    case MainGameManager.gameType.Post_test:
        prac.SetActive(false);
        pre.SetActive(false);
        post.SetActive(true);
        PlayerScoreBoard_sc.post_test.score.text = other.GetComponent<ScoreCollection>().points + "";
        PlayerScoreBoard_sc.post_test.distance.text = distanceCp.distance + "0m";
        PlayerScoreBoard_sc.post_test.time.text = time.text;
        break;
```

Figure 6.28: Shows an algorithm's logic for a score collection during different tests sessions

```
public class ScoreBoardManagerForScene1 : MonoBehaviour
{
    public valuesForScene1 practice_env;
    public valuesForScene1 pre_test;
    public valuesForScene1 post_test;
    // Start is called before the first frame update
    void Start()
    {
        gameObject.SetActive(false);
    }
```

Figure 6.29: Shows an algorithm's logic for a score board manager

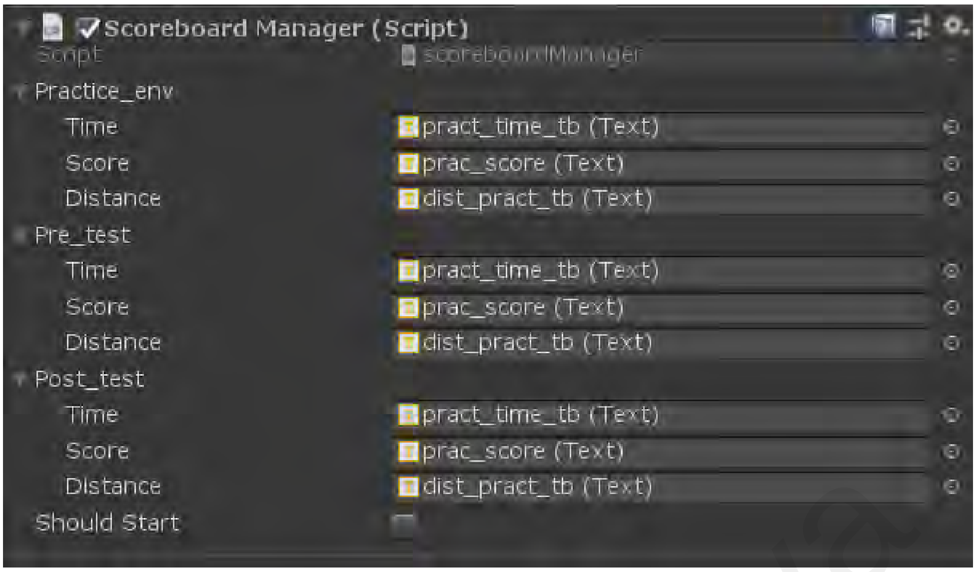


Figure 6.30: Shows a configuration setting for the score board manager in Unity environment

(b) Configuration: Score Collection (Data Repository)

This component is responsible for storing the data that was obtained from users' interactions within the virtual environment and for enabling the querying of that data so that it can be displayed to users via scoreboards (component: user achievement). The MySQL online server was utilised for the purposes of storing and processing the data. The MAMP controller allowed this to maintain a direct connection and control with the Unity engine. Figure 6.31 illustrates the logic that must be implemented in Unity in order to establish a direct connection to the MySQL server. In addition, the current status of the MAMP (Apache and MySQL Server) connection is displayed in Figure 6.32.

```
IEnumerator Register()
{
    Debug.Log("register" + nameField.text+" age:"+ ageField.text);
    WWWForm form = new WWWForm();
    form.AddField("action", "add_new_user");
    form.AddField("uname", nameField.text);
    form.AddField("age", ageField.text);
    //http://localhost:81/autism_hbve/api.php?action=add_new_user&uname=test3&age=23
    using (UnityWebRequest www = UnityWebRequest.Post("http://localhost:81/autism_hbve/api.php", form))
    {
        yield return www.SendWebRequest();
        if (www.isDone)
        {
            var N = JSON.Parse(www.downloadHandler.text);
            if (N["success"].Value == "1")
            {
                loginMenu.SetActive(false);
                optionsMenu.SetActive(true);
            }
            else
            {
                Debug.Log("unable to login");
            }
```

Figure 6.31: Shows an algorithm's logic for a direct connection to the server

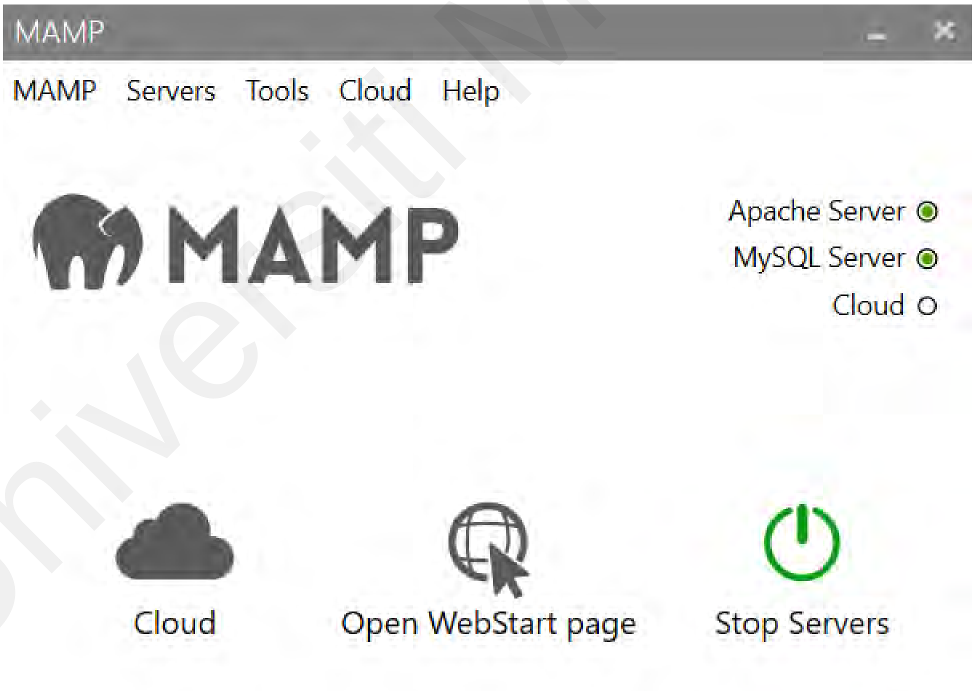


Figure 6.32: Shows a configuration setting for the MAMP connection

(c) ***Configuration: MatLab with MyoMex for Signal Generation (Haptic/Sensory Feeback)***

The signal, which was produced as a sensory feedback output from the MYO Armband in response to user interaction, will be defined and processed through MATLAB in order to gain an understanding of the pattern of the users' reactions. IMU and EMG signals were processed as signal data. Because of the signal captured from the MYO Armband, MyoMax library files were used in MATLAB to process and generate the plot. There are a number of variables that are utilised in the plotting of the data to indicate and calculate the gyroscope, accelerometer, and magnetometer. Figure 6.33 shows how the algorithm works to define the variable and connect it to the MYO Armband, while Figure 6.34 shows how the algorithm works to plot the data.

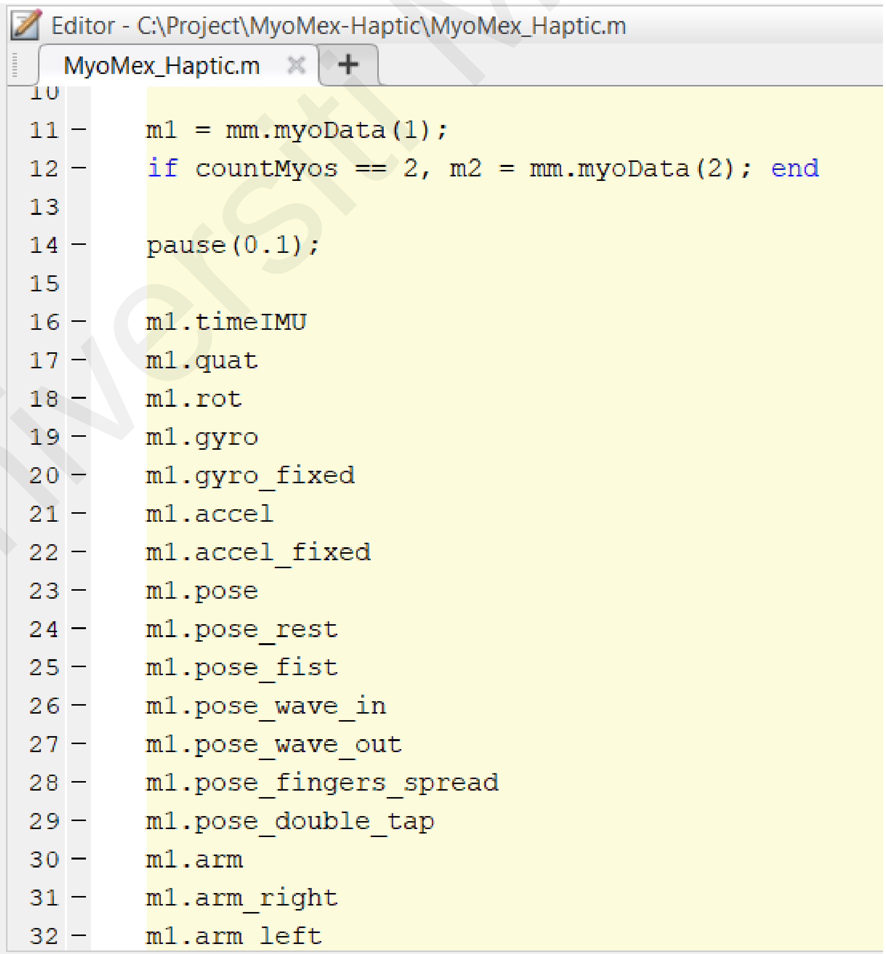


Figure 6.33: Depicts an algorithm for connecting the MYO Armband and capturing signal data

Editor - C:\Project\MyoMex-Haptic\MyoMex_Haptic.m

MyoMex_Haptic.m

```
figure;
subplot(3,1,1); plot(m1.timeIMU_log,m1.gyro_log);  title('gyro');
subplot(3,1,2); plot(m1.timeIMU_log,m1.accel_log); title('accel');
subplot(3,1,3); plot(m1.timeEMG_log,m1.emg_log);   title('emg');

T = 25;
m1.clearLogs()
m1.startStreaming();
```

Figure 6.34: Depicts the logic of an algorithm for plotting signal data

6.1.5 Haptic Based Virtual Environment Simulation Direction Flow

The overall simulation flow through the virtual screens is depicted in Figure 6.35. There are three levels to the data flow process: 1) Circles represent the main virtual screens; 2) Rectangles represent the parent sub-screens; and 3) Rectangles with a dashed outline represent the child sub-screens. While the direction of an arrow represents the movement of users between screens.

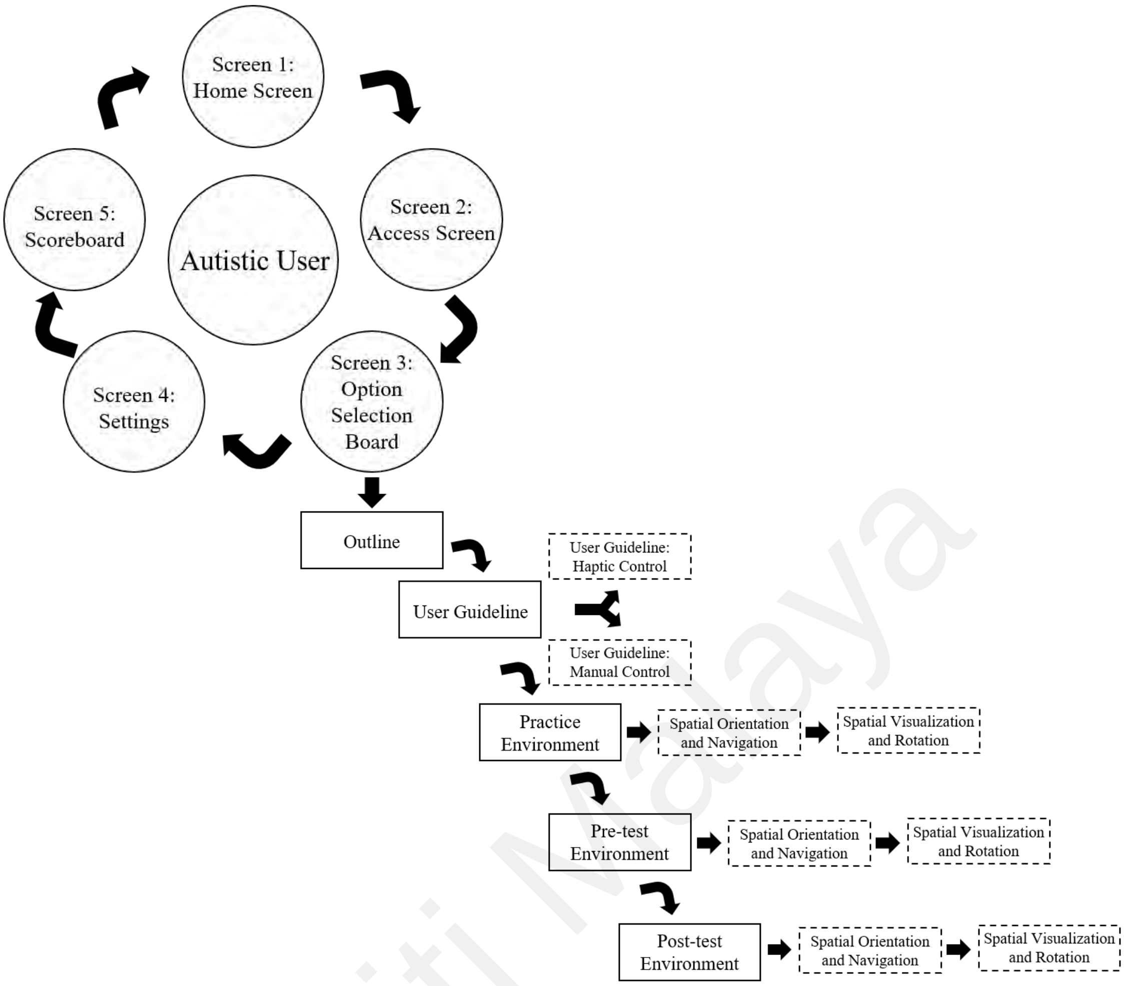


Figure 6.35: The flow of the simulation thru the virtual screens

6.1.6 Virtual User Interface of the Simulation

The following sub-section explains the details of all the virtual screens of the simulation as per Figure 6.35.

6.1.6.1 Screen 1: Home Screen

This screen is required to load and start the virtual environment platform (Figure 6.36). This screen handled all the primary controllers before access to the virtual environment, and this screen also shows some basic information about the application objective.

Figure 6.36: Home Screen of HBVE application

6.1.6.2 Screen 2: Access Screen

This screen requests a user nickname as an entry requirement to access this simulation, as well as to track their scores at the end of each practise and test (Figure 6.37).

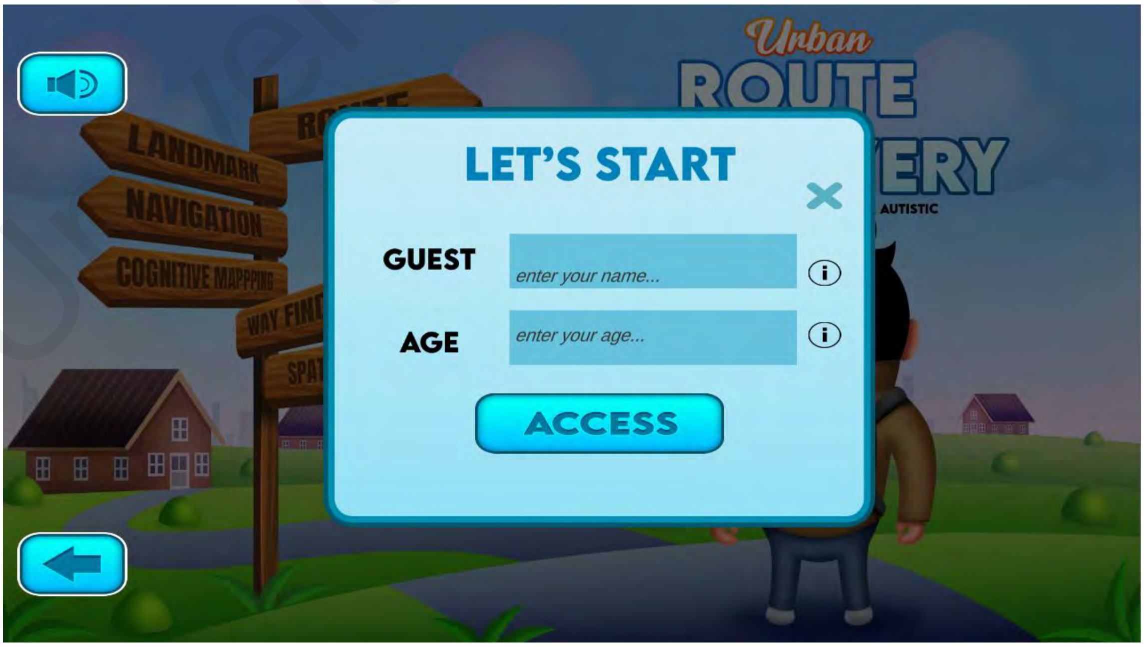


Figure 6.37: Access Screen of HBVE application

6.1.6.3 Screen 3: Option Selection Board

This screen shows the options available in this virtual simulation for autistic people, which are limited to the following: outline, user guideline, practise environment, pre-test, and post-test (Figure 6.38). The user guidelines option provides information on the specifics of this simulation, as well as how to interact with and navigate through the virtual environment using a haptic interface aid. In this simulation, three levels of testing are used: practise (baseline), pre-test (generalisation), and post-test (maintenance). Each level of testing is comprised of three different types of spatial ability tasks, which will be discussed in greater detail in the following section. Choosing the outline option (basic knowledge of spatial learning and cognitive mapping) allows autistic people to have a thorough understanding of the concepts of spatial learning and spatial working memory. The practise environment option, on the other hand, allows autistic people to experience simulation in order to determine the impact of spatial learning and the capabilities of a haptic interface as an interaction support to convey the feeling of touch to them.

Figure 6.38: Option selection board of HBVE application

6.1.6.4 Screen 4: User Guideline

This screen provides the details on how to control their interaction and navigation within the virtual environment through the haptic interface (refer to Figure 6.39). The user should use the "MYO Armband" haptic interface as an input method to interact with the virtual environment. This haptic device is equipped with various different sensors to detect the user's hand gestures and the movements of their arms. There are various different pre-defined gestures for the MYO armband, as shown in Figure 6.40, which are used to interact and navigate within the virtual environment.

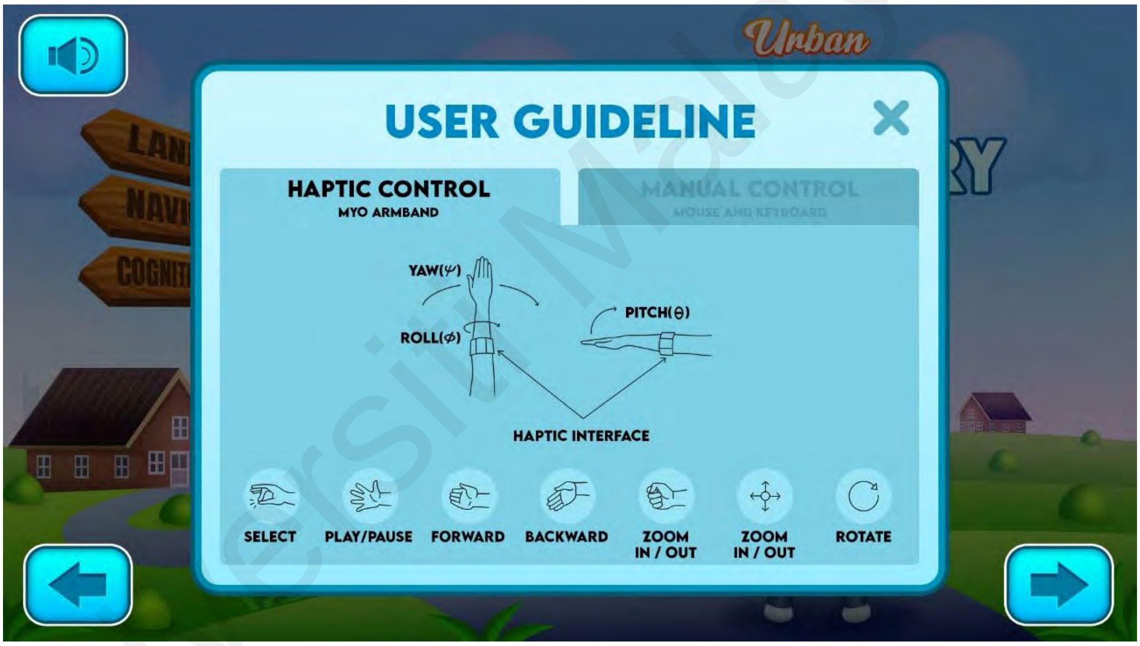


Figure 6.39: The guideline for end-user with MYO armband gesture (Haptic Device) details

Figure 6.40: The guideline for end-user with Mouse and Keyboard function details

6.1.6.5 Screen 5: Outline: Spatial Learning and Cognitive Mapping Stage

As shown in Figure 6.41, the list of spatial learning and cognitive mapping tasks that have been displayed to autistic people is an option for them to choose to improve their spatial cognition. The following tasks are to be learned by autistic people through this simulation: 1) spatial visualisation and mental rotation: this sub-task measures the autistic people users' ability to mentally rotate 3D objects in a virtual environment through the hole-peg task, 2) spatial orientation and navigation: this sub-task assesses autistic people's ability to determine and identify the position or direction of 3D objects and move towards the selected object, and also this sub-task assesses autistic users' ability to be aware of their relationship with the virtual environment (proposed virtual environment: urban environment) and with themselves. In addition, this screen also provides an overview and purpose of each task to let autistic people users have an introduction and knowledge of the task they choose before proceeding with the test.

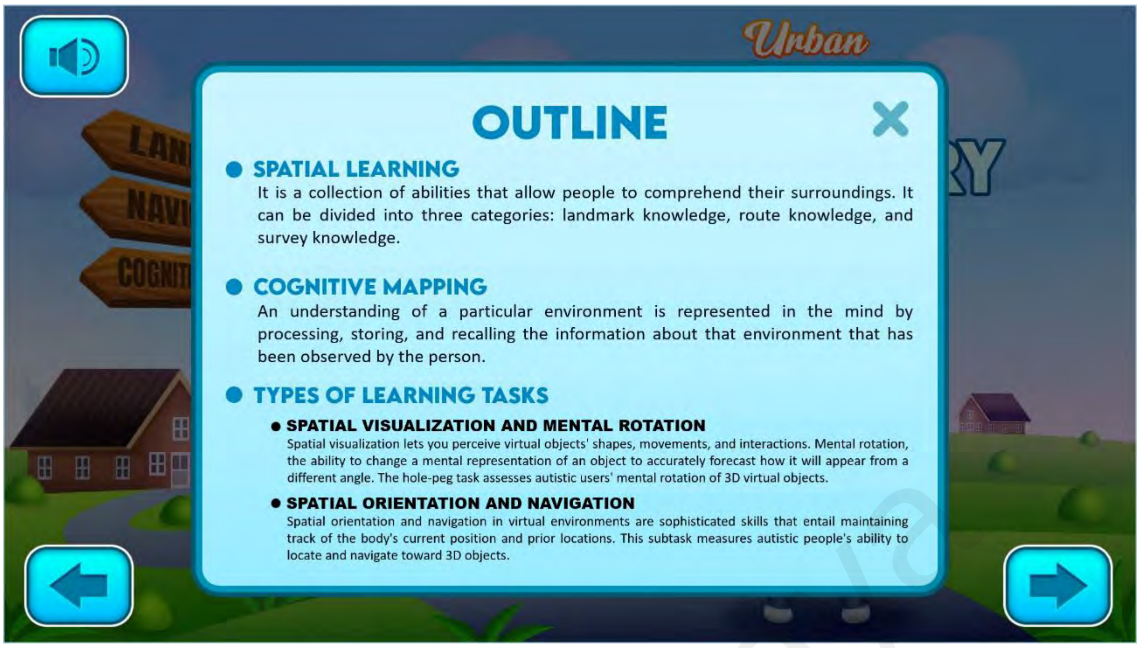


Figure 6.41: Shows the list of tasks in spatial learning and cognitive mapping stage and the overview and purpose of each task

6.1.6.6 Screen 6: Settings

This screen allows the user to monitor their level of speed of movement in the virtual environment by adjusting the "Speed" bar from left to right (Figure 6.42). The left indicates "Low" speed, while the right indicates "High" speed. Also, the user is able to adjust the volume and brightness of the virtual environment screen according to their preferences.

Figure 6.42: Shows the virtual environment' setting options

6.1.6.7 Screen 7: Virtual Environment (Urban Environment)

In line with this research objective, on this screen is a simulation of a virtual environment developed with some gaming features based on spatial learning and cognitive mapping methods as proposed in the framework. There are a few sub-screens built into this virtual environment, such as a minimap, acceleration/speed level adjustment, cognitive map, direction indicator, right/wrong mark indicator, and sound effect indicator.

(a) Sub-Screen 5.1: MiniMap

This screen provides assistance for autistic people users in orienting themselves within the virtual environment (Figure 6.43). This minimap is usually placed in the corner of a virtual environment along with a rectangle-shaped miniature map. The common provided features are the current position or location of the autistic people user in a virtual environment, agents' characters, objects, and surrounding terrain. Additionally, this minimap provides the facilities by rotating the minimap when the autistic people point in different directions.

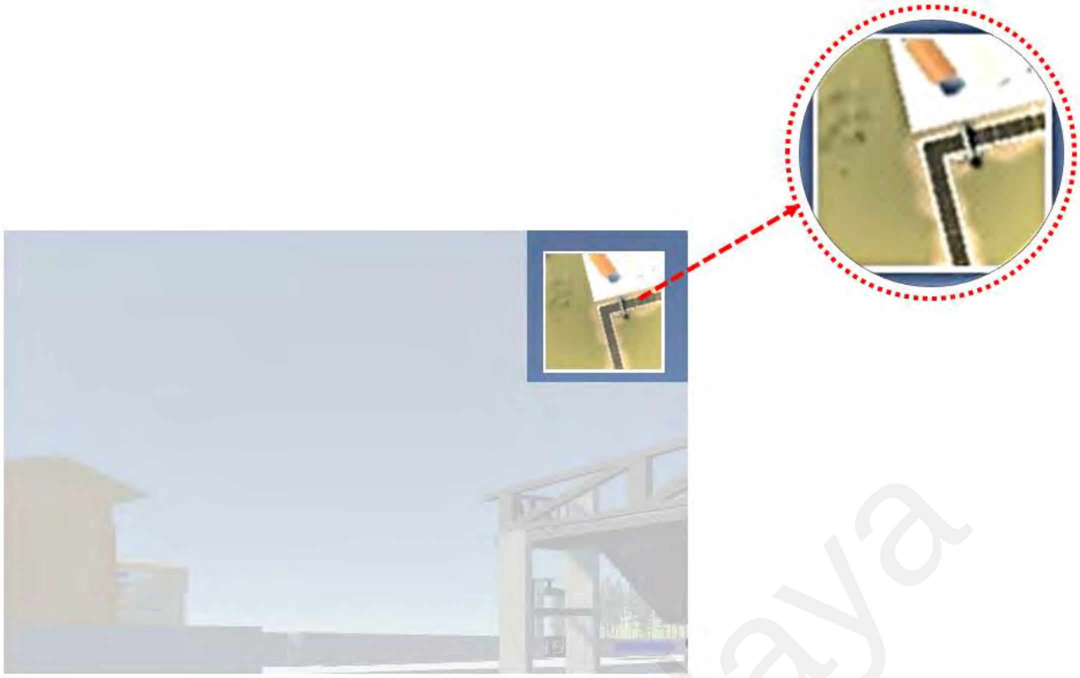


Figure 6.43: Shows the MiniMap in virtual environment as assistive features

*(b) **Sub-Screen 5.2: Cognitive Map***

One of the primary objectives of this research is to form cognitive mapping skills in autistic people by creating the ability to acquire, code, store, recall, and decode information about objects and locations in a virtual environment using spatial learning methods. According to the researchers, normal people can forget what they have seen; how could this rule out autistic people as users? Therefore, to reinforce this statement more, this simulation provides a cognitive map that can facilitate autistic people in performing their assigned tasks or activities by locating objects and locations in the virtual environment (García-Catalá et al., 2020; Lahav & Mioduser, 2008; Robins et al., 2012; Schiller et al., 2015; Vaez et al., 2016). Figure 6.44 depicts a cognitive map of an urban virtual environment with a user activity guideline that should be followed by autistic people.

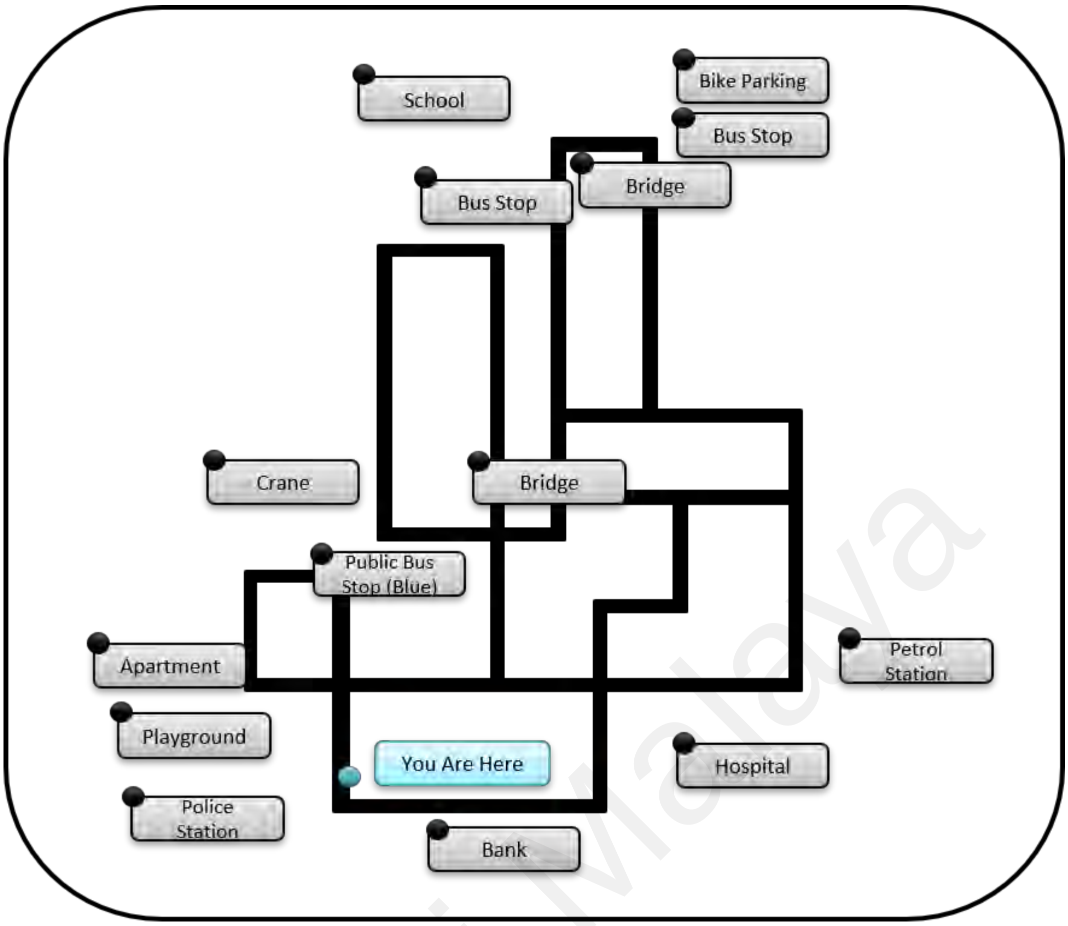


Figure 6.44: The narrative of the spatial cognition mapping task in urban's virtual environment

(c) Sub-Screen 5.4: Direction Indicator

To access spatial learning ability, it has been introduced with a directional indicator for autistic people users to help them find the direction and navigate towards their targeted object in virtual environments, and this can also enhance their ability in terms of their spatial knowledge indirectly. According to most studies, there are problems in terms of mobility for autistic people in virtual environments, where they may lose their way or forget to get their way to reach the target or their desired location. Due to this issue, this simulation can automatically provide alternative directions to autistic people by redirecting the user's path to the alternative route. The "Left and Right" instructions are one way in which this direction indicator can help autistic people continue their navigation to the desired location in a virtual environment.

(d) Sub-Screen 5.5: Right and Wrong Mark Indicator

This screen can provide indicators to users who choose objects, whether they are right or wrong. For example, if the user can select the correct virtual object successfully, this simulation can display the "Right" icon as an indicator.

(e) Sub-Screen 5.6: Sound Effect Indicator

Because the virtual environment implies a real environment indirectly, this screen will provide a real-world sound effect as an indicator for certain virtual environment interactions, tasks, or activities to maintain the effect of a real-world atmosphere for autistic people and to indicate that the selected answer is correct.

6.1.6.8 Screen 6: Recall Stage

The purpose of this screen is to examine the ability of autistic people to use spatial learning skills by attempting to recall their spatial knowledge from the spatial information they stored during the learning stage. It means that autistic people will try to recall spatial information through mental images of locations and attributes of the environment, estimating the distance between objects from their first attempts at the tasks in the learning stage. At the end of this recall stage, autistic people who have spatial knowledge and cognitive mapping skills should be able to identify objects, locations, landmarks, and compass information and figure out their navigation route to their desired location (see Figure 6.45). Meanwhile, these three screens depict the interaction and manipulation environment for comprehending the spatial visualisation and rotation aspects (Figure 6.46, 6.47, and 6.48).

Figure 6.45: Shows the recall stage of the spatial learning and cognitive mapping

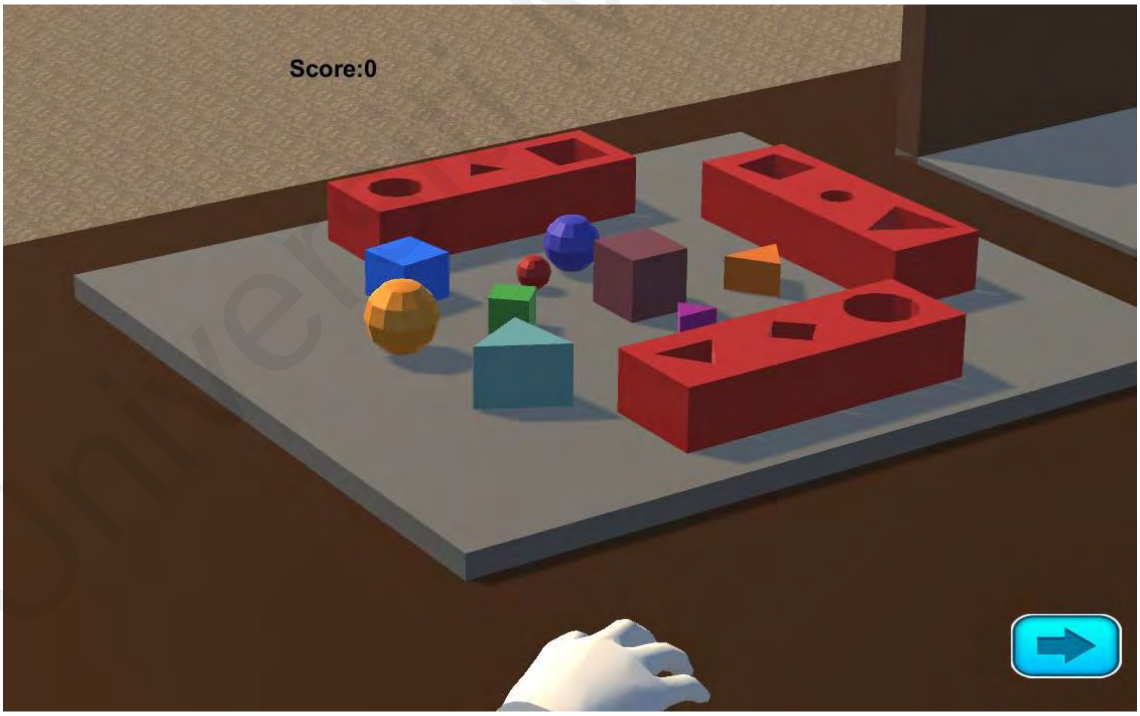


Figure 6.46: Shows the spatial visualization and rotation: Hole-Peg Task

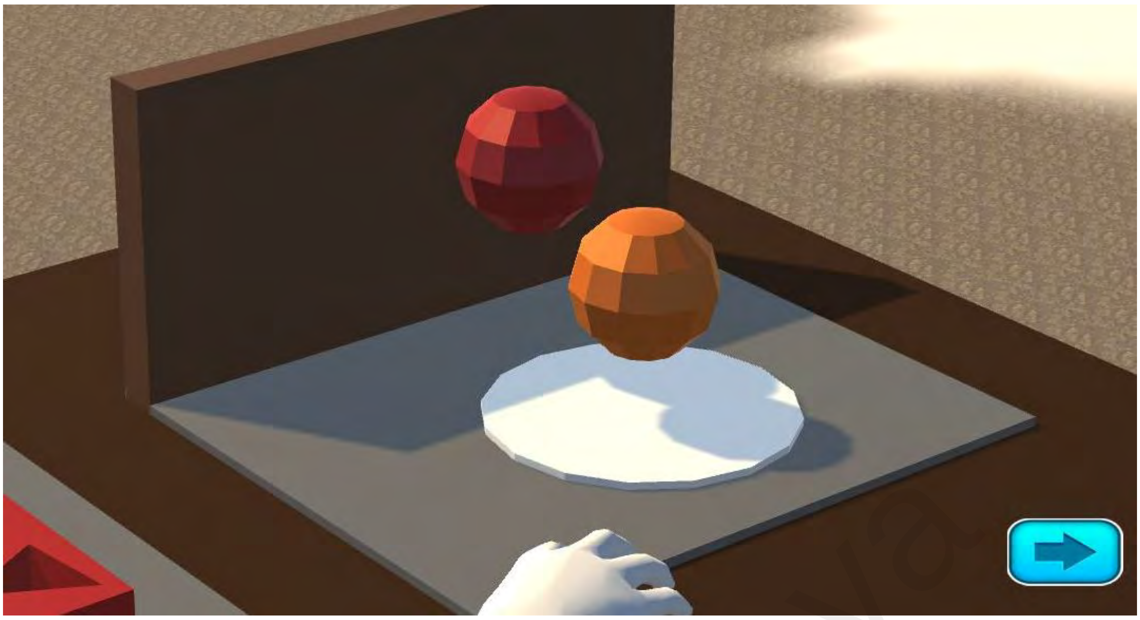


Figure 6.47: Shows the spatial visualization and rotation: Object Force Pushing Interaction Task

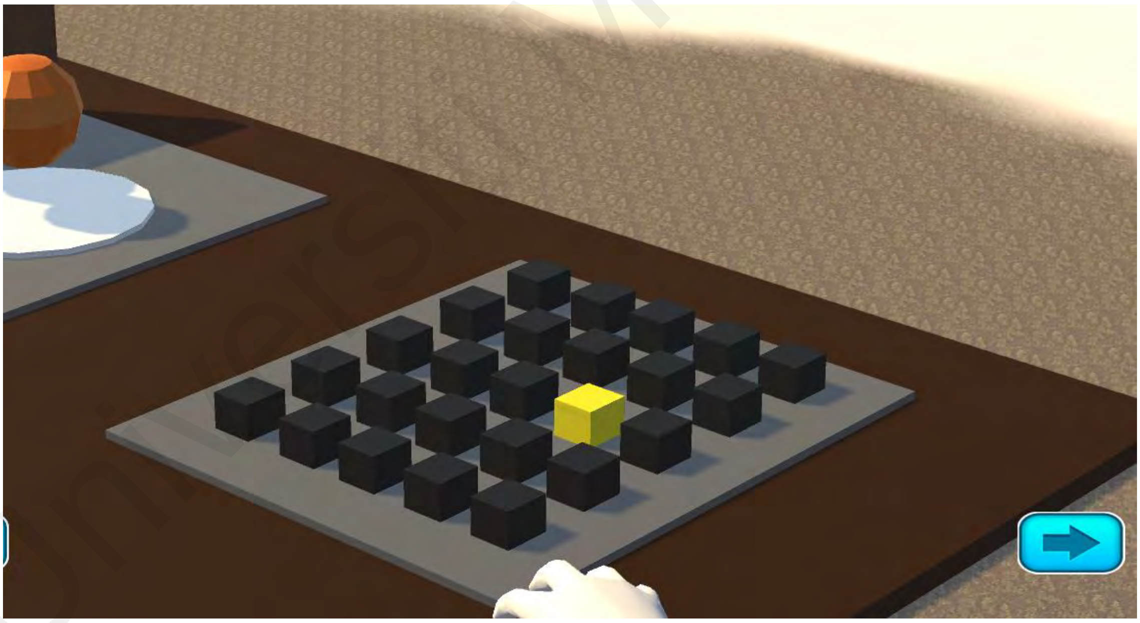


Figure 6.48: Shows the spatial visualization and rotation: Corsi Block-Tapping Task

6.1.6.9 Screen 7: Pre-Learning to Post-Learning

This screen is intended to measure the performance of spatial learning and cognitive mapping method skills before (pre-learning) and after (post-learning) using this simulation. These three different levels of testing were referred to as pre-learning (baseline), partial learning (intervention) and post-learning (maintenance). On this screen, both the partial learning and post-learning almost use the same virtual environment as used during the pre-learning stage, but there will be some differences: during the pre-learning, the direction indication cognitive map clue is still provided, but during the partial and post-learning, there is no cognitive map clue provided, and the obstacles in the virtual environment are changed in terms of their position.

6.1.6.10 Screen 8: Scoreboard

This screen provides the scores achieved by autistic people during the spatial learning task and practise (refer to Figure 6.49). It was presented according to the user's performance in all three types of spatial learning methods: 1) spatial visualisation and mental rotation, 2) spatial orientation and navigation.

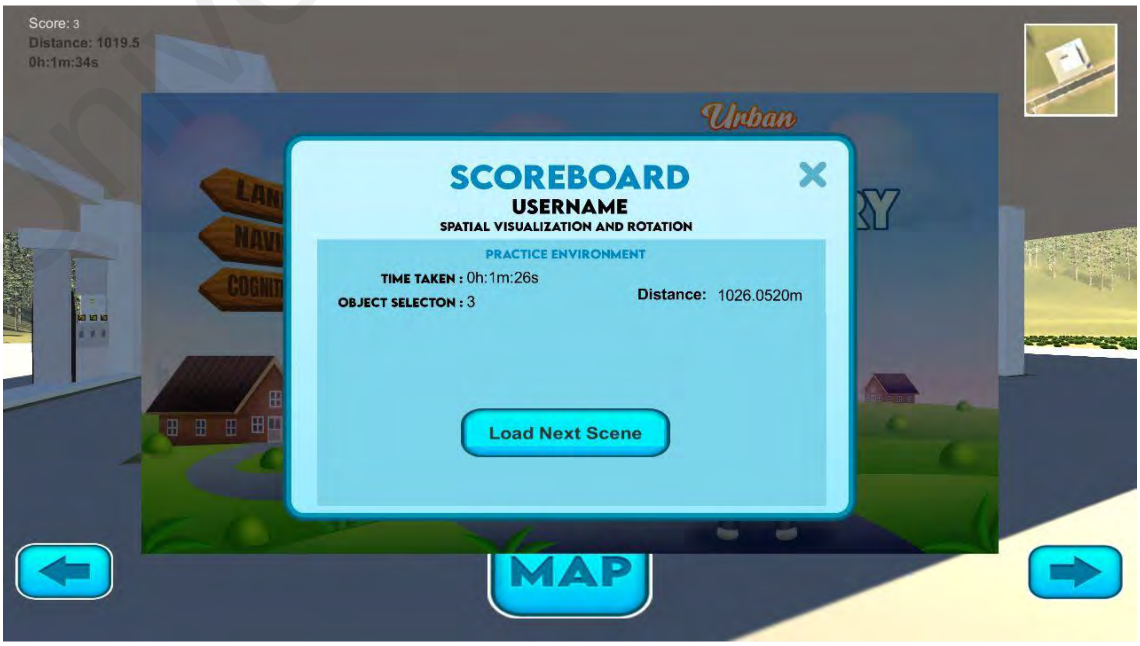


Figure 6.49: A sample of scores board

6.2 Testing of the Haptic-Based Virtual Environment Simulation

In this section, a description was provided about the testing method as well as the results of the testing process. Unit testing, integration testing, and system testing are the types of testing that were carried out during this application development process. In the meantime, testing and evaluation of usability will take place in section 6.3.

6.2.1 The Importance of Testing

This task examines the implications for the HBVE application development process. These tests are classified as unit tests, integration tests, and system tests, and they can make three (3) significant contributions to HBVE development and implementation:

(1) It makes it possible to write interaction code that works and cuts down on development threads that are wrong or not needed.

(2) Recognize the challenges and problems that could come up during the development stages of the HBVE application process. These problems can be solved by bringing in new methods and solutions.

(3) It is capable of producing documentation about the solution chosen and the experience gained during development for future reference in order to maintain and secure the system.

6.2.2 Methodology for Testing HBVE

Several types of tests were performed during the testing phase to identify anomalies in the HBVE application. It was divided into two (2) types of testing methods, which are white box testing and black box texting. White box testing refers to testing on HBVE design or implementation elements that are known to the user, such as unit testing and integration testing. Meanwhile, block box testing refers to testing on HBVE design or implementation elements that are unknown to the user, such as system testing and usability testing (refer to Section 6.3). Therefore, the HBVE application employs both white box (unit testing and integration testing) and black box (system testing and usability testing) testing techniques. These tests were carried out to ensure that the functionalities met the needs of end users and that the system was efficient. The sections that follow provide a brief explanation of these four stages of testing.

6.2.2.1 Unit Testing

White box testing and black box testing are the two categories that make up unit testing in haptic-based virtual environments. The HBVE's white box is tested based on its internal logic, whereas the HBVE's black box is used to test the output of all of its functions. Both of these types of testing can be partitioned into three distinct modules in accordance with the proposed framework components in these studies, which are referred to as the controller, the module, and the view, respectively. The programmers, not the testers, were responsible for identifying all of the testing cases under each module and preparing a comprehensive test case for each module, which was then used to test at each of the stages of execution for each module. This testing is carried out to ensure efficiency and effectiveness, as well as to reduce the risk of failure at the end of the development process. Table 6.2 displays the unit testing cases based on the module.

Table 6.2: Unit test modules for the HBVE application

Controller Module			
Test No.	Execute Test Case	Expected / Actual Results	Result
UT01	Click "connect" button <EventType.Connected> to perform calibration.	Connected to haptic device via calibration profile (MYO Armband).	Pass
UT02	Perform common gestures (zooming, rotating, and waving). public enum PoseType { Rest = 0, Fist = 1, WaveIn = 2, WaveOut = 3, FingersSpread = 4, DoubleTap = 5,	Each gesture reaction should respond appropriately to its function and appear in the virtual scene as "Sign" gestures type.	Pass

<table>
<tr><td></td><td>Unknown = 0xffff
}</td><td></td><td></td></tr>
<tr><th colspan="4">Model Module</th></tr>
<tr><th>Test No.</th><th>Execute Test Case</th><th>Expected / Actual Results</th><th>Result</th></tr>
<tr><td>UT03</td><td>Click the “Tap to Start” button in HOME screen.</td><td>The “Access Screen” should pop up.</td><td>Pass</td></tr>
<tr><td>UT04</td><td>Type in username in the “Guess” field <nameField>.</td><td>Cursor should move to the “Guess” field and allowed to input values.</td><td>Pass</td></tr>
<tr><td>UT05</td><td>Type in age in the “Age” field <ageField>.</td><td>Cursor should move to the “Age” field and allowed to input values.</td><td>Pass</td></tr>
<tr><td>UT06</td><td>Click the “Access” <register> button in ACCESS screen.</td><td>The “Access Screen” should pop up.</td><td></td></tr>
<tr><td>UT07</td><td>Validate whether the user is able to pick up a virtual object by using the virtual "hand":

if (other.tag == "hand" && Count==1)
{
this.transform.position = theDest.position;
this.transform.parent = GameObject.Find("destination").transform;
}</td><td>It should allow the user to pick up the virtual object by using the virtual "hand" and change the position accordingly.</td><td>Pass</td></tr>
<tr><td>UT08</td><td>Validate whether the user is able to use the control key to move or navigate in the virtual environment:

float z = Input.GetAxis("Vertical") * moveSpeed;
float x = Input.GetAxis ("Horizontal") * moveSpeed;
if (!isGameOver)
{
if (x > 0 || z > 0)
waypntCtrl.enabled = false;
else
waypntCtrl.enabled = true;
}
else
{
waypntCtrl.enabled = false;
}
Move (new Vector3 (x, 0, z));</td><td>It should allow the user to navigate or walkthrough the virtual environment with the control key.</td><td>Pass</td></tr>
<tr><td>UT09</td><td>Validate whether the dialogue text can display the next task in the virtual scene after completing each task:

continueBtn.onClick.AddListener(hideDialouge);
dialogueText.text = sentences[taskNo - 1] + "";</td><td>Once the user has completed the current task, it should display the next task.</td><td>Pass</td></tr>
<tr><th colspan="4">View Module</th></tr>
<tr><th>Test No.</th><th>Execute Test Case</th><th>Expected / Actual Results</th><th>Result</th></tr>
<tr><td>UT10</td><td>Validate common gestures (zooming, rotating, and waving) by capturing the MYO value:

value.OrientationData += myo_OnOrientationData;
value.AccelerometerData += myo_OnAccelerometerData;</td><td>Each gesture reaction should respond appropriately to its function and appear in the plot (MatLab</td><td>Pass</td></tr>
</table>

	value.GyroscopeData += myo_OnGyroscopeData;	platform) as a sensory signal with the output value as “roll - x,” “pitch - y,” and “yaw - z” for orientation, accelerometer, and gyroscope.	
UT11	Validate the haptic device's (MYO Armband) vibration as haptic feedback: libmyo.vibrate(_handle, (libmyo.VibrationType)type, IntPtr.Zero);	It should be responded to with a haptic/sensory response, such as a short, medium, or long vibration.	Pass

UT12	Validating scores to display to the user:
	
	practice_env.score.text = N["practice_env"]["score"].Value;
	practice_env.distance.text = N["practice_env"]["distance"].Value;
	practice_env.time.text = N["practice_env"]["time"].Value;
		It should be captured from the database and displayed to the user as a score in the "Scoreboard" screen.	Pass

6.2.2.2 Integration Testing

Integration testing is carried out in order to produce a well-structured algorithm or programme and to eliminate any errors or bugs that may have been identified during the development of the user and the virtual interface. This method of integration testing will be used to define the algorithm or programme. The "Collision Detection" function was initially under integration testing, followed by the "Control Algorithm" function. Both the function and the threads are rechecked in order to eliminate the possibility of either being faulty. In addition to this, various other features of the HBVE were put through their intervals using the same method and procedures for testing. Table 6.3 provides an illustration of the integration test that is used for the HBVE.

Table 6.3: Integration test modules for the HBVE application

Test No.	Component	Action	Expected Result	Actual Result
IT1	Controller	Capable of controlling and monitoring all functions.	Every single one of the functions ought to be precisely controlled and devoid of any errors.	Each of the interaction buttons and menus has been fine-tuned for optimal control.
IT2	User Interface	Presenting all of the interactive pages that pertain to the HBVE application.	Every single piece of content should be presented well and without a single mistake.	Each and every one of the interaction buttons and menus worked perfectly.
IT3	Virtual Interface	Demonstrate each and every virtual object and interaction.	It is expected that all of the virtual objects and their interactions will be presented without any errors.	Each and every interaction that takes place within the virtual object and environment is functioning correctly.

6.2.2.3 System Testing

System testing is the final step in the testing process, and it comes after both unit testing and integration testing have been completed successfully. This is particularly important to show that the application works as expected, which allows the developer to verify that the application is capable of meeting the specified requirements and fulfilling the functional requirements planned. This test will be performed in terms of functionality, performance, and installation:

*(a) **Functional Testing***

The HBVE system testing began with function testing, which focused on the functionality of each component (refer to Table 6.4 for functional testing of requirements). As an example, the "wayfinding" component was evaluated based on the function that was carried out by every one of the activities. These validations are to see if the user got to the right location or picked the right object. It's also to validate the scores and decide if the user can move on to the next level of testing once the maximum score has been reached.

(b) Performance Testing

Evaluations of the HBVE's performance were done to see how quickly the application responded to user commands.

(c) Installation Testing

HBVE needs to put installation testing at the top of its list of priorities to make sure that installation and configuration steps are tested thoroughly and that no dependencies are missed.

Table 6.4: System test based on requirement for the HBVE application

Req. No	Requirement Description	Result
Access Info (Autistic User Registration)		
RE01	The user must enable access to the application by entering user information.	Pass
Availability of the Menu and The Button		
RE02	The user must be able to view the home and access screens.	Pass
RE03	The option board must be visible to the user.	Pass
RE04	The user must be able to view the user guideline.	Pass
RE05	The user must be able to view the outline.	Pass
RE06	The user must enable the view of the settings.	Pass
RE07	The user must be able to see the cognitive map navigation.	Pass
User Navigation in Virtual Environment via Haptic Device		
RE08	The user must be able to view virtual objects in the virtual environment.	Pass
RE09	The haptic device must allow the user to walk or travel in the virtual environment.	Pass
RE10	The user must be able to move up in the virtual environment using a haptic device.	Pass
RE11	The user must be able to move down in the virtual environment using a haptic device.	Pass
RE12	The user must be able to move to the right in the virtual environment using a haptic device.	Pass
RE13	The user must be able to move to the left in the virtual environment using a haptic device.	Pass
RE14	The user must be able to hear the sound effect.	Pass
Direction or Target Selection via Haptic Device		
RE15	The user must be able to view the virtual object by pointing to the object's direction/target with a haptic device/virtual hand.	Pass
Selecting or Controlling the Setting		
RE16	The user must be able to select and view the velocity/acceleration, volume, and brightness.	Pass
RE17	The user must be able to control the velocity/acceleration, volume, and brightness.	Pass
Virtual Object Manipulation or Interaction via Haptic Device		
RE18	The user must be able to view and select virtual objects using a haptic device.	Pass
RE19	The user must be able to drop/pick up a virtual object using a haptic device.	Pass
RE20	The user must be able to push a virtual object using a haptic device.	Pass
RE21	The user must be able to rotate a virtual object using a haptic device.	Pass
RE22	The user must be able to view the special effect on the 3D objects.	Pass
RE23	The special sound effect on 3D objects must be audible to the user.	Pass
Display User Performance Metrics or Score		
RE24	The user must be able to select and view the displayed score.	Pass

6.2.3 The Discussion of Testing

In this section, the entire process of testing the HBVE application has been prepared and also carried out in order to ensure that all of the essential features of the system are operating as precisely as they were designed to do. The outcomes of all of the testing cases, which included unit testing, integration testing, and system testing, either based on functional and non-functional requirements or on a module-based basis, showed satisfactory outcomes and fulfilled the requirements. On the other hand, this will be tested more based on the criteria for usability that are explained in Section 6.3.

6.3 Usability Testing of the Haptic-Based Virtual Environment Simulation

The most effective technique for evaluating the functionality of the HBVE simulation is to use it. Therefore, the purpose of this research is to conduct usability testing in order to identify and correct any faults before releasing the final product to the end users. Usability testing can be carried out with potential users (in this case study, autistic people) as well as with a group of experts who will act as observers and transmit information on the simulation's progress. The following subsections provide details on the methodology that was used to test the usability of this HBVE simulation during the testing phase.

6.3.1 Experts and Requirement

To conduct this testing, academic staff and researchers with expertise in virtual environments and haptic devices, as well as previous experience performing testing with heuristic evaluation, are sought after. Consequently, academic staff profiles from institutions, social media sites such as LinkedIn, and the Google search engine were used to identify the specialists who would be participating in the study. After conducting a search for specialists, a total of eight experts were selected and invited to participate in this test by email and chat box. However, only four experts volunteered to take part in this testing, out of a total of eight experts that were contacted. Table 6.5 shows the demographics of the expert group that was assembled.

Table 6.5: Demographic Information of Expert's Group

Expert ID	Gender	Role	Experience
AE1	Male	Academic Staff	6 years
AE2	Male	Academic Staff	4 years
AE3	Male	Researcher	5 years
AE4	Male	Researcher	5 years

6.3.2 Instrument Used

The following types of instruments were utilised in this study to conduct the usability testing: 1) simulation of a HBVE, as described in Section 6.1 of this document. Meanwhile, 2) a modified version of the heuristic evaluation for haptic and virtual reality applications is being used to evaluate the HBVE for autistic people. The following are the modified versions of the heuristic assessment factors drawn from Nielsen and Mack (1994) that were used to assess the quality of this proposed HBVE application (refer to Table 6.6):

Table 6.6: The List of Heuristic and Description

Heuristics	Descriptions
Natural engagement	Interaction between the haptic device and the virtual environment should be as natural as it is in the real world.
Compatibility with the user's task	Object behaviour in a virtual environment should correspond to the user's expectations of real-world objects.
Natural expression of action	With the presence of haptic feedback, the virtual environment should allow the user to explore in a natural manner.
Close coordination	The virtual environment should update in real time with the user's movement and action with the haptic device.
Realistic feedback	The real-time effect of the user's activities on virtual objects in a virtual environment should be apparent and realistic.
Faithful viewpoints	The visual representation of the virtual environment should correspond to the user's perception, and the user's movement should change the viewpoint consistently and without delay.
Navigation and orientation support	The user should be able to explore and orient themselves in a virtual environment with the assistance of a haptic device.
Support for learning	The virtual environment should provide detailed instructions on how to interact with virtual objects using the haptic device.
Sense of presence	During the interaction with the haptic device, the user should naturally feel as though they are in a real environment and have a sensation of touch.

6.3.3 Testing Method

Usability testing is conducted based on the following steps as part of the testing protocol:

The experts were invited to take part in this usability testing using email or a chat box (LinkedIn); they were informed that all of the evaluation and testing data would be kept confidential and handled anonymously. The usability tests were conducted in their own space. All experts were given a briefing on the following aspects of usability testing: the purpose of the testing, the simulation of the HBVE to be tested, the modified version of the heuristic evaluation for usability testing, simulation exploration, the two segments of the evaluation, recognition of usability problems, and finally, evaluation submission. The expert was requested to become familiar with the HBVE simulation and with both types of devices: a haptic device and a mouse and a keyboard. The expert is then asked to accomplish the following tasks independently using both device methods: 1) navigation and wayfinding task: navigate in the virtual environment to reach the desired destination; 2) interaction and manipulation: move virtual objects by grabbing and releasing them; 3) object force pushing interaction: push the 3D ball from one point to another. After completing the job, the expert was asked to provide feedback by identifying the problems based on the heuristic factors and rating them from "0" (not a problem) to "4" (problematic).

6.3.4 Procedure

The following sub-sections provide details about the usability testing of the simulation, which was conducted in two segments:

6.3.4.1 First Segment

The experts begin by evaluating the simulation of the HBVE for autistic people, and all usability issues are documented in a report and forwarded via email. Consequently, the identified problems based on all of the experts' perspectives were compiled and documented in order to have a proper understanding of the highlighted usability problems and, finally, carry out a discussion with the simulation HBVE's developer. Meanwhile, the developer will investigate the problems raised by the experts and resolve them by making the appropriate changes to the HBVE simulation.

6.3.4.2 Second Segment

In this segment, the experts were asked to participate in the usability testing once more, this time to provide feedback on their perceptions of the changes made to the simulation of HBVE. It was necessary to present the experts with both the initial and updated versions of the HBVE simulation as well as a set of questionnaire forms that contained the specifics of the problem highlighted by the experts during their initial segment in order for them to carry out this study. According to the questionnaire, the experts were asked to state whether the identified problem had been resolved, remained unresolved, or whether they were unsure about the changes for each of the problems they had highlighted. Finally, the experts needed to submit the completed questionnaire through email so that it could be analysed further by the researcher.

6.3.5 Results

The following sub-sections provide analysis of the results of the usability test conducted in the previous section:

6.3.5.1 First Segment

The results of the first segment of heuristic evaluation are provided in Table 6.7. The data presented is based on each heuristic's rating and description of the problem. Among all nine heuristics, most experts agreed on these three heuristics: "natural engagement," "close coordination," and "sense of presence" with no problems. Meanwhile, the remaining heuristics reported problems, which were mapped to application characteristics in order to be improved. Table 6.8 shows the application's characteristics, the problem encountered, and the referenced heuristic (referenced from Table 6.7).

Table 6.7: Heuristic rating and problems

No.	Heuristic	Rate	Problems
1.	Natural engagement	3	The non-existence of a natural lighting system makes the VE appear less natural.
2.	Compatibility with the user's task	3	The user is able to penetrate some of the 3D objects. For example, this can be seen during the interaction with nine different objects of shape and size in the hole peg task.
3.	Natural expression of action	2	The absence of natural movement when pushing the ball towards the ground or a wall, regardless of the fact that it occurs with the level of acceleration during haptic device interaction with virtual objects.
4.	Close coordination	0	No problem encountered.
5.	Realistic feedback	0	No problem encountered.
6.	Faithful viewpoints	0	No problem encountered.
7.	Navigation and orientation support	2	Even though it had navigation support (for example, the AHSON algorithm and a landmark map), the ability to penetrate the virtual solid object caused the user to lose track of their destination.
8.	Support for learning	3	The requirement for a direct link from the virtual environment to the haptic device instruction menu itself, rather than just offering comprehensive instructions at the beginning of interface scenes (menu selection).
9.	Sense of presence	0	No problem encountered.

Table 6.8: The categorizing of problems based on the components of the application

No.	Components of Application	Heuristic	Subject
1.	Motion and Visual Effects (MVE)	1, 3	The application should be improved by including realistic visual effects, particularly during push and pull tasks, as well as a natural lighting system.
2.	Object Detection and Object Avoidance (ODOA)	2	To avoid penetration of virtual objects during interaction and manipulation tasks, the application should be upgraded with more presided object detection and avoidance.
3.	Interaction and Manipulation	7	The application should be improved in terms of user navigation in the VE by avoiding virtual object penetration.
4.	Instruction and Navigation Support	8	As supportive information during the interaction with VE, the application should provide a direct link feature (button) to the "user guidance" screen.

As a result, the following enhancements were considered during the implementation of the new version of the application, as listed below:

Motion and Visual Effects: The requirement for ultimate effect in VE is a significant practise in order to bring things to life as they exist in the real world. It can also improve the realistic response or performance of users in a virtual environment by practising visual effects (W. Wu et al., 2017). Creating realistic object motion and environments, such as providing realistic motion effects while pushing the ball towards the wall or including a natural sun light system into the environment, can stimulate users' imaginations when navigating and interacting with the virtual world. Therefore, specialised components like the visual effect graph, which uses node-based visual logic, can enable us to produce simple-to-sophisticated effects on the virtual object or environment, particularly during the pushing task. Aside from that, the application may be used with directional light to create natural sun light effects on the VE with soft shadows.

Object Detection and Object Avoidance: Providers of VE services must consider improving the user navigation system as part of their overall strategy in order to achieve their goal. The system should take notes at all points of interaction during the design stages of VE, and this should be done throughout the entire process as well (Bliss et al., 1997; Johnston et al., 2019). The use of the clustering method and the application of surface subdivision should significantly improve both haptic collision detection and visual collision detection in the future. This can enhance the precision of collision detection while at the same time increasing the performance speed of collision detection by avoiding penetrating through virtual solid objects, both of which are beneficial.

Interaction and Manipulation: It was found that users were unable to complete their objectives because of the ability of their navigation system to penetrate virtual solid objects. This was truly the case even though the AHSON algorithm and landmark map existed as supportive guideline tools to assist users in completing their objectives. Therefore, implementing methods such as clustering, and surface subdivision can increase the performance of the user's navigation system (Andreasen et al., 2019).

Instruction and Navigation Support: It is possible to improve instruction and navigation support by ensuring that there is clear communication between the user and the HBVE application. A well-designed interface, particularly throughout the navigation process in VE, makes it easier for users to achieve their goal by completing the tasks that have been assigned to them in the application (Bowman et al., 2005). The consistency provided by giving interaction features such as "user guideline" on all of the screens makes the user more comfortable, and they will adopt and get more accustomed to VE a little more quickly as a result.

6.3.5.2 Second Segment

This segment was reviewed based on the changes that were made in response to the issues that were identified in the previous segment. The outcomes were determined by selecting one of the following options: whether the identified problem had been resolved, whether it had remained unresolved, or whether the respondent was unsure about the changes. According to the expert comments, the vast majority of the highlighted issues have been resolved, with the exception of two issues that are still listed as unresolved by the experts. Those categories that were identified as unsolved difficulties were taken into consideration and changed accordingly in the HBVE application, as explained below:

Occasionally, while doing the peg and hole tasks, the virtual hand will select multiple virtual objects at the same time for a single destination. This was fixed by including a simple algorithm and collision mechanism to check whether the virtual hand is already holding another object before moving in the direction of the destination.

It was discovered that the scores generated in scene 2 for all of the test environments overlapped with one another's measures, and this was resolved by constructing scoreboard managers to update the values as distinct and placed at various row levels, respectively.

6.3.6 Discussion

This evaluation described how the produced HBVE application satisfies the proposed framework components as well as how haptic technology was used. The majority of the application's usability problems raised in the first segment have been addressed in the second segment. Meanwhile, those concerns that remained unresolved at the end of the second segment were resolved and produced as the final application. This evaluation also plans to test this application with end users through exhaustive testing sessions with various sets of spatial cognition tasks in order to demonstrate the effectiveness of this application, which is based on the proposed framework component with haptic technology. This will be covered in further detail in the following subsections.

6.4 Experimental Evaluation of the Implementation of Autonomous Haptic Spatial Orient-Navigate Algorithms for Autistic people

This experimental evaluation was carried out in order to determine the effectiveness of the autonomous haptic spatial orient-navigate algorithm (AHSON) in the sense of wayfinding, in order to reach the intended object or location among autistic people. The method and procedure used in this experiment are described in the next subsection, which is followed by the results and discussion.

6.4.1 Methods

The main objective of this test was to examine whether the proposed algorithm was able to assist an autistic people to reach the targeted object by navigating through autonomous landmark detection in a virtual environment without the use of cognitive maps as assistive tools. Therefore, based on the proposed algorithm's four sections (refer to Figure 4.1 and the sub-sections of 4.4), this experimental study was conducted. In the beginning, this study examines the availability of the vibration sensor (haptic feedback) during navigation and moves on to tracking for estimating the orientation of autism navigation. Once the sensor and orientation data are gathered, this study investigates the ability of obstacle avoidance during navigation and, lastly, object landmark detection through landmark knowledge. This study was conducted through two stages after familiarisation with the virtual environment: learning and testing stages. The test is conducted between 45 minutes and 1 hour, which still depends on the participant's desires. There are two conditions proposed to be compared: with the AHSON algorithm and without the AHSON algorithm:

(1) **HwAHSON:** Haptic feedback with AHSON algorithm assistance

(2) **HwoAHSON:** Haptic feedback without AHSON algorithm assistance

The participants visually experienced the virtual environment and the proposed wayfinding task (refer to section 6.4.4) as the test case could be considered as a spatial learning and cognitive mapping task, which involved acquiring, storing, and recalling spatial information. The data was collected based on the nonprobability sampling method and verified according to the following hypotheses:

(1) **H_0:** Providing without the AHSON algorithm does not significantly improve performance in wayfinding tasks for autistic people;

H_1: Providing without the AHS0N algorithm does significantly improve performance in wayfinding tasks for autistic people;

(2) **H_0:** Providing with the AHSON algorithm does not significantly improve performance in wayfinding tasks for autistic people;

H_1: Providing with the AHSON algorithm does significantly improve performance in wayfinding tasks for autistic people.

(3) **H_0:** Providing without the AHSON algorithm does not significantly improve overall performance in wayfinding tasks for autistic people;

H_1: Providing with the AHSON algorithm significantly improve overall performance in wayfinding tasks for autistic people.

Specific experimental comparison: the efficacy of the AHSON algorithm for non-autistic people

The purpose of this experiment is to evaluate the level of performance exhibited by participants who are autistic as opposed to non-autistic participants when utilising the HBVE application, which is implemented with the AHSON algorithm. This is to determine whether or not the AHSON algorithm can provide navigational support for participants who are not autistic as well as autistic participants.

Specific experimental comparison: comparison of the parameters between algorithms

The purpose of this experiment is to compares four different types of navigation assistive algorithms by determining whether the route chosen by the AHSON algorithm is actually associated with a lower risk of becoming disoriented compared to the routes chosen by the other three algorithms (SLAM (Megalingam et al., 2018), UWB S-BA (Kagawa et al., 2014), and RDW (Meng et al., 2020)).

6.4.2 Participants and Recruitment Limitations

This section provides a detailed description of the participants' characteristics and the method used to recruit them for the research. Additionally, it discusses the limitations involved during the recruitment process, which could potentially impact the generalizability of the results:

Participants:

Twenty autistic people as participants were recruited from Pondoku centre and Fitrah Academy. Based on the Autism Diagnostic Interview-Revised (ADI-R) (Rutter et al., 2003), all of these participants confirmed that they had been diagnosed with autism syndrome symptoms, which include the following: high-functioning autism (HFA) that still requires support; poor non-verbal communication; nonverbal learning disorders that struggle with spatial awareness; abnormal sensitivity; and poor spatial awareness that has difficulty differentiating between directions and prepositions and accurately defining distance. There were sixteen males and four female (refer to Table 6.9). All the participants had experience with computers, but none of them had experience with haptic devices before. The participants' ages ranged from 9 to 27 years, with a mean age of 17.05

and SD = 5.949 In the meantime, for the group of non-autistic participants, in order to avoid a conflict in the comparison study, the same number of non-autistic people were recruited: sixteen males and four female, ranging in age from 9 to 27 years (with a mean age of 17.40 and SD = 6.007), and they were given the exact same procedure and tasks as the autistic participants.

Table 6.9: Demographic Information of Autistic's Participants

Participant ID	Gender	Age	Diagnosis
P1	Male	21	HFA
P2	Male	21	HFA
P3	Male	26	HFA
P4	Male	22	HFA
P5	Male	18	HFA
P6	Male	26	HFA
P7	Male	22	HFA
P8	Male	18	HFA
P9	Male	22	HFA
P10	Male	27	HFA
P11	Female	16	HFA
P12	Female	12	HFA
P13	Female	10	HFA
P14	Female	9	HFA
P15	Male	11	HFA
P16	Male	16	HFA
P17	Male	13	HFA
P18	Male	13	HFA
P19	Male	9	HFA
P20	Male	9	HFA

Recruitment Limitations:

This study investigates the use of HBVE among autistic people in Malaysia, with a primary focus on Selangor and Negeri Sembilan. Although haptic technology has the potential to offer numerous benefits, it is important to highlight and critically examine the limitations of the research's sample procedure. This research intentionally maintained the gender distribution at a ratio of 4 males to 1 female to accurately represent the well-acknowledged higher occurrence of autism among males (El Shemy et al., 2024; Fombonne, 2005; Haddod et al., 2019; B. Kim et al., 2023). This ratio is consistent with worldwide patterns in autism research. Therefore, these research findings may not fully represent the experiences and responses of females with autism, limiting their generalizability. The investigation specifically focused on the urban areas of Selangor and Negeri Sembilan, Malaysia. Although these regions have a high population density and are characterised by diversity, they may not accurately reflect the larger autistic population in Malaysia, especially in less developed regions where individuals may have distinct environmental and social experiences (Norbury & Sparks, 2013). The limited geographical coverage can impact the generalizability of the findings to all states in Malaysia. Moreover, this research restricted the inclusion criteria for autistic participants to individuals aged 9 to 27 years. This research chose this range to encompass a wide range of developmental stages, from late childhood to young adulthood. Nevertheless, this decision does not include younger children and older adults, potentially disregarding the significant advantages in terms of development and ageing that haptic technology can provide for autistic individuals' learning capacities (Gerhardt & Lainer, 2011). Excluding the age group may restrict our understanding of how applicable and effective haptic technology is in current and future research.

6.4.3 Experimental Apparatus and Environment

In this experiment, this study used the MYO Armband as a haptic wearable interface (device) to simulate haptic interactions or navigation (see Figure 6.50) and to understand both autistic and non-autistic people performance using the MYO Diagnostics application (MATLAB). Furthermore, to display the virtual environment, this study used a standard window-based LCD screen computer with Intel's Core (TM) i5-3570 CPU @3.40GHz. An urban modal of HBVE is implemented for wayfinding tasks with spatial and cognition information to analyse the haptic feedback based automated navigation algorithm in both conditions of with landmark clue and without landmark clue. All the participants learned to control the gesture movement of the MYO Armband haptic interface in a HBVE. This gesture movement method was guided in real-time with haptic feedback. Participants are able to control their navigation or movement in a virtual environment by specifying a direction of navigation and a speed, and this can be done through the MYO Armband haptic interface's orientations (roll ($\boldsymbol{\phi}$), pitch ($\boldsymbol{\theta}$), yaw ($\boldsymbol{\psi}$)), as shown in Figure 6.51. The participants' arms' roll and pitch were mapped, respectively, to the haptic interface speed and direction while holding a fist in order to move the haptic device. Also, with roll, the participants are able to navigate to the left and right, while pitch is used to navigate backwards and forwards in a virtual environment. Yaw was used to point the participants' direction of view (from the start point to the targeted object), and this is shown in Figure 6.52.

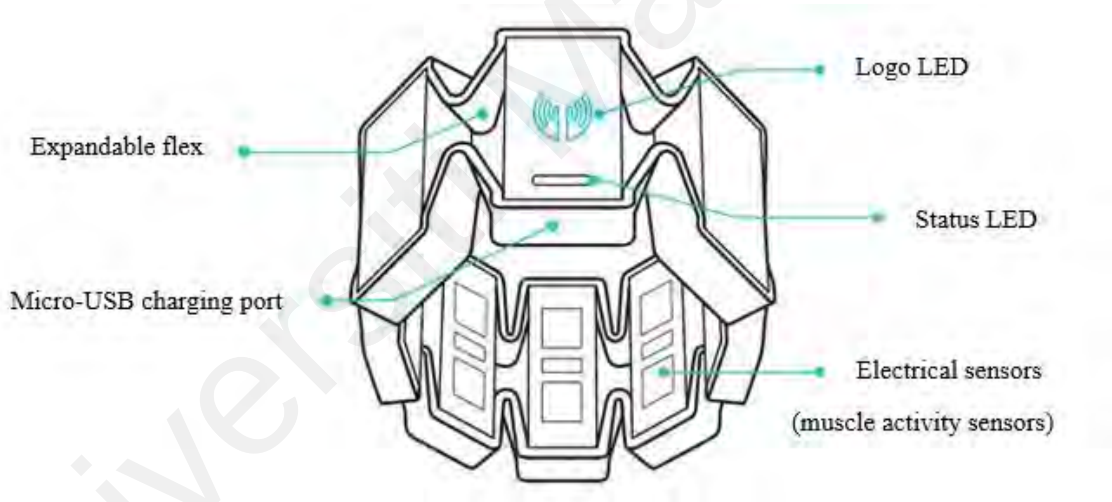


Figure 6.50: The MYO Armband gesture (haptic device) movement orientation

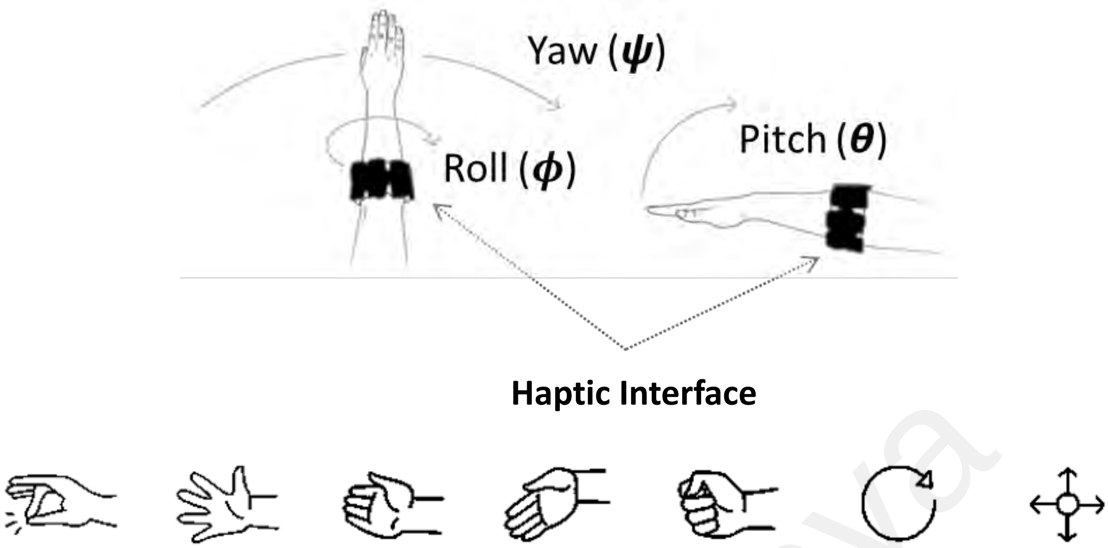


Figure 6.51: The MYO Armband gesture (haptic device) movement orientation

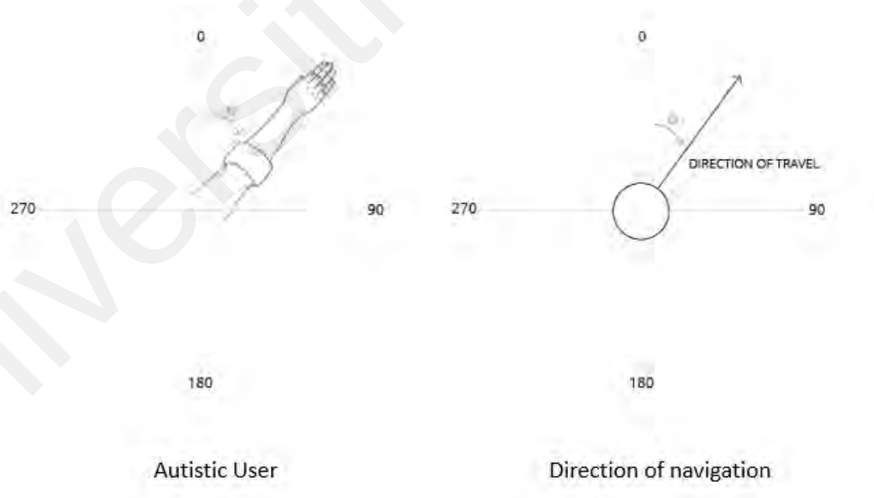


Figure 6.52: The MYO Armband gesture (haptic device) movement direction process towards targeted object

6.4.4 Wayfinding Task

The participants were asked to navigate in a virtual environment in order to find five objects under the condition of a landmark clue and another five objects under the condition of without landmark clue (refer to Figure 6.53). In the first condition with a landmark clue, the participants were provided with a cognitive map of the targeted object. Meanwhile, for the second condition, without landmark clues, the autistic people participants were not provided with a cognitive map of the targeted object.

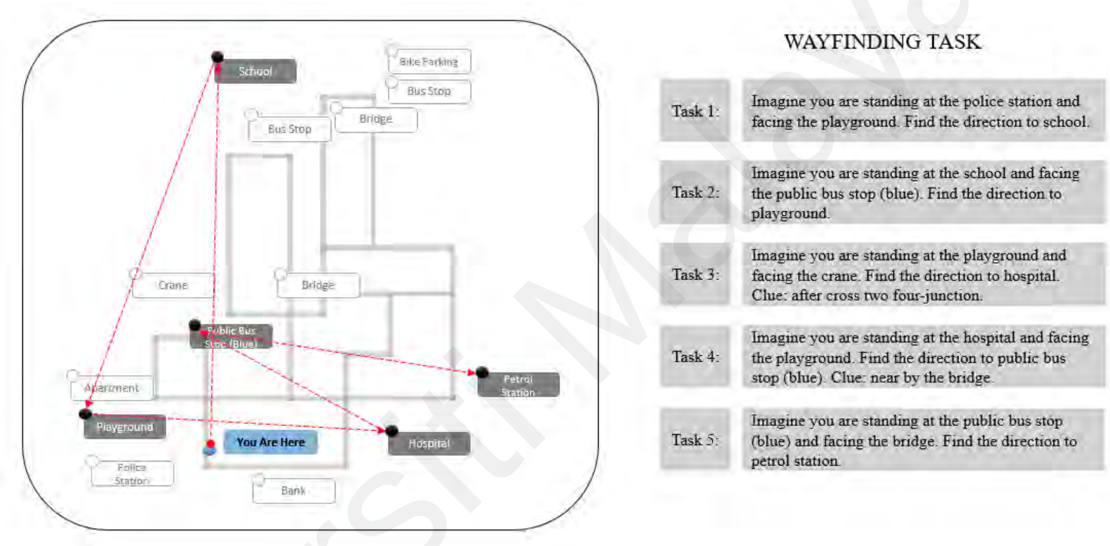


Figure 6.53: Example of wayfinding task and environment schema

6.4.5 Procedure

Before conducting the wayfinding tasks with both autistic and non-autistic people as participants, the participants requested to navigate and explore the virtual environment in order to familiarise themselves with the surroundings. The participants navigate along the virtual environment using the autonomous haptic spatial orient-navigate algorithm (AHSON), and when an object landmark is detected from the starting point (position of participant) through the haptic sensors (MYO Armband), the autonomous AHSON algorithm creates an eclipse based on the sensors and recalls and discovers the nearest next object landmark. For this wayfinding task, the urban virtual environment defines ten object landmarks: ObjL1: Restaurant, ObjL2: Crane, ObjL3: Statues, ObjL4: Police Station, ObjL5: Bank, ObjL6: Petrol Station, ObjL7: Clinic, ObjL8: Restaurant, ObjL9: Bus Stop, and ObjL10: School. The targeted object landmark is defined as $tObjL_n$ according to the objective of the task, which needs to be set as the targeted object to reach.

6.4.6 Data Measurement and Analysis

Three different experiments have been conducted in order to present the effectiveness and performance of the proposed algorithm with the wearable MYO Armband haptic device. The first experiment objective is to analyse the performance of autistic people participants in terms of wayfinding through landmarks with the proposed algorithm as an assistive technology to identify the targeted object or locations. The independent and dependent variables used for the first analysis are as follows, with the t-Test used at a significance level of 0.05:

(1) **Independent variables:** number of trials, the virtual environment;

(2) **Dependent variables:** number of object landmarks or targeted object identified correctly; the total distance travelled, the time taken to complete the task, the number of obstacles avoided.

Meanwhile, the second experiment objective is to demonstrate the effectiveness of the proposed algorithm in terms of orientation detection through IMU sensors. This test was examined based on the probability plot distribution and p-value at the 0.05 level of significance:

(1) **Independent variables:** number of trials, the virtual environment, parameters;

(2) **Dependent variables:** number of object landmarks or targeted object identified correctly.

Finally, the third experiment objective is to determine the effectiveness of the proposed algorithm by comparing it with other available navigation assistive algorithms. The independent and dependent variables used for the first analysis are as follows, with the t-Test and risk value analysis:

(1) **Independent variables:** number of trials, the virtual environment;

(2) **Dependent variables:** risk value of getting lose (ratio); risk value of getting lose (confidence intervals); path length (mm); time taken (sec); number of turns; number of interactions.

6.4.7 Results

To assess the performance of the proposed AHSON algorithm, a specific urban-based virtual environment was developed with a different set of conditions, with or without the AHSON algorithm as navigation assistance tools in a virtual environment (refer to section 6.4.1) during the learning and testing stage. The data was also presented in three ways based on the measures: 1) the overall performance of participants with autism (including non-autistic participants for comparison) in terms of wayfinding with or without the AHSON algorithm as assistance tools in a HBVE; 2) the effectiveness of the AHSON algorithm based on generated signals; and 3) the comparison of the parameters between an example of three different navigation algorithms and the AHSON algorithm.

6.4.7.1 Overall performance of autistic people participants in terms of wayfinding with/without the AHSON algorithm as assistance

Table 6.10 presents the results based on the objective measures in two different stages without the AHSON algorithm's assistance. Table 6.11 shows the results based on the AHSON algorithm's assistance. Meanwhile, Table 6.12 shows the overall results based on with and without AHSON algorithm assistance.

Table 6.10: The overall performance of autistic people participants in terms of wayfinding without the AHSON algorithm assistance

Objective measures	*Learning Stage*		*Testing Stage*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects identified	38.50	8.58	54.75	4.03	.045
Distance Travelled	49354.58	13382.25	29635.43	9131.43	.035
Time taken to complete	4:41:18	1:03:35	3:10:48	0:35:20	.023
Number of obstacles avoided	44.75	13.57	73.75	20.17	.004

Overall performance without the AHSON algorithm on learning and testing stage:

H_0: Providing without the AHSON algorithm does not significantly improve performance in wayfinding tasks for autistic people;

In terms of overall performance of participants during the learning stage without AHSON algorithm assistance, the number of objects (landmark or targeted object) identified (*t= 8.971*), distance travelled (*t= 7.376*), time taken to complete the wayfinding tasks (*t= 8.847*), and number of obstacles avoided during navigation (*t= 6.594*) show less effectiveness. Meanwhile, during the testing stage without AHSON algorithm assistance, there was reported slightly higher improvement compared to the learning stage on the number of objects (landmark or targeted object) identified (*t= 27.164*), the distance travelled (*t= 6.491*), the time taken to complete the wayfinding tasks (*t= 10.799*), number of obstacles avoided during wayfinding (*t= 7.312*) (refer to Table 6.10). Therefore, the null hypothesis 1 (H_0) is rejected, which effectively indicates that there is no significant difference in the p-values of all the four measures between the learning and testing stages. This demonstrated with 95% confidence that the testing stage shows a slight improvement in terms of wayfinding in the virtual environment compared to the learning stages, even without the assistance of AHSON.

Table 6.11: The overall performance of autistic people participants in terms of wayfinding with the AHSON algorithm assistance

Objective measures	*Learning Stage*		*Testing Stage*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects identified	59.50	6.25	80.50	3.11	.015
Distance Travelled	30007.59	14990.04	16660.42	7568.06	.042
Time taken to complete	3:00:29	0:41:24	2:14:01	0:34:05	.027
Number of obstacles avoided	70.00	20.94	116.00	19.17	.001

Overall performance with the AHSON algorithm on learning and testing stage

H_0: Providing with the AHSON algorithm does not significantly improve performance in wayfinding tasks for autistic people;

There was present effectiveness in terms of overall performance of autistic people participants during the learning stage with AHSON algorithm assistance on the number of objects (landmark or targeted object) identified (t= *19.055*), the distance travelled (t= *4.004*), the time taken to complete the wayfinding tasks (t= *8.719),* number of obstacles avoided during navigation (t= *6.684*). Furthermore, during the testing stage with AHSON algorithm assistance, there was higher effectiveness presented in the number of objects (landmark or targeted object) identified (t= *51.783*), the distance travelled (t= *4.403*), the time taken to complete the wayfinding tasks (t= *7.863),* number of obstacles avoided during wayfinding (t= *12.105*) (refer to Table 6.11). Based on the findings, the above null hypothesis 2 (H_0) is rejected, which effectively indicates that there is no significant difference in the *p-values* of all the four measures between the learning and testing stages. This demonstrated with 95% confidence that the testing stage shows significant improvement in terms of wayfinding in the virtual environment when compared to learning stages with AHSON support.

Table 6.12: The overall performance of autistic people participants in terms of wayfinding with and without the AHSON algorithm assistance

Objective measures	*Without AHSON*		*With AHSON*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects identified	93.25	9.18	140.00	5.29	.007
Distance Travelled	78990.00	20204.64	46668.00	22434.85	.006
Time taken to complete	7:52:06	1:33:58	5:14:30	1:12:20	.004
Number of obstacles avoided	118.50	33.67	186.00	40.09	.001

Comparison in between overall performance with and without the AHSON algorithm

H_0: Providing without the AHSON algorithm does not significantly improve overall performance in wayfinding tasks for autistic people;

Overall, the pairwise comparison results showed higher with the use of AHSON algorithm assistance, where the number of objects identified (t= *6.553*) and the number of obstacles avoided (t= *18.661*) increased when compared to without AHSON algorithm assistance. This possibility is due to the autonomous wayfinding via the IMU sensor and also due to the spatial information gained during the learning stage. Furthermore, the distance travelled (t= *-7.173*) and the time taken to complete the wayfinding tasks (t= -*7.775*) also decreased with AHSON algorithm assistance when compared to without AHSON algorithm assistance (refer to Table 6.12). Therefore, the null hypothesis 3 (H_0) is rejected, which effectively indicates that there is overall no significant difference in the *p-values* of all the four measures between without and with the AHSON algorithm. This demonstrated with 95 percent confidence that the with AHSON algorithm shows there has high improvement in terms of wayfinding in virtual environment compared to without AHSON algorithm.

Table 6.13: The overall performance of the AHSON algorithm between autistic and non-autistic participants during the learning stage

Objective measures	*Learning Stage*				
	Autistic		*Non-autistic*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects identified	59.50	6.25	82.00	10.55	.008
Distance Travelled	30007.59	14990.04	18205.68	8281.63	.039
Time taken to complete	3:00:29	0:41:24	1:27:53	0:19:47	.003
Number of obstacles avoided	70.00	20.94	90.25	23.54	.001

Table 6.14: The overall performance of the AHSON algorithm between autistic and non-autistic participants during the testing stage

Objective measures	*Testing Stage*				
	Autistic		*Non-autistic*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects identified	80.50	3.11	133.25	18.84	.017
Distance Travelled	16660.42	7568.06	9196.97	3786.18	.045
Time taken to complete	2:14:01	0:34:05	0:55:44	0:14:53	.004
Number of obstacles avoided	116.00	19.17	152.25	15.84	.001

Comparison of the overall performance of the AHSON algorithm between autistic and non-autistic people for both staging's

Overall, the results of the pairwise comparisons showed that the assistance provided by the AHSON algorithm resulted in higher levels of performance in non-autistic people when compared to autistic people (refer to Table 6.13 and 6.14). This included an increase in both the number of objects identified (learning stage: t= *6.429,* testing stage: t = *4.811*) and the number of obstacles avoided (learning stage: t= *12.258,* testing stage: t = *11.826*). This is a distinct possibility as a result of the autonomous wayfinding provided by the IMU sensor as well as the participant's capabilities to process spatial information. In addition, it was reported that non-autistic people travelled less distance (learning stage: t= - *3.501,* testing stage: t= - *3.322*) and completed the wayfinding tasks (learning stage: t= - *8.482,* testing stage: t= - *8.146*) in significantly less time compared to autistic people. Therefore, this comparison effectively indicates that there is an overall significant difference in the p-values of all four measures between these two groups of people using the AHSON algorithm. Overall, this demonstrated with a confidence level of 95 percent that the AHSON algorithm shows there has been a significant improvement in terms of wayfinding in virtual environments for non-autistic people not only during the learning stage but also when comparing the testing stage and the learning stage. Anyhow, when it comes to comparing and contrasting these stages of learning, this improvement is not ignored for autistic people either, despite the fact that the difference in contribution is on a relatively minor scale.

6.4.7.2 The effectiveness of AHSON algorithm based on signals generated

The highly sensitive nine-axis inertial measurement unit (IMU) data utilised to evaluate the proposed algorithm has the ability to assist autistic people navigate and find the desired object/landmark. The results are interpreted using the probability plot and the p-value to determine the level of significance for the following hypotheses:

(1) **H0:** Providing with the AHSON algorithm improves performance in wayfinding tasks for autistic people.;

(2) **H1:** Providing with the AHSON algorithm did not improved performance in wayfinding task for autistic people.

Special Note: The fitted distribution line refers to the straight middle line on the probability plot, whereas the other two outer solid lines refer to the confidence intervals for each of the individual percentiles on the probability plot.

Overall performance of the Pitch-position for the selected landmark

Figure 6.54 shows the results of participant three for all nine sessions of testing, with ObjL10: School as the targeted landmark used to examine the probability distribution. Furthermore, the accuracy of landmark detection is determined by the acceleration (the position of the *x* and *y* values) of those identified landmark detection points in the probability plot. As a result, this probability plot exhibits a normal distribution, which can be determined based on the landmark detection points that closely followed the fitted distribution line.

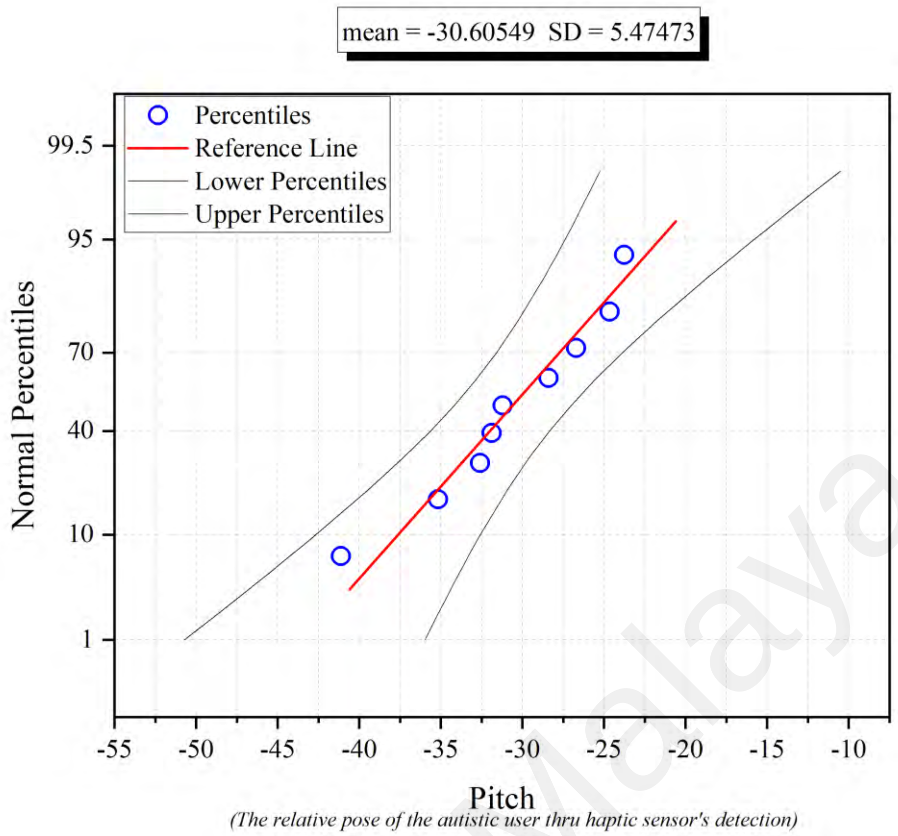


Figure 6.54: The overall performance of pitch-position for selected landmark of the participants through acceleration signal

Overall performance of the Yaw-position for the selected landmark

In the same way that the findings of pitch-position for a selected landmark are displayed, the results of yaw-position for a selected landmark are also presented based on all nine sessions of testing and with the same targeted landmark by participant three as well. This can be seen in Figure 6.55, where the acceleration (the positions of the x and z values) is utilised to measure the accuracy of landmark detection. Because of the existence of an interaction between pitch and yaw during haptic interaction in the virtual environment, the yaw-position probability plot also exhibits a normal distribution, which can be determined based on the landmark detection points that are located close to the fitted distribution line on the probability plot.

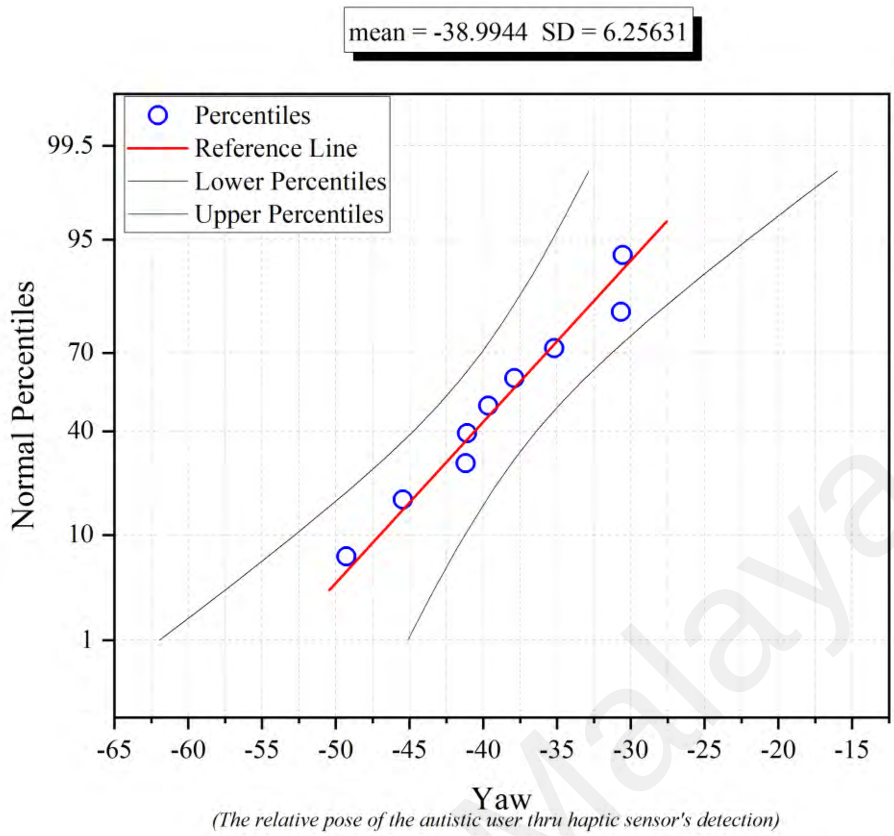


Figure 6.55: The overall performance of yaw-position for selected landmark of the participants through acceleration signal

Overall performance of the Pitch-position

Throughout the testing sessions, the overall performance of pitch-position was depicted in Figure 6.56 for all twenty of the participants. When looking at the probability plot, it appears that there is a normal distribution, with the majority of the landmark detection points following closely to the fitted distribution line. Despite the fact that there were only a few landmark detection points that fell between the upper percentiles and lower percentiles lines, this did not have an impact on the overall performance of the haptic sensor in terms of landmark detection in a virtual environment.

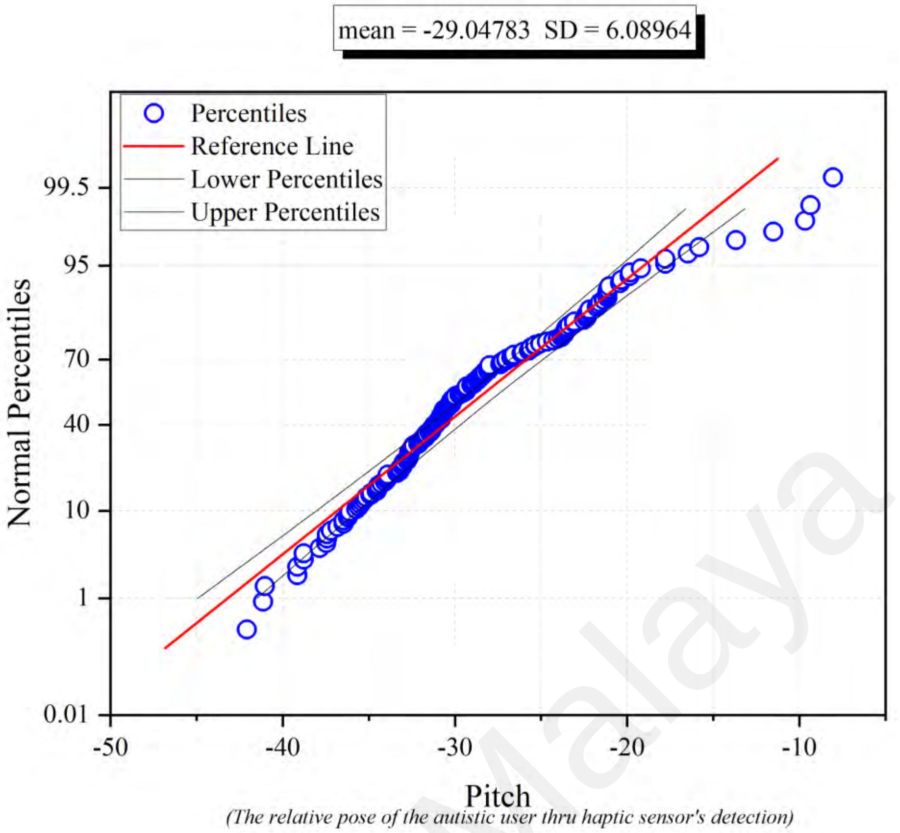


Figure 6.56: The overall performance of the pitch-position of the participants through the acceleration signal

Overall performance of the Yaw-position

The overall performance of yaw-position is comparable to pitch-position in situations where nearly all of the landmark detection points do not cross the upper and lower percentile lines, as presented in Figure 6.57. Consequently, the results reveal that the overall performance of yaw-position follows a normal distribution, which can be inferred based on the landmark detection points that were located close to the fitted distribution line for all twenty participants and all of the testing sessions.

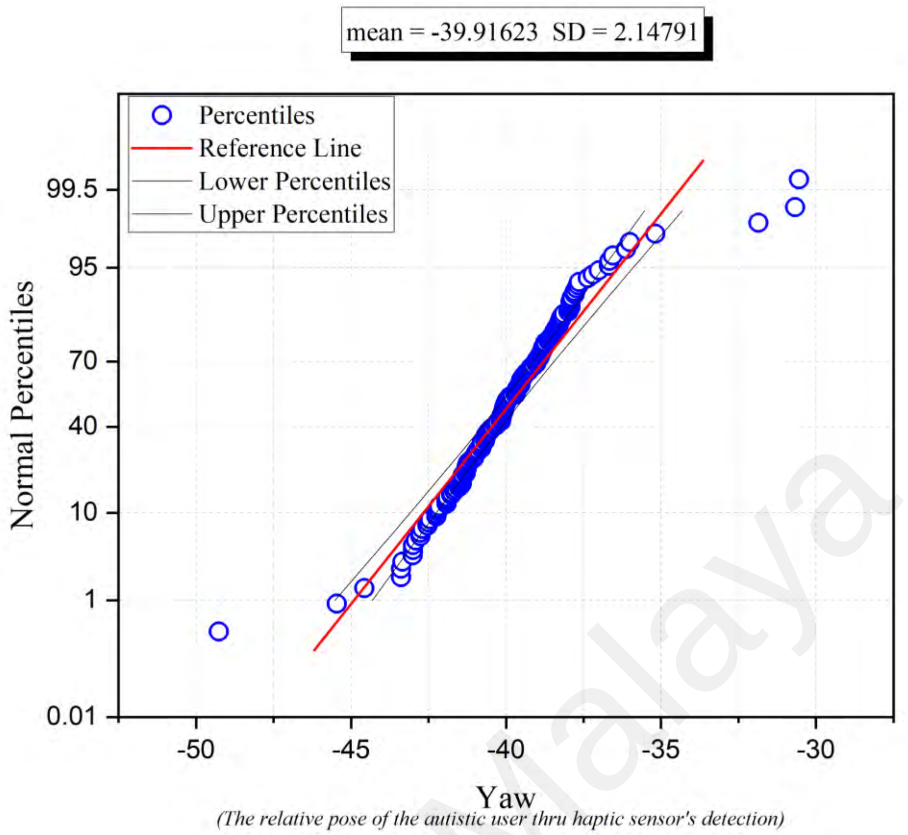


Figure 6.57: The overall performance of the yaw-position of the participants through the acceleration signal

6.4.7.3 Comparison of the parameters between an example of three different navigation algorithms and the AHSON algorithm

This section specifically compares four different types of navigation assistive algorithms and this presented in the Table 6.15. The theoretical precariousness of these was taken into account during the analysis, and the results were interpreted in terms of a standard parameter set (refer to Table 6.15). In a variety of wayfinding experiments, these parameters have been shown to be able to both lead to an understanding of the likelihood of becoming disoriented and of reaching the desired destination. Furthermore, this comparison is only carried out between two distinct objects or locations (source and destination) with one obstacle.

Table 6.15: Comparison of the parameters between an example of three different navigation algorithms and AHSON algorithm

Benchmark parameters	AHSON	SLAM	UWB S-BA	RDW
Risk values of getting lose (ratio)	0.9998	0.9984	0.9996	0.9934
Risk value of getting lose (confidence intervals)	40.998	42.848	41.556	50.242
Path length (mm)	4286.02	4153.28	16058.5	897.4
Time taken (sec)	19.6	36.1	120.0	29.7
No. of turns	3	3	6	5
No. of intersections	2	3	4	3

Comparison of path length and time taken with risk value

In terms of the overall results, the AHSON path length used is on average 46.7% (form total average) shorter than the lengths used by its respective other algorithms. In addition, the time taken by AHSON is on average 89.4% less than the time taken by the other three algorithms. In principle, this suggests that the AHSON path is a route with a lower potential for risk (6.8% less risk value), and the reason for this could be the implication of automated route navigation. These findings indicate that the AHSON algorithm, in comparison to the paths taken by other algorithms, is the one that is suitable for wayfinding in a virtual environment. This is because the AHSON algorithm calculates routes that involve a lower risk of becoming disoriented with regard to the availability of haptic sensors.

Analysis of navigation complexity

The AHSON algorithm's primary goal is to reduce the overall risk of becoming disoriented while navigating through a virtual environment. This goal can be achieved by reducing the complexity of the navigation. The number of intersections that must be navigated through and the number of turns constitute the complexity of the navigation. The results presented in Table 6.15 demonstrate that the AHSON algorithm has a lower number of intersections and a lower average number of turns when compared to the other three algorithms. As a result of the differences' relatively high level of sophistication, the AHSON algorithm is able to significantly reduce the complexity of navigation, which indirectly reduces the overall risk of becoming disoriented while navigating through a virtual environment.

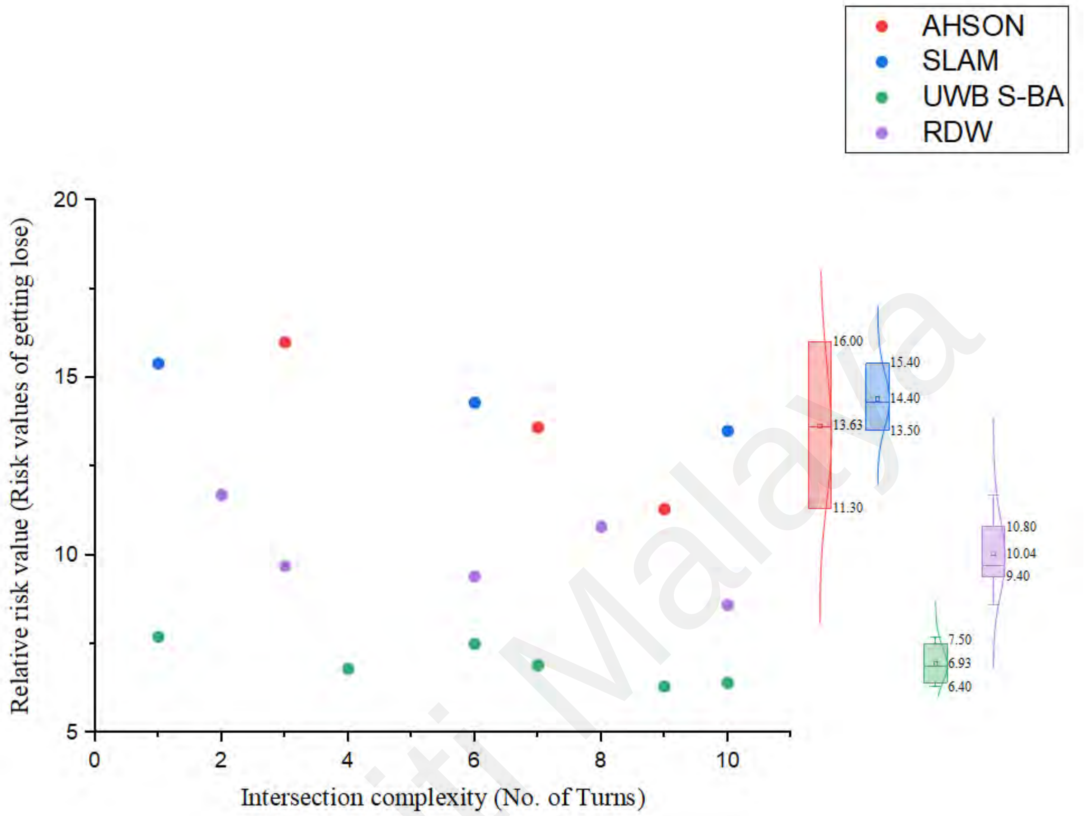


Figure 6.58: The relationship between intersection complexity and relative risk value increases

The relationship between the intersection complexity and risk value for the AHSON algorithm and the other three separate algorithms is depicted in Figure 6.58. According to Figure 6.58 an exponential relationship can be seen between an increasing level of intersection complexity and an accompanying rise in the risk value of the intersection. This demonstrated that the number of turns supportive of the haptic sensor signal do, in fact, play an important role in determining the overall risk value. In conclusion, it would appear that certain components of the AHSON algorithm make sense when it comes to assisting autistic people in avoiding becoming disoriented while navigating to the destination they had anticipated in a virtual environment.

6.4.8 Discussion

This autonomous algorithm for navigation in a virtual environment by autistic people using a haptic sensor and a landmark mapping method has been evaluated, and the findings have been given in accordance with the hypothetical conditions that were used. This AHSON algorithm is designed to move autonomously across virtual environments using haptic sensors as a navigation technique. Aside from that, the detection of the haptic sensor determines an object landmark for the self-location of the participants, where the participants are able to re-orient their navigation route in a virtual environment in order to arrive at their final destination. There are several advantages to using this algorithm. In fact, while it has the potential to lose direction during navigation, it makes use of spatial orientation information and landmark mapping methods to maintain navigational continuity until it reaches the target destination point. In consideration of the experimental findings, it can be concluded that this algorithm is capable of assisting autistic people in finding the desired destination in a virtual environment. Aside from the participants performance experience during the learning and testing phases, this can be proven by the high accuracy of landmark detection based on the user's self-position and orientation information (self-awareness and spatial awareness) during the interaction with a haptic device. There is a positive correlation between the existence of the AHSON algorithm and wayfinding performance in the virtual environment, and this can be seen through the high number of objects identified and obstacle avoidance by participants, as well as the fact that the participants use less time when compared to the performance of wayfinding without the AHSON algorithm. Furthermore, this AHSON algorithm has also been tested with non-autistic people in both learning stages in comparison to autistic people in order to determine whether this proposed algorithm is able to support those non-autistic people while they navigate in a virtual environment. According to the findings, the AHSON algorithm has a significant amount of success when applied to non-autistic people, just as it does when apply to autistic people. In addition, the performance of this algorithm was evaluated in comparison to that of three other navigation-assistance algorithms in order to determine the most effective way to navigate through a virtual environment without becoming disoriented. The AHSON algorithm demonstrated significantly better performance in terms of the potential for becoming disoriented. However, in order to provide improved navigational assistance, this AHSON algorithm will need to investigate other factors in the future as well. These factors include the number of curves, the number of decision nodes that have been traversed, and the number of options that can be selected at any given intersection stage of navigation. Overall, the AHSON algorithm performs well in assisting autistic people to reach their target destination without losing direction during navigation or wayfinding in a virtual environment. In addition to testing the proposed algorithm in a non-immersive environment, this experimental evaluation will be used to develop and evaluate the algorithm in an immersive environment in the future, with the goal of improving navigation for autistic people.

6.5 Experimental Evaluation of the Haptic Feedback Uses Vibrations towards Autistic people as Tactile Sense

This section presents the experimental studies of haptic feedback as a vibration measurement among people who have autism. There are a number of measurements that can be used to identify and confirm the ability and presence of haptic feedback in autistic people. Detailed descriptions of the assessment method and findings are provided in the following subsections.

6.5.1 Methods

The following sections explain the types of instruments, procedures, and data analysis used to conduct the testing. In addition, this method can be split into two types: 1) using a sensory profile to analyse behavioural responses; 2) using vibration detection to analyse touch sensory patterns.

6.5.1.1 Method of Analyzing Behavioral Response (Short Sensory Profile 2 – SSP2 and Adolescent/ Adult Sensory Profile – AASP)

A two-way mixed ANOVA analysis method was used to study the behavioural responses of autistic people (participants) between the use of a haptic device (experimental group) and without a haptic device (comparison group) during interaction in a virtual environment. This experiment was conducted based on the modified Short Sensory Profile 2 (SSP2) for the children's group (ages ranged between 3 and 10 years) and the Adolescent/Adult Sensory Profile (AASP) for the adolescent or adult group (ages > 11) to study sensory sensitivity. The SSP2 and AASP each contain 86 and 60 (item) self-reported questionnaires, respectively, with access to sensory processing across various sensory modalities (such as touch, visual, auditory, movement, and taste/smell), but this study only focused on the touch (haptic feedback) aspect. Each participant will take approximately 15 minutes to complete with support by caregivers or teachers to evaluate the participant's behavioural response. Participants are requested to specify the frequency of responses to touch sensory during the interaction with the haptic device on a five-point scale (1 = almost never, 2 = occasionally, 3 = half the time, 4 = frequently, 5 = almost always).

6.5.1.2 Method of Analyzing Touch Sensory Pattern

In general, the haptic device includes or integrates 9-axis IMU sensors and EMG sensors to quantify vibration as haptic feedback during contact with a three-dimensional environment. The vibration signal observed on the MYO armband haptic device toward the experimental group is the consequence of autistic people's muscles contracting and their arms interacting or moving when handling a virtual object. As a result, the purpose of this study was to analyse the usage of 9-axis IMU sensors signal and EMG sensors by reflecting vibration information as vibration sensitivity to determine the presence of touch sensory in autistic people. This study focused on detecting vibration correlations between experimental group users and critical data metrics. The procedure and parameters used to study the touch sensory pattern in autistic people are described and defined in the following section.

6.5.2 Participants

The sample sizes for this study were influenced by various factors, particularly the study purpose and the characteristics of the study population. Nevertheless, the following studies employed an insignificant sample size, ranging from 16 to 27 participants, to investigate the impact of haptic technology and virtual environments on autistic participants (Fornasari et al., 2013; Sophie E Lind et al., 2013; M. Ring et al., 2018; Umesawa et al., 2020; J. Zhao et al., 2022). Hence, this research aims to carry out an experiment involving a total of twenty participants (children: 2 female, 2 male, mean age 9.25, SD =.434; adolescents or adults: 2 female, 14 males, mean age 19.00, SD = 5.016) for both methods of research: 1) analysing behavioural response; and 2) analysing touch sensory pattern. As highlighted in recruitment limitation, the distribution of autistic people in this research reflects a gender ratio of 4:1 (male to female), which is consistent with the widely documented gender discrepancy in autism found in other studies (El Shemy et al., 2024; Haddod et al., 2019; B. Kim et al., 2023). In addition, all participants confirmed that they have an ASD diagnosis and computer experience, but none of them had previously used haptic devices.

6.5.3 Material and Designs

This experiment used the MYO Armband as a haptic wearable device to simulate haptic interactions (refer to Figure 6.50) and it used a MATLAB-based MYO Armband patten analysis application to understand autistic people's sensory performance. Furthermore, this experiment used a standard window-based LCD screen computer with an Intel Core(TM) i5-3570 CPU @3.40GHz.

6.5.4 Object Force Pushing Interaction Task

This study proposed an *object force pushing interaction task* to evaluate the performance of haptic (tactile) sensitivity among autistic people. This task was conducted in two different aspects, and this can be seen in Figure 6.59: 1) Right-to-left force direction; 2) Top-to-bottom force direction. The user should use the virtual finger to push the 3D ball towards the floor and wall until a collision occurs in between. This task was implemented in both the comparison and experimental groups.

6.5.5 Procedure

All participants took part in both methods (Behavioral Response and Touch Sensory Pattern) and were observed separately. The experiments were conducted based on the following steps:

(1) Before the comparison group and experimental testing, all the participants were asked to complete the initial Analyzing Behavioral Response profile (dimension: *General Tactile Sensitivity*) with caregivers or teacher's assistance to study the level of sensory processing disorder.

(2) During the comparison group testing, all the participants were asked to become familiar with the virtual environment and keyboard and mouse as interaction devices only, and after the completion of the task, the participants were asked to complete the Analyzing Behavioral Response profile (dimension: *Before VR Communication Device – Mouse and Keyboard*) with caregivers or teacher's assistance.

(3) During the experimental group testing, all the participants were asked to become familiar with the MYO Armband haptic interface and with the virtual environment, and after the completion of the task, the participants were asked to complete the Analyzing Behavioral Response profile (dimension: *After VR Communication Device – Haptic Device*) with caregivers or teacher's assistance.

(4) During touch sensory pattern testing, all the participants were asked to familiarise themselves with the MYO Armband haptic interface and with the virtual environment.

This evaluation involved two different stages: 1) Behavioral Response Profile stage; 2) Touch Sensory Pattern stage. Each participant with autism had a maximum of fifteen minutes to complete the tasks for each stage. The autistic people participants provided general knowledge about the virtual environment and features involved, and also introduced the haptic interface (MYO Armband) features and the way to control and manipulate them in HBVE. The initial test begins with the behavioural response profile stage, which is tested in both comparison and experimental groups to study the level of sensory processing disorder among the participants. During the comparison group testing, the autistic people participants were asked to perform the *object force pushing interaction task* by pushing the 3D ball (**a**) to the 3D wall (**b**) (refer to Figure 6.59 (1)), and the 3D ball (**a**) to the 3D floor (**b**) (refer to Figure 6.59 (2)) using the mouse and keyboard only. Meanwhile, during the experimental group testing, they were asked to repeat the same procedure as the comparison group but with the MYO Armband haptic interface only. After the completion of each test, the participants were asked again to complete the behavioural response profile with caregivers' or teacher's assistance. Furthermore, in the second stage (touch sensory pattern), the experimental group testing is carried out only to extract the real-time sensory signal (3-axis accelerometer) via MYO Armband pattern analysis software (MATLAB).

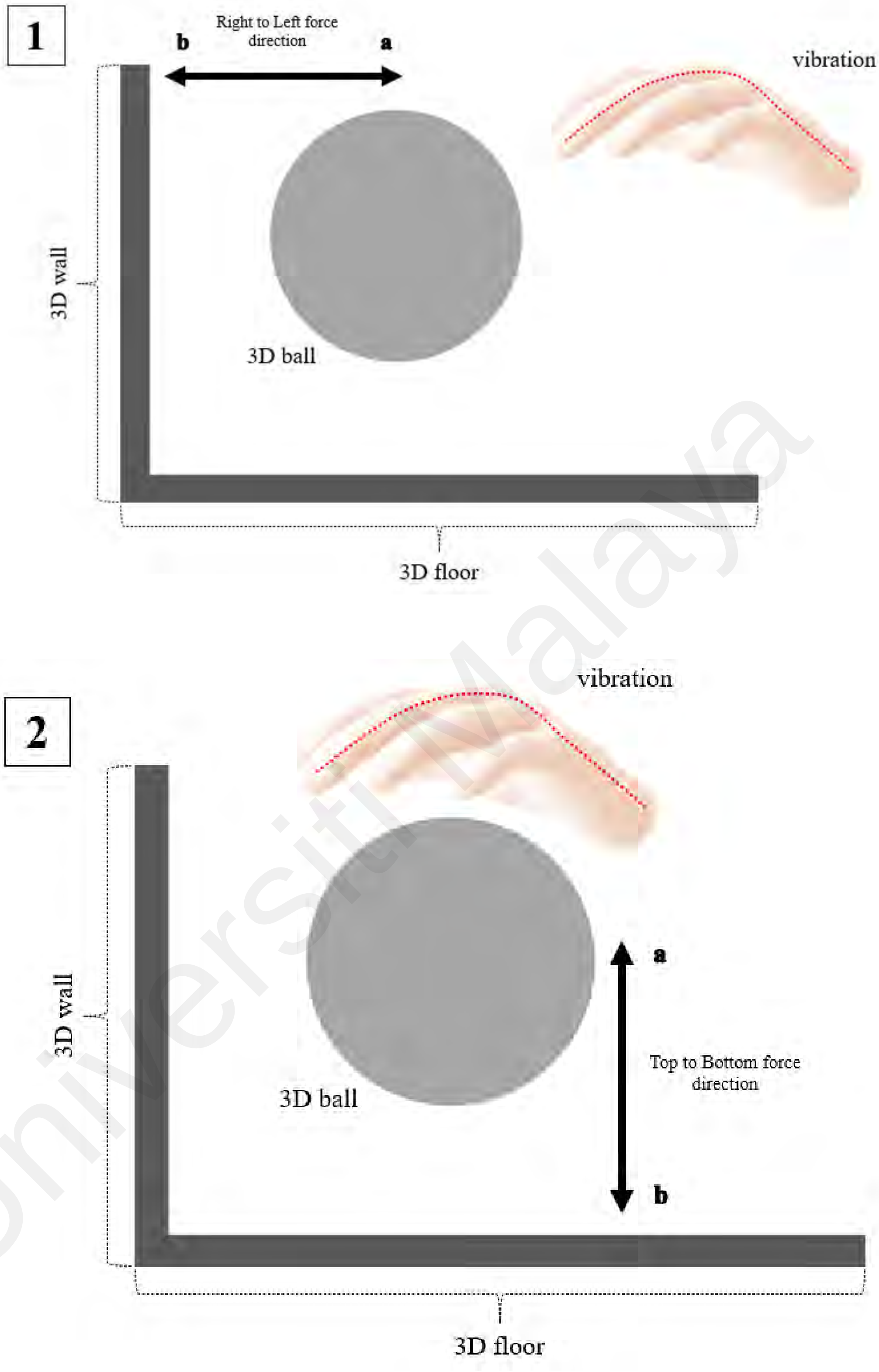


Figure 6.59: The two force direction methods to detect the vibrations through the accelerometer signal

6.5.6 Data Measurement and Analysis

In order to examine the effectiveness of the haptic device in terms of detection of sensory sensitivity level towards autistic people, the following measures are used:

6.5.6.1 Data Measurement for Behavioral Response

The Paired Samples T-Test method is used to examine if there aren't any differences in the types of sensory profiles between experimental and comparison groups of autistic people. The mean, standard deviation, and p-value were used to determine the significance levels in this analysis.

6.5.6.2 Data Measurement for Touch Sensory Pattern

The experimental data will be measured and interpreted based on the following types of measurements:

Acceleration (g)

This parameter is used to determine the rate of change of velocity of a virtual object. This is measured based on the net force acting upon the virtual object and inversely upon the mass of the virtual object. The acceleration value is measured based on the equation 6.1:

$$acceleration\ (g) = \frac{F\ (resultant/\ net\ force)}{m\ (mass)} \tag{6.1}$$

Electromyography sensor (mV)

This parameter data was captured based on eight electromyography (EMG) sensors from the haptic device, which are used to measure the muscle activity in millivolts (mV).

The equation 6.2 shows how the average mean absolute deviation (MAD) was computed for the EMGs sensors:

$$MAD\ of\ electromyography\ sensor\ (mV) = \frac{\sum |mV - \overline{mV}\,|}{n} \tag{6.2}$$

Accelerometer Sensitivity (mV/g)

This parameter is used to measure the dynamic acceleration of a haptic device as a voltage. This means this accelerometer is used to monitor autistic people sensitivity levels. During muscle activities, the accelerometer signals produce real-time sensitivity to autistic people. The accelerometer sensitivity value is measured based on the equation 6.3:

$$accelerometer\ sensitivity\ (mV/g) = \frac{mV\ (millivolts)}{g\ (acceleration)} \tag{6.3}$$

Frequency (f)

This parameter is required to determine the sensitivity of the accessing muscle. It is necessary to obtain the equation 6.4 to measure the frequency of the wave, which is 200Hz and completes once every second:

$$frequency\ (f) = \frac{1}{T\ (time\ taken\ to\ complete\ one\ cycle)} \tag{6.4}$$

Overall, the frequency response towards accelerometer sensitivity will show participants' muscle sensitivity during the usable frequency range.

6.5.7 Results

This section presents the findings from both experimental methods (Behavioral Response and Touch Sensory Pattern) using different sets of metrics or measurements to determine the presence of haptic feedback (vibration) as a sense of touch among autistic people during interaction with virtual objects.

6.5.7.1 Behavioral Response (modified Short Sensory Profile 2 – SSP2 and Adolescent/ Adult Sensory Profile – AASP)

The Paired Samples T-Test was used in this study to determine whether there was a significant difference in the overall outcome of the modified SSP2 and AASP sensory profiles between the experimental group (with haptic technology experience) and the comparison group (without haptic technology experience) of autistic people. The sensory profile quadrant is treated as a dependent variable, while the experimental and comparison groups are treated as independent variables. Overall, the general tactile sensitivity based on different age groups (SSP2: 3 to 10 years; AASP $>$ 11 years) shows that there is a significant difference ($p < 0.001$). The AASP slightly shows less reading (mean and SD) in terms of low registration, sensory sensitivity, and sensation avoiding, compared to SSP2 due to age gaps, which are more stable in terms of sensation seeking (refer to Table 6.16).

Following the significant of overall sensory processing profile outcome through the Paired Samples T-Test, the same test analysis method was conducted to compare the sensory profile quadrant scores of autistic people with and without haptic experience. The results of this study indicate that there are significant group differences in all the factors (low registration, sensation seeking, sensory sensitivity, sensation avoiding), where the experimental group shows higher scores compared to the comparison group on the sensory sensitivity for both types of sensory profile, respectively (SSP2 and AASP), and this can be seen in Table 6.17.

Table 6.16: Sensory processing quadrant scores for the SSP2 and AASP in autistic people (age factor)

Factor in types of sensory profile	Sensory processing (SSP2)		Sensory processing (AASP)	
	Mean	*SD*	*Mean*	*SD*
General Tactile Sensitivity				
Low registration	59.58	10.83	42.81	15.19
Sensation seeking	22.92	5.67	33.54	15.30
Sensory sensitivity	64.06	14.48	40.55	14.16
Sensation avoiding	83.75	4.78	41.98	16.50

Table 6.17: Sensory sensitivity quadrant scores for the experimental and comparison groups in autistic people

Factor in types of sensory profile	*Experimental group*		*Comparison group*		*Group differences*	
	Mean	*SD*	*Mean*	*SD*	*t*	*p*
Sensory processing (SSP2) – VR Communication Device	44.06	7.78	65.78	1.79	5.45	.012
Low registration	35.63	13.44	80.63	3.75	5.51	.012
Sensation seeking	81.25	2.50	32.50	10.23	-9.90	.002
Sensory sensitivity	31.88	21.15	77.50	11.73	3.75	.033
Sensation avoiding	27.50	16.58	72.50	16.58	5.35	.013
Sensory processing (AASP) – VR Communication Device	41.09	5.96	49.51	10.89	2.50	.025
Low registration	40.63	16.06	54.22	15.29	2.91	.011
Sensation seeking	74.38	11.78	28.65	13.95	-9.65	.001
Sensory sensitivity	23.75	12.52	53.59	16.73	5.14	.001
Sensation avoiding	25.63	18.43	61.56	22.19	4.65	.001

In order to further understand sensory sensitivity through haptic feedback as the use of touch to interact with autistic people, the correlation analysis was conducted to examine the strength of the relationship between sensory sensitivity and age. The two-tailed significant level ($p < 0.01$) was used to avoid the issue of type 1 errors due to the fact that this study used a minimum number of within-group correlations. Pearson correlations demonstrated significant among sensory sensitivity in the experimental group ($r = -0.482$ to 0.369, $p > 0.05$) and when compared to the comparison group ($r = -0.660$ to -0.153, $p > 0.05$), and this indicates that sensory sensitivity is present in autistic people during the interaction with haptic technology, while unusual sensory sensitivity is found in autistic people before the haptic technology experience.

Furthermore, the SSP2 shows that significant correlations were observed between sensory sensitivity and autistic people traits in the experimental and comparison groups ($p > 0.05$), but not in the AASP for the experimental and comparison groups ($p > 0.05$). This shows autistic people traits do not influence the sensory sensitivity of AASP compared to SSP2 during the interaction with haptic technology.

6.5.7.2 Touch Sensory Pattern

As a haptics device and an interaction platform, the MYO armband was used in this study. The virtual environment served as the test environment. The accelerometer is most typically measured with the use of a haptic device that vibrates. This means that the accelerometer is a sensor that is capable of measuring the dynamic acceleration of a haptic device (such as the MYO Armband) as a voltage output signal (C. Salisbury et al., 2009). This sensor is comprised of a 9-axis IMU sensor (3-axes accelerometer, 3-axes gyroscope, and 3-axes magnetometer), and this study only extracted the 3-axes accelerometer and eight dry surface EMG sensors in order to provide real-time sensory data to pattern analysis software (MATLAB) for further investigation of sensory detection. An intelligent machine method was used to analyse data from a 3-axis accelerometer as well as EMG data. To investigate touch sensory patterns, the IMU data and EMG sensors use two domain features: Accelerometer Sensitivity (mV/g) and Frequency (Hz). The haptic vibrations on the surface of the IMU and EMG sensors in the MYO Armband were used to determine the threshold of sensory sensitivity for the MYO Armband.

Figure 6.60 presents a sample of the detection of real-time acceleration signals via haptic devices during the interaction and manipulation activity in the virtual environment by participant number three. Meanwhile, Figure 6.61 displays the real-time signal from eight EMG sensors, which is captured by the electrical impulses generated by the forearm muscles during interaction and manipulation activities in a virtual environment.

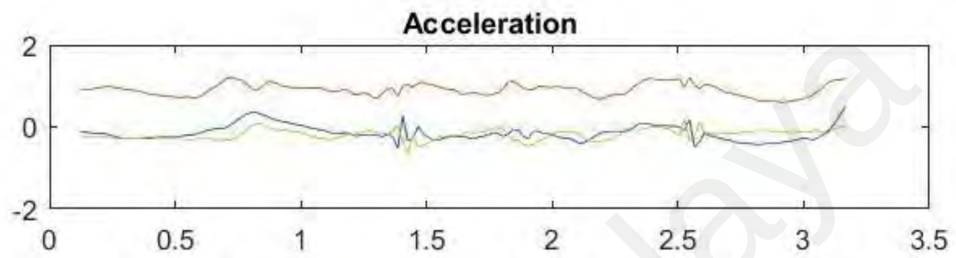


Figure 6.60: The detection of acceleration signals via haptic device for participant number three during the testing

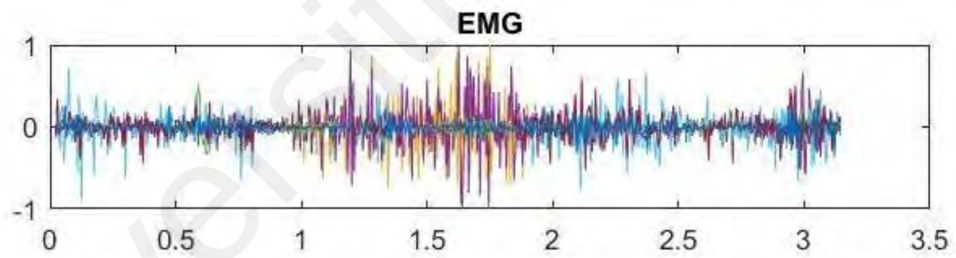


Figure 6.61: The detection of EMG signals via haptic device for participant number three during the testing

Table 6.18 shows the average sensitivity results for acceleration (*g*) and EMG sensors (*mV*) when the vibration frequency is 200 Hz, and these average sensitivity values are estimated based on nine trials for each of the participants. The individual standard deviation falls between 0.0 mV/g and 0.1 mV/g.

Table 6.18: Touch sensory pattern scores for the experimental groups at vibration frequency 200Hz

Participants	*Acceleration (g)*			*EMG sensor (mV)*		
	G	*Mean*	*SD*	*mV*	*Mean*	*SD*
1	16.673	1.8526	0.3689	0.0104	0.0012	0.0242
2	17.602	1.9558	0.0108	0.0701	0.0078	0.0210
3	17.540	1.9489	0.0143	0.0365	0.0041	0.0294
4	17.294	1.9216	0.0140	0.0774	0.0086	0.0247
5	16.831	1.8701	0.2853	0.0127	0.0014	0.0051
6	17.445	1.9383	0.0226	0.0814	0.0090	0.0119
7	16.626	1.8474	0.3691	0.0053	0.0006	0.0242
8	17.608	1.9564	0.0109	0.0741	0.0082	0.0210
9	17.461	1.9401	0.0141	0.0322	0.0036	0.0294
10	17.324	1.9249	0.0140	0.0813	0.0090	0.0248
11	16.565	1.8406	0.3689	0.0034	0.0004	0.0242
12	17.692	1.9657	0.0107	0.0689	0.0077	0.0210
13	17.411	1.9346	0.0141	0.0305	0.0034	0.0294
14	17.441	1.9379	0.0138	0.0737	0.0082	0.0247
15	16.708	1.8564	0.2853	0.0311	0.0035	0.0070
16	21.962	2.4402	0.0286	0.0785	0.0087	0.0119
17	16.673	1.8526	0.3689	0.0060	0.0007	0.0242
18	17.540	1.9489	0.0143	0.0321	0.0036	0.0294
19	16.831	1.8701	0.2853	0.0083	0.0009	0.0051
20	16.626	1.8474	0.3691	0.0009	0.0001	0.0242

Participants	*Average Sensitivity (mV/g)*			
	mV/g	*Mean*	*SD*	*%*
1	0.0080	0.0009	0.0123	1.8
2	0.0362	0.0040	0.0108	8.3
3	0.0186	0.0021	0.0151	4.3
4	0.0399	0.0044	0.0129	9.2
5	0.0039	0.0004	0.0032	0.9
6	0.0418	0.0046	0.0061	9.6
7	0.0051	0.0006	0.0123	1.2
8	0.0382	0.0042	0.0108	8.8
9	0.0164	0.0018	0.0151	3.8
10	0.0418	0.0046	0.0129	9.6
11	0.0044	0.0005	0.0125	1.0
12	0.0359	0.0040	0.0109	8.3
13	0.0160	0.0018	0.0154	3.7
14	0.0384	0.0043	0.0130	8.8
15	0.0238	0.0026	0.0059	5.5
16	0.0407	0.0045	0.0061	9.3
17	0.0056	0.0006	0.0125	1.3
18	0.0166	0.0018	0.0153	3.8
19	0.0014	0.0002	0.0033	0.3
20	0.0024	0.0003	0.0125	0.6

Figure 6.62 shows the overall haptic sensitivities detected among all the participants during the interaction with the haptic device at different trial sessions. The high level of sensitivity observed in trial number 9 was attributable to the fact that the majority of participants were seeking sensitivity during their interaction with virtual objects.

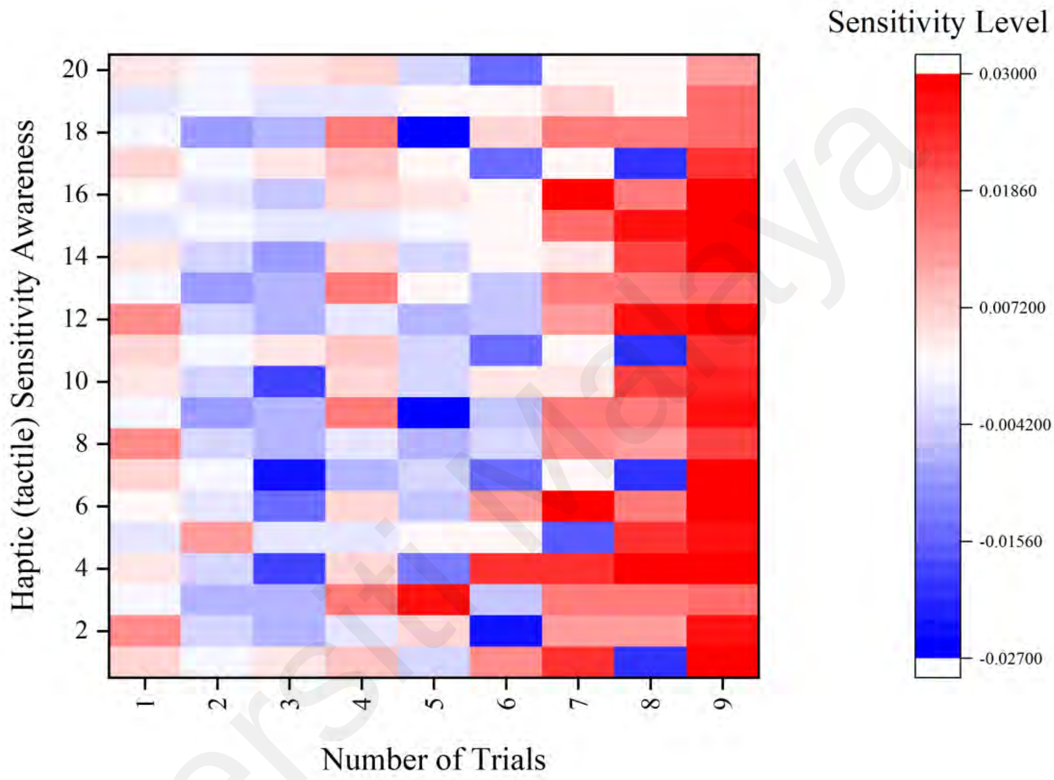


Figure 6.62: The overall haptic sensitivity awareness at frequency 200Hz for all the participants during the interaction with the haptic device

This study separated the captured accelerometer sensitivity data into individual reports in order to conduct a more in-depth investigation. Please refer to Figure 6.63, which depicts the overall findings of the accelerometer sensitivity testing for participant number three during the course of the session. It has been discovered that when the frequency is 130Hz, participants present with resonance frequency towards the accelerometer sensitivity. This demonstrates that there is a high level of touch sensitivity towards autistic people when they engage with virtual objects in a virtual environment.

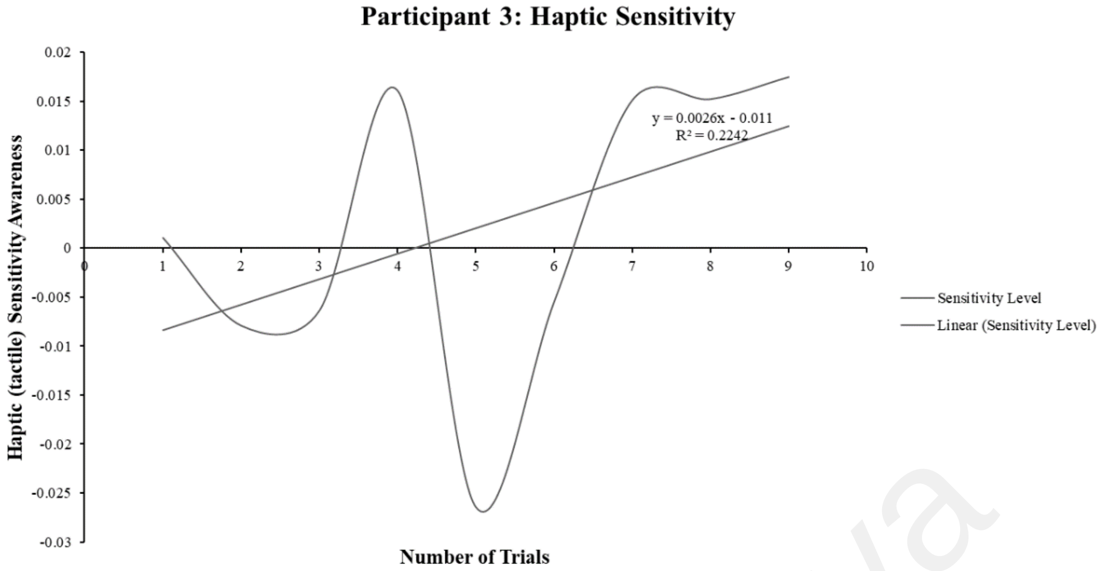


Figure 6.63: Accelerometer sensitivity (mv/g) at frequency 200Hz for participant number three during the interaction with the haptic device

Table 6.19: Touch sensory pattern scores for two different force directions in autistic people at vibration frequency 200Hz

Participants	*Top to Bottom Force Direction (Push to the floor)*			*Right to Left Force Direction (Push to the wall)*		
	Mv/g	*Mean*	*SD*	*Mv/g*	*Mean*	*SD*
1	0.0206	0.0023	0.0246	0.0198	0.0022	0.0246
2	0.0770	0.0086	0.0215	0.0762	0.0085	0.0215
3	0.0418	0.0046	0.0301	0.0410	0.0046	0.0301
4	0.0843	0.0094	0.0258	0.0835	0.0093	0.0258
5	0.0125	0.0014	0.0064	0.0116	0.0013	0.0064
6	0.0882	0.0098	0.0122	0.0874	0.0097	0.0122
7	0.0148	0.0016	0.0247	0.0140	0.0016	0.0247
8	0.0810	0.0090	0.0216	0.0802	0.0089	0.0216
9	0.0374	0.0042	0.0303	0.0366	0.0041	0.0303
10	0.0883	0.0098	0.0258	0.0875	0.0097	0.0258
11	0.0175	0.0019	0.0248	0.0165	0.0018	0.0248
12	0.0795	0.0088	0.0215	0.0785	0.0087	0.0215
13	0.0400	0.0044	0.0303	0.0390	0.0043	0.0303
14	0.0842	0.0094	0.0256	0.0831	0.0092	0.0256
15	0.0087	0.0010	0.0065	0.0077	0.0009	0.0065
16	0.0889	0.0099	0.0121	0.0879	0.0098	0.0121
17	0.0203	0.0023	0.0246	0.0193	0.0021	0.0246
18	0.0415	0.0046	0.0301	0.0405	0.0045	0.0301
19	0.0121	0.0013	0.0064	0.0111	0.0012	0.0064
20	0.0144	0.0016	0.0247	0.0134	0.0015	0.0247

As shown in Table 6.19, the results of this study revealed significant differences in haptic (touch) sensation between the two different force direction groups (Top to Bottom and Right to Left) during the interactions with the virtual environment via a haptic device. The individual standard deviation falls between 0.0 mV/g and 0.1 mV/g, which is within the acceptable range.

6.5.8 Discussion

Sensitivity Response: The objective of this study is to explore sensory processing (SP) in terms of tactile sensitivity among autistic people before and after experiencing haptic interfaces. The sensory profile questionnaire was completed by caregivers for children, compared to adults or adolescents, which gave the impact of the high or low level of tactile sensory detection. Based on the modified SSP2 and AASP questionnaire structures, the sensory quadrant scores were reported in four different factors as: low regression, sensation seeking, sensory sensitivity, and sensory avoidance for autistic people. In general, sensory profile studies show that SSP2 reported slightly higher sensitivities compared to AASP for adolescents or adults, and this may be due to the age factor, where children tend to become physically reactive, which can cause them to attempt to remove themselves from the environment (Puts et al., 2014). Meanwhile, for the comparison between the experimental group (with haptic device) and the comparison group (without haptic device) for the SSP2, the results show that autistic people in the comparison group had high levels of tactile sensory experience when compared to the experimental group who had experience with haptic interface in terms of low regression, sensory sensitivity, and sensory avoidance. The high levels of sensory may affect their learning ability, especially in terms of their spatial awareness, such as feeling and recognising the size and shape of objects (Zapata-Fonseca et al., 2018). Due to oversensitivity, they try to avoid engaging with communication devices (Tavassoli et al., 2014). This shows that an existing haptic interface can become a good sensory therapy to improve their ability to engage with their surroundings. Meanwhile, the AASP profile was reported to be slightly lower in adults or adolescents compared to children, which was likely due to age differences as well as other factors such as environment and tendency (Klintwall et al., 2011). There has been positive significant reported in adult or adolescent autistic people in the experimental group who had experience with haptic technology compared to the comparison group, especially in terms of sensation seeking. As a grown adult or adolescent, they are able to sense their touch in a healthier way compared to children, but there is a possibility that they were not well mastered when it came to organising the sense in terms of feeling during the interaction with an object, and this has been proven from the result of the comparison group (Zapata-Fonseca et al., 2018). However, after being exposed to haptic technology, they progressively learn to organise the senses within their understanding and are able to show good improvement by focusing on touch sensations. This is proven by the quadrant scores for all the factors, especially sensation seeking, which show more than 20% differences. As a result, the ability to organise sensations via haptic feedback (vibration) by a child or adult allows them to control their interaction and response, and as an outcome, they will probably be more engaged with their surroundings, whether in a virtual or real environment.

Touch Sensory Pattern: As presented in the result of the experiment, autistic people were able to receive ordinary touch sensory sensitivity. Mostly, autistic people have different levels of touch sensory sensitivity information, either oversensitive or undersensitive, and the response and expression of their sensitivity awareness will be different (Crane et al., 2009). This can be supported based on the results of participants at the beginning of four testing sessions, where almost all of the participants reported being undersensitive to touch sensory information when they were seeking sensory experience by looking for virtual objects to touch and feel (refer to Figure 6.62). Similar to being oversensitive to touch sensory information, where the participants 2 and 4 faced oversensitivity at the second testing session, this was due to the fact that these autistic people try to avoid touch sensory experiences in virtual environments. Meanwhile, different force directions methods have different levels of seeking touch sensory information by autistic people during interaction with virtual objects via haptic devices. This finding can be supported based on the results from the two different force directions (pushing the virtual ball to the floor and to the wall). The detection of accelerometer sensitivity among autistic people during the pushing of the virtual ball towards the floor task shows slightly higher sensitivity compared to pushing the virtual ball towards the wall task for most of the autistic people participants (refer to Table 6.59), and this might be due to seeking different directions of the virtual object's position and momentum when the time handling with wearable haptic device.

Furthermore, there are studies (Corbett et al., 2016; Green & Ben-Sasson, 2010) that report that there is a possibility where these experimental evaluation results can be impacted due to being overly anxious or stressed during the interaction with a virtual object in a virtual environment via a haptic device. From the outcome of both experimental studies, it can be concluded that the interaction with haptic devices in a virtual environment enables the creation of positive touch sensory therapy among autistic people.

6.6 Experimental Evaluation of the Real-Time Haptic Rendering Interaction in Virtual Environment among Autistic people

The objective of this experimental evaluation is to examine real-time haptic rendering interaction performance in autistic people. The interaction between the autistic user and the virtual environment, achieved through the use of a haptic device, has a direct impact on the effectiveness of the performance. This investigation was carried out on the basis of the following measures: navigation and object selection, selection and manipulation of objects, and detection of stiffness at three separate stages of the investigation process.

6.6.1 Methods

To evaluate the effectiveness of vibrotactile haptic device interaction with a HBVE, three types of cognitive testbeds were implemented, and these testbeds were implemented based on the taxonomy of haptic interaction (refer to Figure 6.64) and the spatial visualisation ability aspects. In Figure 6.65, it shows the three types of spatial cognition testbeds in a virtual environment for spatial visualisation and rotation learning. The reasons for selecting these testbeds, as well as their significance, will be discussed in greater detail in following Section 6.6.2.

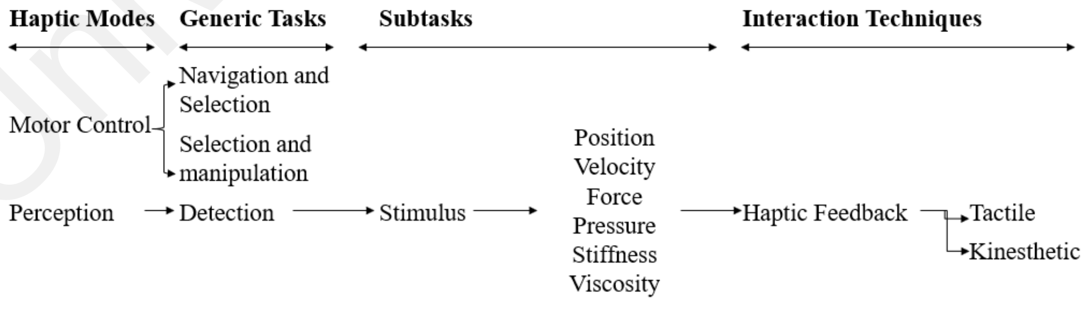


Figure 6.64: The taxonomy of haptic interaction for autistic people

Haptic Interaction	Spatial Cognitive Testbeds	Environment
Navigation and Object selection	Corsi block-tapping	
Selection and Manipulation	Hole-peg	
Detection of Stiffness	Object force pushing interaction	

Figure 6.65: The types of spatial cognition testbeds

6.6.2 The Significant of Spatial Cognition Testbeds

The following testbeds are utilised on a regular basis for the purpose of researching the efficacy of haptic-based interaction (Amon et al., 2018; De Boeck et al., 2005). In addition, one of the factors that should be considered when choosing which kinds of testbeds to use is the individual's spatial awareness. Therefore, the objective of this section is to show how important it is to choose the following testbeds in order to find out how well haptic rendering interaction helps autistic people learn spatial relationships.

(1) Corsi block-tapping: It is essential to explore autistic people's visuospatial short-term and working memories (De Boeck et al., 2005; Steinicke et al., 2006). This means that this task helps to understand autistic people's ability to tell where the specified objects are located in a virtual environment and how far the objects are from the participant and from each other by using their short-term and working memory to recall the objects' attributes and position in the environment.

(2) Hole-peg: This is significant because it helps improve understanding of the various shapes and sizes, and it also gives autistic people the ability to mentally manipulate three-dimensional objects by using their imaginations in innovative ways (De Boeck

et al., 2005; Klintwall et al., 2011). Additionally, the purpose of this task is to test autistic people's ability to mentally rotate objects in their surroundings and to determine whether or not they can keep their orientation and attributes consistent throughout the transition of spatial knowledge.

(3) Object force pushing interaction: A force can be thought of as a push or pull that applies to an object as an outcome of that object's interactions with its surroundings, particularly in a real-world environment (De Boeck et al., 2005; Dennerlein & Yang, 2001; Pérusseau-Lambert, 2016). It's possible that the demands imposed on autistic people's movements (push or pull) and the complexity of their surroundings contribute to their impaired spatial learning. Therefore, conducting research on the haptic interface representation within the virtual environment for autistic people is extremely important. Also, this output will be beneficial for autistic people to apply in real-world environments when interacting with any objects.

6.6.3 Apparatus

In this experiment, the MYO Armband was used as a haptic wearable device to simulate haptic interactions (see Figure 6.50) and the MYO Diagnostics application was used to understand autistic people performance (MATLAB). Furthermore, to display the virtual environment, it used a standard Windows-based LCD screen computer with Intel’s Core(TM) i5-3570 CPU @3.40GHz.

6.6.4 Participants

Pondoku centre and Fitrah Academy served as the source for the recruitment of twenty autistic people to take part in the study. After completing the Autism Diagnostic Interview-Revised (ADI-R) (Rutter et al., 2003), all twenty participants: four females and sixteen males confirmed their autism spectrum disorder diagnosis. All participants were computer savvy, but none had used haptic devices. The study participants ranged in age from 9 to 27, with a mean of 17.05 years and a standard deviation of 5.949 years.

6.6.5 External Aspects

According to (Carvalheiro et al., 2016; Chertoff et al., 2010; Pfeuffer et al., 2019), there is a need for consideration of other external aspects that could influence the performance of a haptic interaction technique in a virtual environment. Therefore, these aspects will be taken into account implicitly in the evaluation of the spatial cognition testbed, so that there will be a reduction in the difference in the evaluation. These external aspects have been divided into four categories based on their features: task feature, environment feature, user feature, and system feature.

6.6.5.1 Task Features

Although there are various techniques that can satisfy most of the haptic interaction tasks, sometimes there are also some techniques that cannot meet each other, and this can be determined through the following task features: the space between the user and the object, object accuracy prerequisite, and complexity of task or cognitive load.

6.6.5.2 Environmental Features

User performance may differ or be affected if the surrounding environment differs for the same task, and this will likely impact or influence the results. The recognised features have been stated as: size of the virtual environment; number of objects; shape of objects; size of objects; type of tasks; and perceptibility of the environment.

6.6.5.3 User Features

Sometimes the person itself becomes the main reason for handling the haptic interaction techniques. For example, the external-arm technique is less effective if the user's arms are shorter. In addition, the inability factor (especially the other aspects of the condition for autistic people) for a user to move spontaneously in a virtual environment may also affect user performance, such as: age and gender of the user; spatial learning and cognitive mapping ability; experience with virtual environments; user experience with technical; and type or level of symptoms for autistic people, such as: a learning disability, social communication, restricted range of behaviors, sensory difficulties, difficulties in understanding the perspective of objects and others, and decrement of operational tasks such as planning and prevention.

6.6.5.4 System Features

As a final aspect, the use of software and hardware in the implementation and validation of virtual environment systems may also affect the performance of users. These are classified as: the use of haptic rendering techniques; implementation of shadows; representation of a virtual body; implementation of collision detection; realism of physical models such as gravity; type of display; system frame rate; and latency of the system.

6.6.6 Procedure

All participants took part in each specified spatial cognition task (refer to sections 6.6.1) and were observed separately. The experiments were conducted based on the following steps:

(1) Participants were asked to become familiar with both virtual control devices (physical visual control: keyboard and mouse; haptic virtual control: MYO Armband haptic interface) based on the testing condition, as well as the virtual environment concepts and features.

(2) Before the actual practice and testing began, the participants were asked to become familiar with the anonymous set of three different virtual environments (scenes) (refer to Figure 6.65) and their virtual control interfaces.

(3) The spatial visualization and rotation tasks were assigned to the participants in accordance with the activities that they were required to complete.

During this experiment, there are four stages: (1) exploration with HBVE stage; (2) baseline stage; (3) intervention stage; and (4) maintenance stages. Each participant was given a maximum of five minutes to complete each task. As underlined previously in the experimental steps (1 and 2), for the exploration with the HBVE stage, each of the autistic people participants provided knowledge about the virtual environment and features involved, and also introduced the haptic interface (MYO Armband) features (apart from keyboard and mouse as physical control) and the way to control and manipulate in HBVE. Apart from that, they were required to explore the three different sets of virtual environments (refer to Figure 6.65) to become familiar with objects and tasks. After exploring and familiarising themselves with the virtual environment and virtual control, the rest of the experimental stages were conducted based on the three spatial visualisation and rotation tasks. During the baseline stage, the participants were asked to perform the three spatial cognition testbeds. Participants were required to retest with the same tasks during the intervention stage in order to record and observe the effectiveness of their performance. Finally, at the maintenance stage, with the same environment and tasks, the autistic people participants were tested again to determine their ability to maintain their knowledge of spatial knowledge and cognitive skills in visualisation and rotation aspects.

6.6.7 Data Measurement and Analysis

The growing number of virtual object interaction techniques has naturally raised the question of how to evaluate their performance. In order to evaluate the performance, a few measurements have been carried out, and this is explained in more detail in the following sub-sections.

6.6.7.1 Navigation and object selection

The Corsi block-tapping task is a spatial ability test and was chosen for the navigation and selection testbed. Through this test, the user will be able to touch and select the target objects, and during the process, it able to measure the movement time between tapping the target objects. Therefore, the Shannon formulation of the *Fitts' law* (6.5) will be used to amplify the movement time (*MT*):

$$MT = a + blog_2\left(\frac{D}{W}\right) + 1 \qquad (6.5)$$

Based on the formula, a and b are represented as dependable variables which are driven by the testing through curve fits, while *D* focuses on the distance of movement, and *W* determines the width of the target. The logarithm $blog_2\left(\frac{D}{W} + 1\right)$ is known as index difficulty (*ID*), and the unit of information is in bits. However, the index of performance (*IP*) will examine the performance level in bits per second, and this can be identified in the formula (6.5) as the reciprocal of *b*. The constants *a* (intercept) and *b* (slope) are constants that can be influenced by the haptic device as input in the virtual environment. Apart from this, the success of this task will be measured based on the number of objects identified and the distance travelled.

6.6.7.2 Selection and manipulation of object

In the context of the spatial visualization ability, the hole-peg test was chosen to study the selection and manipulation task, which will involve precision and accuracy in handling this task. This testbed is tested according to these two criteria, where a user must recognise object attributes such as shape and size of the object from a group of objects by comparing them with target area attributes and then select the recognised object (peg) and place it on the target area (hole). Furthermore, this component will be assessed based on the following perceptual factors in order to measure and understand the autistic user perception of both physical and haptic virtual control during virtual object manipulation:

Table 6.20: The list of perceptual factors items

Perceptual factors	**Item**
Real-time	Interaction with a physical or haptic interface in the virtual environment provides real-time feedback.
Comfort	Interaction with a physical or haptic interface in the virtual environment is comfortable.
Realistic Rendering Object	Interaction with a physical or haptic interface in the virtual environment is present with realistically rendered objects.

6.6.7.3 Detection of Stiffness

The stiffness of a virtual object is an important measure to consider when evaluating the tactile contact between an autistic user and the virtual object. It is possible to define stiffness as the responsive deformation of a virtual object's surface in response to the application of a force. Furthermore, the changes that occurred in muscle activity as a result of the engagement with virtual objects have an impact on stiffness detection. The stiffness (k) of a virtual object is measured based on the magnitude of a force (F) value divided by the deformation (δ) of the virtual object, as shown (6.6) *Hooke's law*:

$$k = \frac{F}{\delta} \tag{6.6}$$

Therefore, the stiffness of the virtual object will be assessed based on the force applied during the *object force pushing interaction task* to determine the stiffness of the virtual object's contacting surface. The changes in the length of deformation are caused by the autistic user's force applied during the interaction task.

6.6.8 Results

The following section presents the performance of each testbed in three different stages as baseline, intervention, and maintenance to evaluate the effectiveness of real-time haptic rendering interaction in autistic people.

6.6.8.1 Baseline

Navigation and object selection: For navigation and object selection, the t-Test was used to validate the interaction between haptic virtual control (object touching) and physical virtual control (pointing) with the direction of autistic people participants in the virtual environment. The results are interpreted based on the curve of *Fitt's law,* which measures the time taken to move from one position to another targeted position. The comparison results between haptic physical control and virtual control show a significant effect (*t=0.6776*), whereby using haptic physical control (*t = 2.7647*), the navigation of autistic people participants was faster than that of autistic people participants who used virtual control (*t = 3.2942*) (refer to Table 6.21). The total time required to navigate from the initial location to another targeted location using haptic physical control is very short, indicating that the haptic device's real-time interaction improves and is effective to some extent.

Table 6.21: The overall baseline performance of autistic people in terms of navigation and object selection

Objective measures	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects identified	0.320443	0.044042	0.368305	0.048991	.002
Distance Travelled	45195.73	7108.39	37756.16	9807.79	.009
Movement Time (MT)	3:24:10	1:27:49	2:16:46	1:11:26	.008

Selection and manipulation of object: Based on the baseline, the results for the selection and manipulation of virtual objects show a significant result (*t =-6.278*). The task was tested with two different types of selection techniques and object indication methods: haptic virtual control (object touching) and physical virtual control (pointing). The object touching (means 0:26 seconds) method shows significantly higher than the pointing (means 0.45 seconds) method ($t = 12.419$). The pointing method is based on two-dimensional (2D) operation with a virtual hand compared to object touching, which uses haptics with a virtual hand to place the object in the targeted area (hole). Meanwhile, Table 6.22 shows the effect of size, shape, and position accuracy compared to different sets of virtual communication devices to complete. There is a significant effect that can be seen for both the object touching and pointing methods for both the levels of position accuracy (longitude: $t = 10.809$, latitude: $t = -7.509$) (refer to Figure 6.66 and 6.67) and the time taken to complete the particular task. However, compared to the pointing method, the object touching method shows that the time taken to complete the task and rotate decreased slightly with the different sizes and shapes of virtual objects. In addition, the different sizes and shapes of objects also show significant effects for both object touching and pointing methods (small size: $t = -2.142$, medium size: $t = -4.180$, large size: $t = -4.656$). The time taken to select the small-sized object via the object pointing method takes more time when compared to the object touching method. Aside from that, the time taken to manipulate the object by either the participants over a short or long distance, or by the size of the objects, shows that the time spent by the participants is nearly equivalent for both the object touching and pointing methods, as shown in Table 6.22. Furthermore, based on the participants' perception in terms of haptic rendering interaction in haptic virtual control and compared to physical virtual control, most of the participants reported high significance in terms of real-time interaction ($t = -10.258$), comfort ($t = -8.718$), and realistic rendering of virtual objects ($t = -13.077$) (refer to Table 6.23).

Table 6.22: The overall baseline performance in terms of navigation and manipulation

Objective measures	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects selected	0.479630	0.500048	0.650000	0.477412	.001
Size and Shape:					
Small Sphere	0.466667	0.503098	0.516667	0.503939	-
Medium Sphere	0.533333	0.503098	0.766667	0.426522	-
Large Sphere	0.716667	0.454420	0.800000	0.403376	-
Small Cube	0.366667	0.485961	0.416667	0.497167	-
Medium Cube	0.550000	0.501692	0.683333	0.469102	-
Large Cube	0.666667	0.475383	0.883333	0.323732	-
Small Pyramid	0.183333	0.390205	0.383333	0.490301	-
Medium Pyramid	0.250000	0.436667	0.533333	0.503098	-
Large Pyramid	0.583333	0.497167	0.866667	0.342803	-
Overall time taken to complete	0:00:45	0:00:35	0:00:26	0:00:13	.001
Time taken to rotate	0:00:21	0:00:19	0:00:13	0:00:06	.001
Position Accuracy (Actual Longitude)	-0.002145	0.000028	-0.002145	0.000028	-
Position Accuracy (Actual Latitude)	1.323855	0.000726	1.323855	0.000726	-
Position Accuracy (Longitude)	-0.000844	0.001109	-0.001535	0.001320	.001
Position Accuracy (Latitude)	0.743361	0.658044	0.980493	0.580606	.001

Table 6.23: The overall participant perception in terms of haptic rendering interaction (Baseline)

Perceptual Factors	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Real-time	1.20	.410	2.40	.503	.001
Comfort	1.15	.366	2.35	.489	.001
Realistic Rendering Object	1.75	.444	2.95	.510	.001

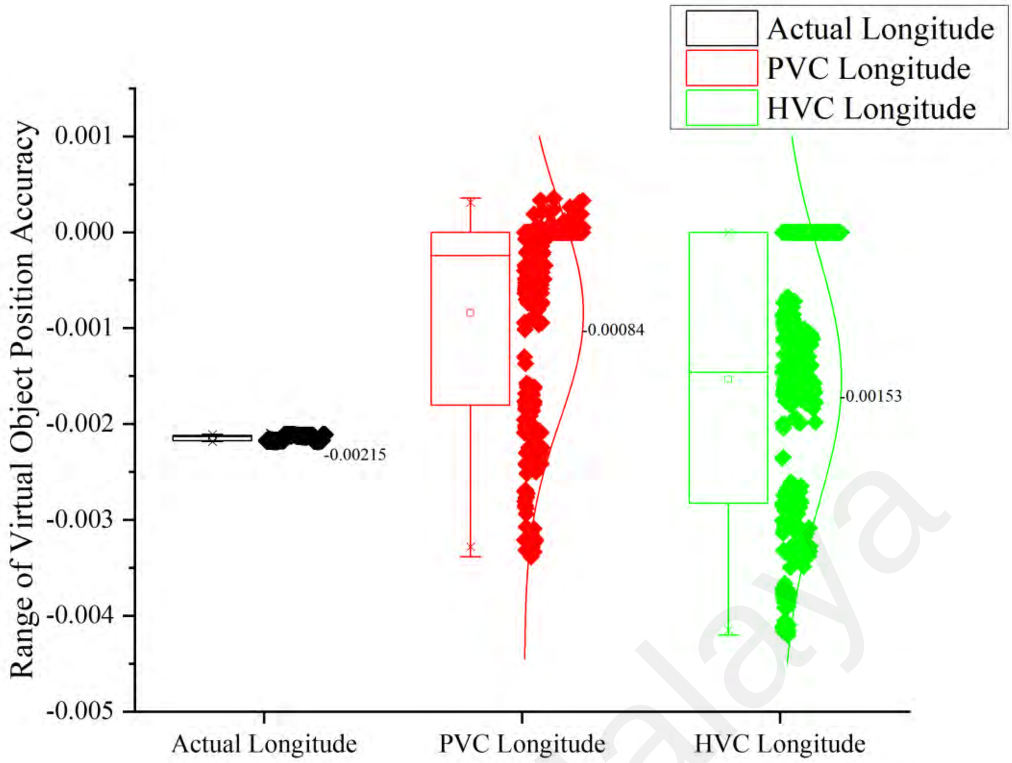


Figure 6.66: Comparison of virtual object position accuracy estimation via longitude in the baseline

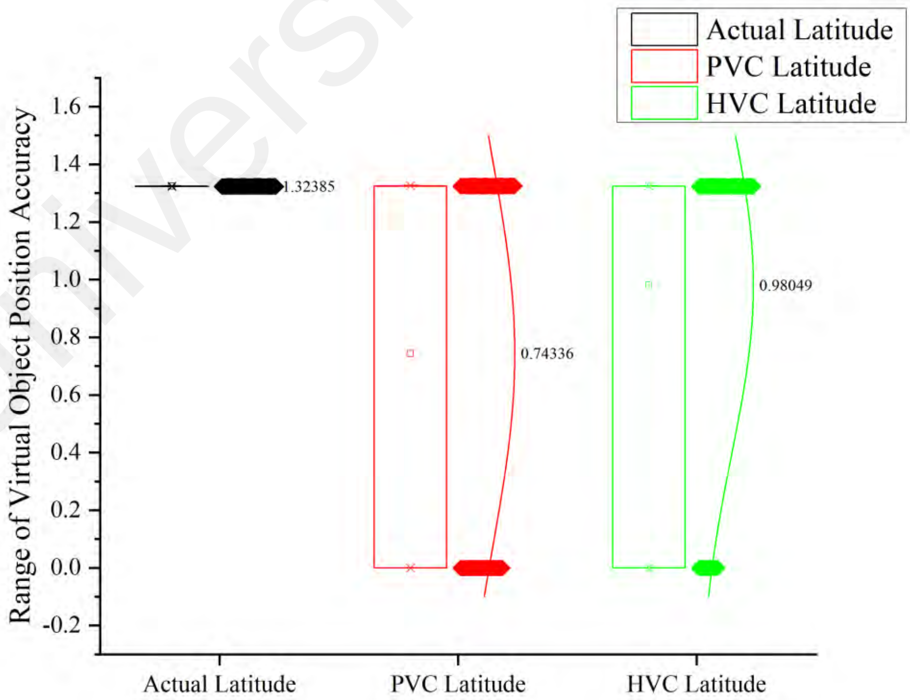


Figure 6.67: Comparison of virtual object position accuracy estimation via latitude in the baseline

Detection of Stiffness: This result is based on stiffness detection, which measures the force applied by participants to manipulate the virtual object (refer to Table 6.24). Therefore, to detect stiffness, the force coefficients from the IMU and EMG signals, which are generated from the participants' muscle activities and muscle tension during the interaction with virtual objects, are used. In addition, because stiffness variation coefficients are absolute values of force coefficients, the force coefficients for each participant's muscle action were estimated using stiffness variation coefficients. The stiffness levels of the participants were measured using the t-Test. The experiment demonstrates a significant effect for both conditions: pushing the ball to the floor (t = *70.890*) and pushing the ball to the wall (*-2.622*). Figure 6.68 shows the result of individual participants' stiffness coefficient estimation based on IMU and EMG signals from the MYO Armband haptic device during interaction with a virtual object. The results indicate that there is strong stiffness in the first 0.6 and 1.6 seconds when the participant increases muscle force to push the ball into the collision detection floor. Meanwhile, the same Figure 6.66 shows a weak stiffness when the participant releases the virtual ball from his/her grasp after 2.5 to 3.1 seconds, indicating less muscle activity or muscle tension.

Table 6.24: The overall participant stiffness detection (Baseline)

Objective Measures	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Top to Bottom Force Direction	-.0096	.00022	-.0180	.00093	.001
Right to Left Force Direction	5.8181	3.768	14.3873	25.149	.011

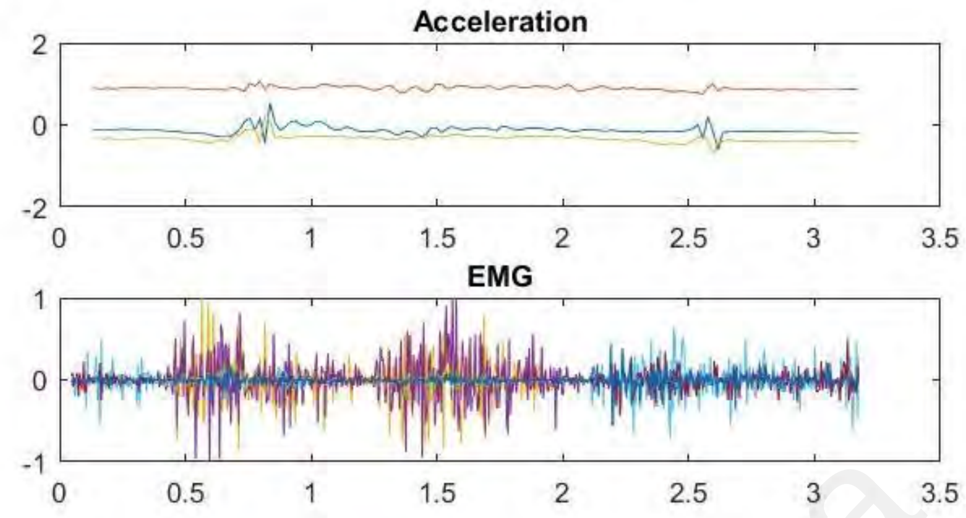


Figure 6.68: The detection of force in the baseline via a haptic device

6.6.8.2 Intervention

Navigation and object selection: The results improved significantly during the intervention stage when compared to the baseline stage (*t=0.7295*). To validate the interaction, both haptic virtual control (object touching) and physical virtual control (pointing) are used, as in the baseline stage. Table 6.25 shows that haptic visual control is more significant than virtual control during navigation in virtual environment. Aside from that, the movement time taken to reach the destination by using haptic virtual control is less than that of physical virtual control, indicating that it is more effective and improved over the baseline stage.

Table 6.25: The overall intervention performance of autistic people in terms of navigation and object selection

Objective measures	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects identified	0.524309	0.068648	0.605383	0.091597	.003
Distance Travelled	31146.29	4193.03	15666.35	7894.62	.001
Movement Time (MT)	2:32:38	0:32:43	1:36:15	0:24:36	.001

Selection and manipulation of object: In comparison to the baseline stage, the overall results at this stage show more improvement with significant effects (*t =-8.579*), as well as slightly higher improvement for both pointing and object touching methods, but the pointing method (means 0.37 seconds) shows less significant improvement than the object touching method (means 0.18 seconds) (*t =14.818*), (refer to Table 6.26). Furthermore, the results show a highly significant effect in terms of time taken to complete the task for different levels of distance for both the object touching and pointing methods compared to the baseline stage (short distance: $p < 0.001$, middle distance: $p < 0.001$, long distance: $p < 0.001$). Despite the fact that the previous pre-learning stage indicated that the time taken to complete the task increased for objects touched at different levels of distance, the time taken to complete the tasks for each level of distance decreased during this intervention stage. This significant effect also holds true for the different sizes of objects and the time taken to complete the tasks (small size: *t =-5.553*, medium size: *t =-4.008*, large size: *t =-5.476*). Furthermore, both object touching and pointing methods have a significant effect on position accuracy (longitude: *t =13.030,* latitude: *t = -7.148*) (refer to Figure 6.69 and 6.70). For selecting small sizes of objects, the object touching method took less time than the pointing method after many attempts and multiple training sessions. Meanwhile, as shown in Table 2.26, participants spend less time manipulating the selected object when using the object touching method rather than the pointing method. The majority of participants reported a high significance in real-time interaction ($t = -9.488$), comfort ($t = -5.784$), and realistic rendering of virtual objects ($t = -7.429$) in haptic virtual control compared to physical virtual control (Table 6.27). In addition, these participants also show slight high significance compared to baseline (real-time interaction: $p < 0.001$, comfort: $p < 0.001$, realistic rendering: $p < 0.001$) (refer to Figure 6.75).

Table 6.26: The overall intervention performance in terms of navigation and manipulation

Objective measures	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects selected	0.579630	0.494076	0.796296	0.403125	.001
Size and Shape:					
Small Sphere	0.566667	0.499717	0.716667	0.454420	-
Medium Sphere	0.683333	0.469102	0.883333	0.323732	-
Large Sphere	0.833333	0.375823	0.916667	0.278718	-
Small Cube	0.416667	0.497167	0.733333	0.445948	-
Medium Cube	0.633333	0.485961	0.833333	0.375823	-
Large Cube	0.733333	0.445948	0.966667	0.181020	-
Small Pyramid	0.250000	0.436667	0.550000	0.501692	-
Medium Pyramid	0.450000	0.501692	0.616667	0.490301	-
Large Pyramid	0.650000	0.480995	0.950000	0.219784	-
Overall time taken to complete	0:00:37	0:00:30	0:00:18	0:00:06	.001
Time taken to rotate	0:00:14	0:00:13	0:00:08	0:00:03	.001
Position Accuracy (Actual Longitude)	-0.002138	0.000026	-0.002138	0.000026	-
Position Accuracy (Actual Latitude)	1.323848	0.000725	1.323848	0.000725	-
Position Accuracy (Longitude)	-0.001033	0.001163	-0.001776	0.001176	.001
Position Accuracy (Latitude)	0.917414	0.611767	1.137220	0.460676	.001

Table 6.27: The overall participant perception in terms of haptic rendering interaction (Intervention)

Perceptual Factors	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Real-time	1.65	.489	3.35	.671	.001
Comfort	1.95	.605	3.20	.616	.001
Realistic Rendering Object	2.25	.639	3.60	.503	.001

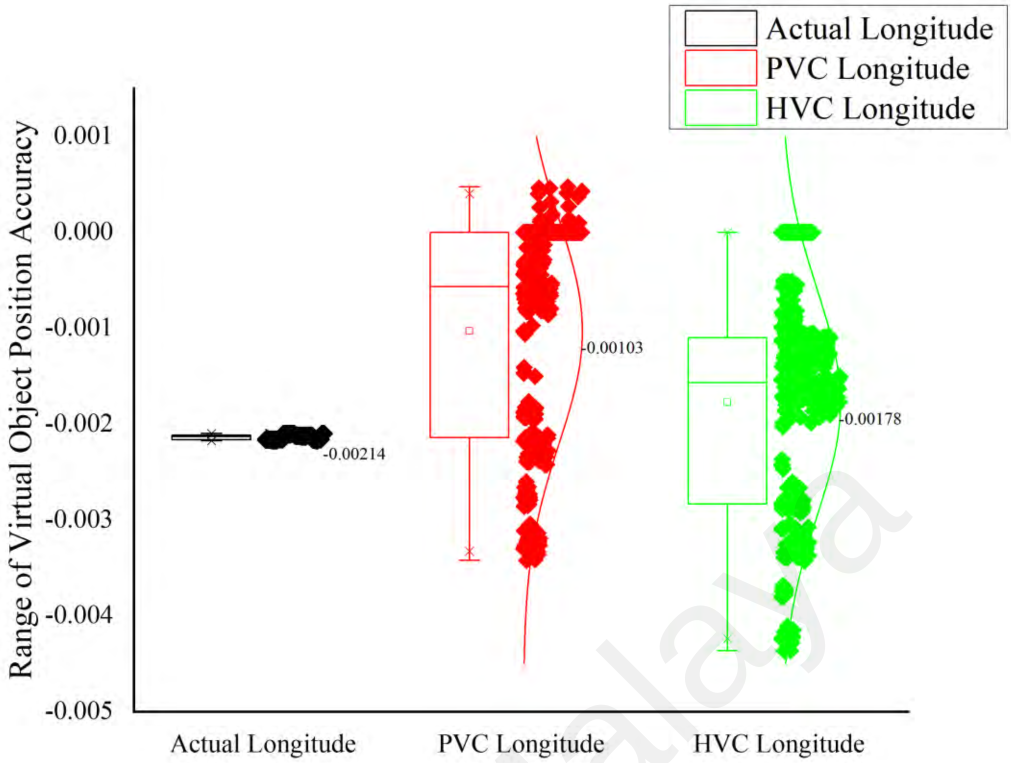


Figure 6.69: Comparison of virtual object position accuracy estimation via longitude in intervention

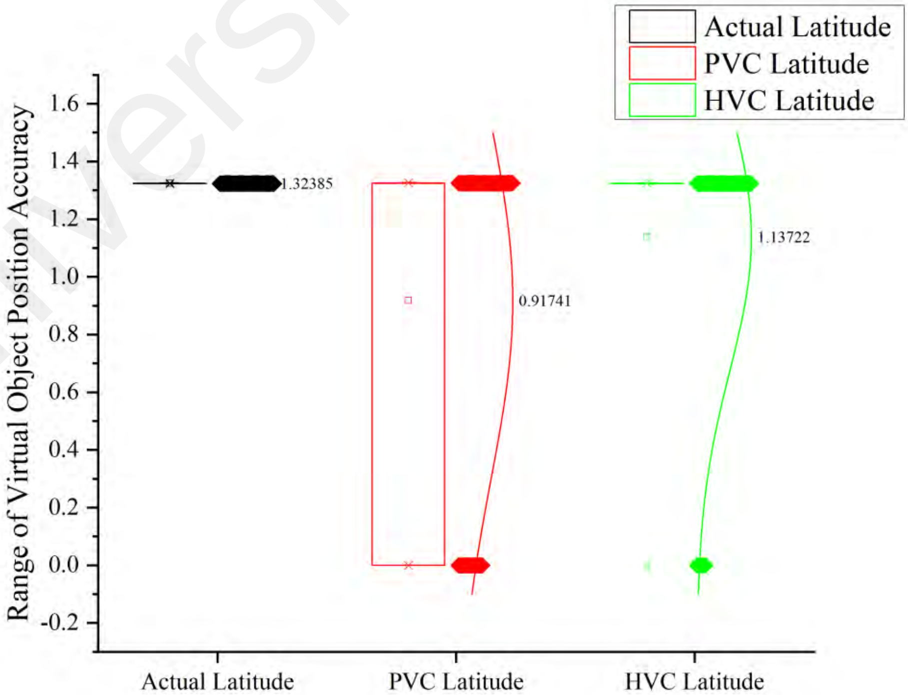


Figure 6.70: Comparison of virtual object position accuracy estimation via latitude in intervention

Detection of Stiffness: After the initial experience and familiarity from the pre-learning stage, the participants show a more significant effect for both conditions: pushing the ball to the floor (*t = 5.063*) and pushing the ball to the wall (*t = -2.841*), and this effectiveness can be seen as force coefficient values from EMG signals in Figure 6.71. The same figure show that there is continuous strong stiffness from 0.2 seconds onwards, especially at 1.0 and 1.7 seconds. The participant stiffness coefficient estimation results reached 74% when the muscle force to push the ball into the collision detection floor is applied, and this becomes a week stiffness from 2.4 seconds onwards. In addition, when the muscle force to push the ball to the wall is applied, the participant stiffness coefficients estimation results show up to 60% (refer to Table 6.28).

Table 6.28: The overall participant stiffness detection (Intervention)

Objective Measures	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Top to Bottom Force Direction	-.0132	.00989	-.1085	.15276	.001
Right to Left Force Direction	8.2840	5.033	23.2890	40.043	.006

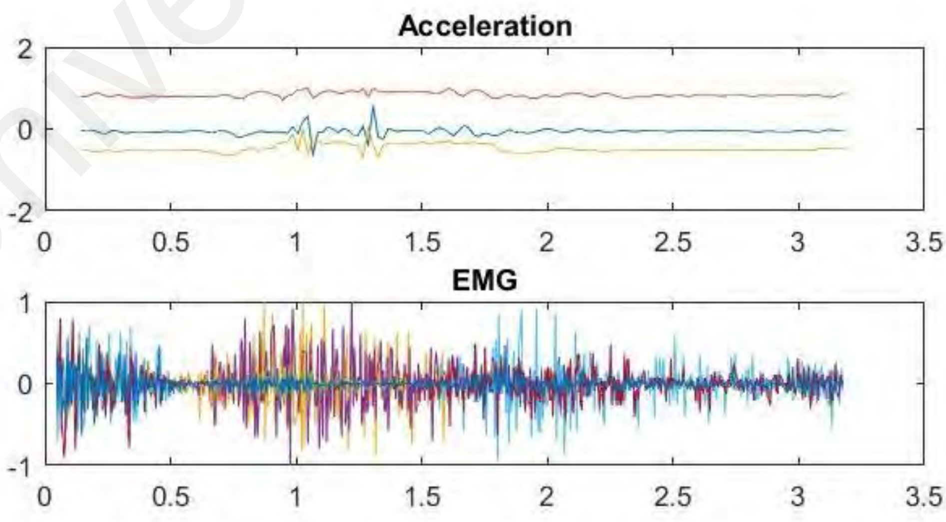


Figure 6.71: The detection of force in intervention via a haptic device

6.6.8.3 Maintenance

Navigation and object selection: In the maintenance stage, the participants were able to maintain the results with an increased significant value from the previous stage for both physical control and virtual control (*t=2.0843*). Nevertheless, physical control still shows more significant results compared to virtual control, and this can be seen in Table 6.28. Also, the time taken to reach the desired location by using physical control is less than using virtual control, and during this stage, the participants were also able to maintain the results well compared to the intervention stage.

Table 6.29: The overall maintenance performance of autistic people in terms of navigation and object selection

Objective measures	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects identified	0.769308	0.071012	1.031025	0.105254	.001
Distance Travelled	19352.22	2235.17	11107.33	1949.29	.001
Movement Time (MT)	1:32:14	0:27:12	1:00:42	0:15:42	.001

Selection and manipulation of object: During the maintenance stage, overall, the participants show increased significant results as compared to the intervention stage (*t=-8.606*) for both the object touching and pointing methods, but the pointing method (mean 0.21 seconds) still maintains the more significant results when compared to object touching (mean 0.05 seconds) (*t=14.111*). As maintenance stage, this stage also shows highly significant results for both object touching and pointing methods in terms of the time taken to complete the task for different levels of distance (short distance: $p < 0.001$, middle distance: $p < 0.001$, long distance: $p < 0.001$), and especially for the object touching method, which shows a decrease in terms of time taken to complete the task for the selection of objects at different levels of distance (refer to Table 6.30). Meanwhile, for the different sizes of objects with the time taken to complete the tasks, this stage still maintains and improves the previous stage range results as (small size: (*t=-4.596*), medium size: (*t=-4.850*), large size: (*t=-6.103*)). In addition, in terms of manipulation of the selected object, the autistic people participants used less time by using object touching compared to the pointing method due to familiarisation and experience from the intervention stage. Moreover, object touching and pointing methods have a higher significant effect on position accuracy (longitude: *t =14.874,* latitude: *t = -7.646*)) (refer to Figures 6.72 and 6.73), and this effect is also significantly higher when compared to earlier stages. In this stage of the experiment, the participants reported a high significance in real-time interaction (*t = -15.387*), comfort (*t = -8.794*), and realistic rendering of virtual objects (*t = -8.107*) in haptic virtual control in comparison to physical virtual control (Table 6.31). In addition, this participant group demonstrates a very high level of significance in comparison to the intervention stage (real-time interaction: p < 0.001, comfort: p < 0.001, realistic rendering: p < 0.001) (refer to Figure 6.75).

Table 6.30: The overall maintenance performance in terms of navigation and manipulation

Objective measures	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Number of objects selected	0.707407	0.455375	0.901852	0.297791	.001
Size and Shape:					
Small Sphere	0.650000	0.480995	0.850000	0.360085	-
Medium Sphere	0.750000	0.436667	0.950000	0.219784	-
Large Sphere	0.916667	0.278718	1.000000	0.000001	-
Small Cube	0.600000	0.494032	0.848000	0.360092	-
Medium Cube	0.733333	0.445948	0.933333	0.251549	-
Large Cube	0.816667	0.390205	1.000000	0.000001	-
Small Pyramid	0.533333	0.503098	0.716667	0.454420	-
Medium Pyramid	0.616667	0.490301	0.816667	0.390205	-
Large Pyramid	0.750000	0.436667	1.000000	0.000001	-
Overall time taken to complete	0:00:21	0:00:25	0:00:05	0:00:04	.001
Time taken to rotate	0:00:06	0:00:09	0:00:02	0:00:02	.001
Position Accuracy (Actual Longitude)	-0.002131	0.000025	-0.002131	0.000025	-
Position Accuracy (Actual Latitude)	1.323841	0.000725	1.323841	0.000725	-
Position Accuracy (Longitude)	-0.001271	0.001217	-0.002035	0.001100	.001
Position Accuracy (Latitude)	1.059654	0.530319	1.252376	0.298626	.001

Table 6.31: The overall participant perception in terms of haptic rendering interaction (Maintenance)

Perceptual Factors	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Real-time	2.30	.470	4.10	.718	.001
Comfort	2.55	.686	4.25	.444	.001
Realistic Rendering Object	2.75	.550	4.35	.587	.001

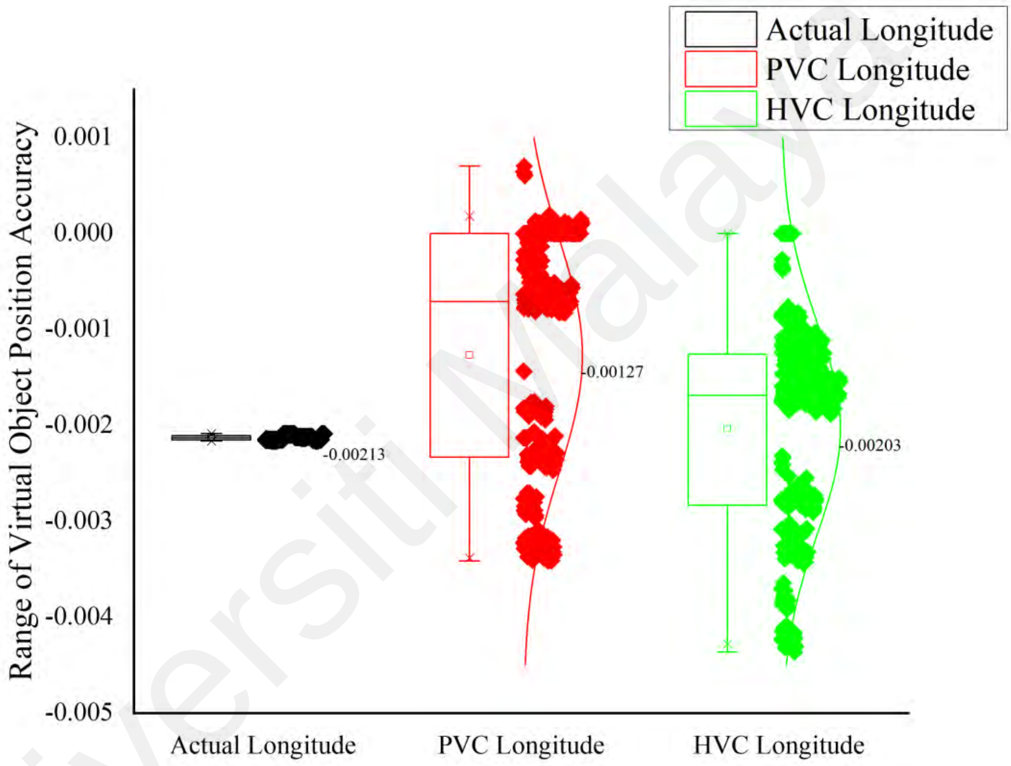


Figure 6.72: Comparison of virtual object position accuracy estimation via longitude in maintenance

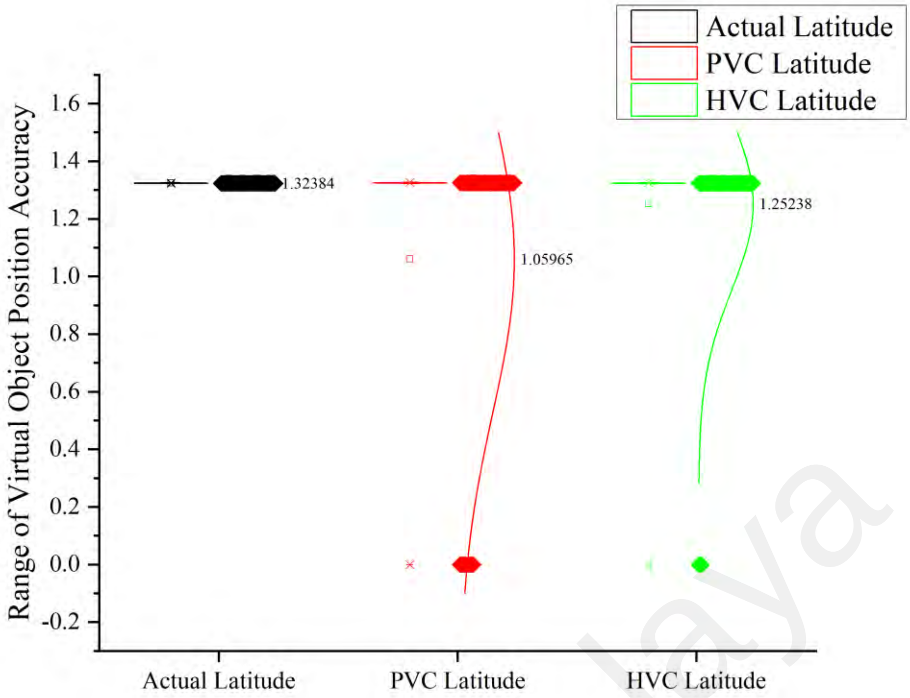


Figure 6.73: Comparison of virtual object position accuracy estimation via latitude in maintenance

Detection of Stiffness: During this maintenance stage, the autistic people participants were still able to show higher significant effects for both conditions: pushing the ball to the floor ($t = 6.006$) and pushing the ball to the wall ($t = -3.234$), and this is shown in Table 6.32. The detection of stiffness among autistic people participants still maintains the result at 89% and above when they push the ball to the wall and 67% and above when they push the ball to the floor (refer to Figure 6.74).

Table 6.32: The overall participant stiffness was detected (Maintenance)

Objective Measures	*Physical Virtual Control (PVC)*		*Haptic Virtual Control (HVC)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Top to Bottom Force Direction	-.0188	.03522	-.1415	.15467	.001
Right to Left Force Direction	11.0148	16.021	34.2272	53.526	.002

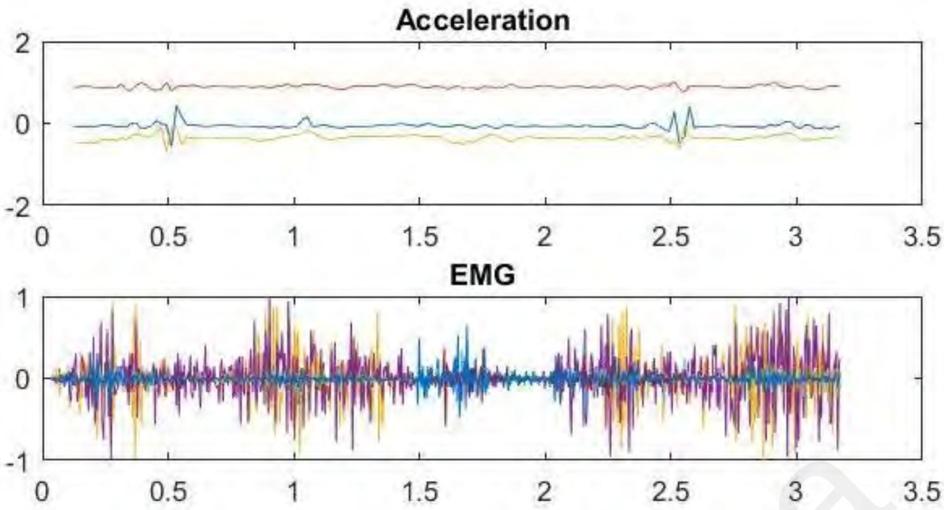


Figure 6.74: The detection of force in maintenance via a haptic device

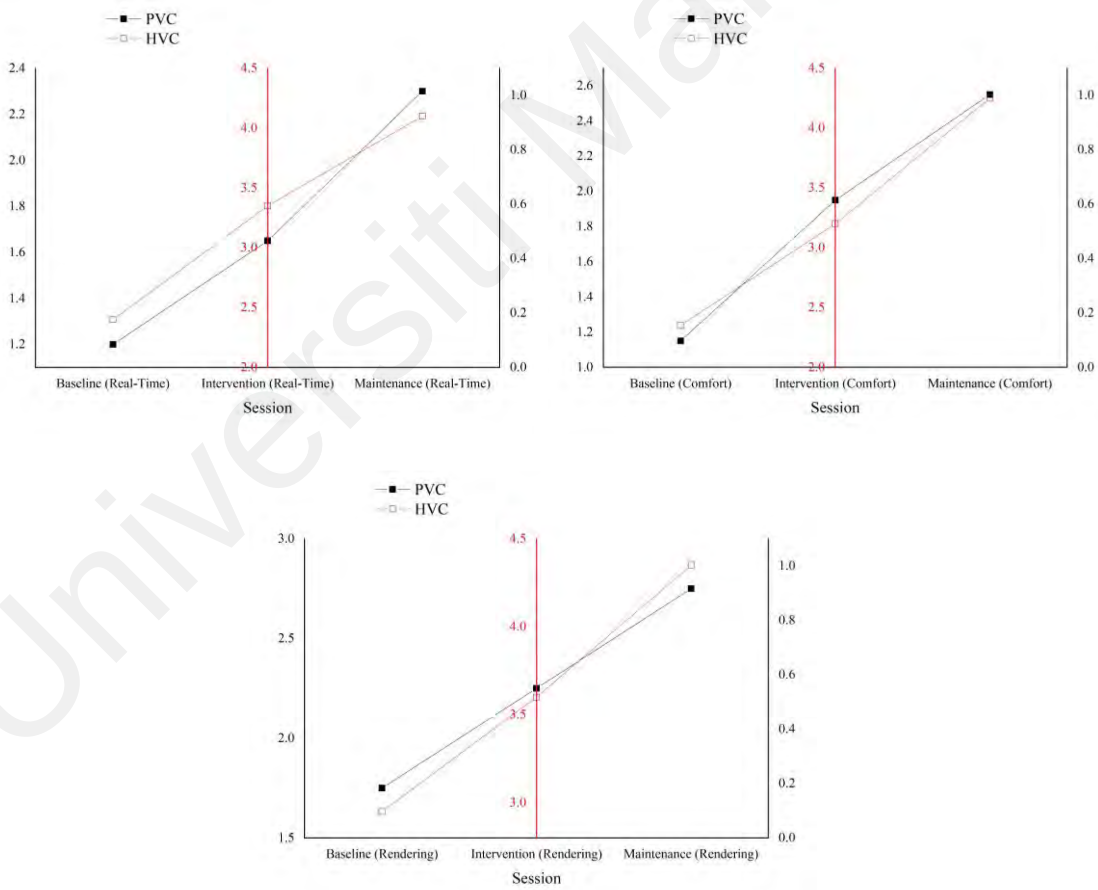


Figure 6.75: Overall perceptual factor performance

6.6.9 Discussion

This study demonstrates that autistic people individuals with haptic control exhibit significant gains in spatial visualization when interacting with virtual objects. This study evaluated how virtual objects were selected and controlled with the haptic device by visualizing their size, shape, and distance from the location of the first-person controller. Additionally, the study considers the participant's behavior during the evaluation, in addition to the haptic device and recommended spatial visualization tasks. The findings of spatial visualization tasks were disclosed using the taxonomy of haptic and virtual reality interaction elements: navigation and object selection, object selection and manipulation, and stiffness detection.

Based on the results that haptic device (haptic virtual control - HVC) is more effective compared to traditional virtual communication devices (physical virtual control – PVC) in the sense of interaction and manipulation with virtual objects. The use of haptic device in real-time rendering, improve the individual interaction skills, and this can be proven based on the time taken to rotate the virtual object in different angle, and also in terms of positioning the virtual object in the respective hole in more accuracy. However, this effectiveness depends on the real-time rendering capabilities, and this not neglected by haptic device since presence of haptic rendering component and hardware accelerator (Robles-De-La-Torre, 2006; S. Zhang et al., 2013). Moreover, the aim of this study not just observe on navigation, selection, and manipulation of autistic user in virtual environment, but also to measure the stiffness of virtual object after amount of force applied.

In addition, qualitative measurements were used to investigate the experiences of autistic users when interacting with virtual objects in the non-immersive environment. In comparison to traditional virtual communication devices (physical: keyboard and mouse), the majority of autistic users reported that they are more comfortable interacting with haptic devices. The majority of autistic users' attribute this to the fact that haptic devices provide the sensation without interfering with the sense of reality. Moreover, the presence of vibration as sensor feedback during the interaction with the virtual environment results in improved real-time performance when compared to traditional virtual communication devices. This may be owing to the presence of vibration as sensor feedback. However, haptic devices in virtual environments also produce a more realistic rendering of objects when compared to traditional communication devices, which is most likely due to the fact that the virtual scene is generated in real time with the use of haptic hardware accelerators, as opposed to traditional communication devices (Lobo et al., 2019; A. Song et al., 2008). It is more convenient for autistic users to use haptic devices due to the presence of sensory feedback, and they can interact with virtual objects at a more precise angle or viewpoint compared to traditional communication devices. In the future, more advanced wearable devices can be used and validated in the sense of interaction and manipulation with virtual objects.

6.7 Experimental Evaluation of the Haptic Technology Assistance on Spatial Learning and Cognitive Mapping among Autistic people

The main objective of this experimental evaluation is to see how well haptic technology helps autistic people develop or improve their spatial learning and cognitive mapping skills. Therefore, this experiment was conducted to investigate these two aspects: spatial learning and the influence of cognitive mapping skills during spatial learning. To determine the relationship between haptic technology and the two previously mentioned aspects for autistic people, those findings will be specified and studied from pre-learning to post-learning while maintaining the knowledge gained.

6.7.1 Methods

The focus of this experiment was to explore whether this HBVE application benefited autistic people with spatial learning and cognitive mapping skills in an unfamiliar environment. The unfamiliar virtual environment (VE) was developed to assist autistic people become more familiar with urban environment concepts by improving their spatial learning and cognitive mapping skills. This VE presents the real concept of environment as relevant in order for autistic people to practice and experience the developed environment as a better learning or training platform. This VE includes a variety of elements such as an apartment, a hospital, a restaurant, a school, a bus stop, a bridge, and naturalistic elements such as trees and lighting systems. This VE is designed with a first-person perspective view and can navigate at various angles, forward or backward, left or right, and rotate the head. The VE is also designed with various obstacles, the AHSON algorithm and navigation map as navigation support, object or landmark finding instructions, and sound effects such as walking steps. Besides, in addition to using traditional interaction tools (mouse and keyboard) for user manipulation and interaction, this environment can be supported by haptic technology. In progress, this experiment was carried out with the three concepts as listed below in order to increase or improve spatial understanding:

(1) Wayfinding: It can be defined as the process of applying spatial knowledge to navigate in an environment in order to identify the direction to a specific destination, or it can be characterised as a spatial problem-solving technique (Chang & Wang, 2010). In the course of determining the route to the desired location, this technique brought all of the factors in their environment together, such as landmarks, the structure of the building, signage, and landscaping, in order to identify the most direct route to the desired location.

(2) Spatial knowledge: It is a collection of abilities that allow people to comprehend their surroundings. It can be divided into three categories: landmark knowledge, route knowledge, and survey knowledge (Ahmadpoor & Shahab, 2019). Landmark knowledge refers to the ability to recall distinct objects in VE. Unlike route knowledge, which is concerned with comprehending the path to navigate from one location to another, route reconstruction is concerned with recreating the path between the two locations by referring to, and relating to, the landmarks observed while navigating. In the end, survey knowledge can be defined as the knowledge of a map-like mental representation of a particular unfamiliar environment that can be used to estimate the relative distance between two points or locations and to determine an alternate path or direction to the targeted object.

(3) Cognitive mapping: An understanding of a particular environment is represented in the mind by processing, storing, and recalling the information about that environment that has been observed by the person (Johns, 2003). This process benefits an individual by providing direction to the targeted locations or objects. This task conducted based on four steps: the participants will estimate relative distances

between each object or locations; then reconstruct the location map based on their mental map formation, point the object or location direction; and finally navigate to the object by choosing the shortest route (refer to Figure 6.76).

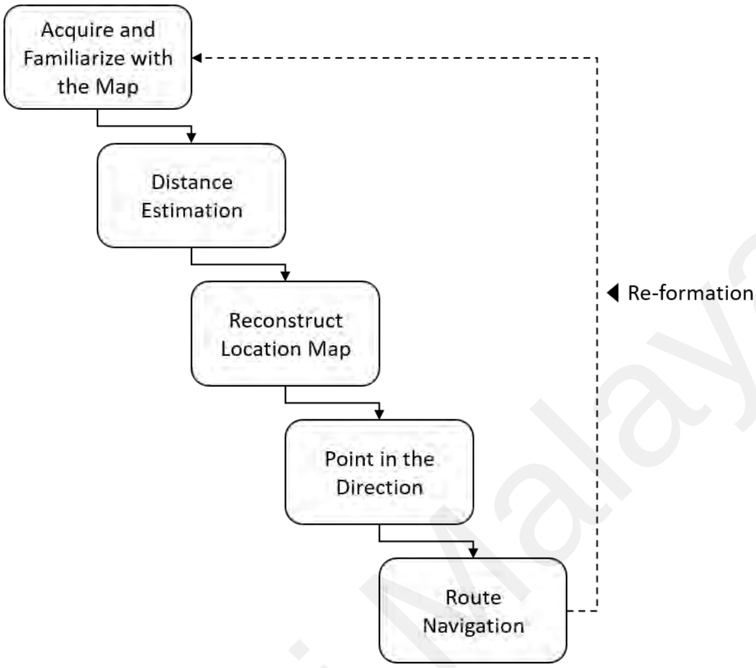


Figure 6.76: Mental map formation steps that are performed for cognitive mapping task

- *Acquire and familiarize yourself with the map*

  In this step of the activity, participants were required to explore the map by starting their navigation from the environment's central position. The participants were asked to acquire knowledge of the location of the objects as well as the relative landmarks or attributes of the objects.

- *Distance estimation*

  Participants were asked to estimate the distances between the objects or locations.

- *Reconstruct the location map*

  At this step, the participants were required to use their mental maps to reconstruct the location that they had previously observed with as much precision and thoroughness as is possible. This was carried out using the empty map that was provided. The scoring will be determined based on how the selected landmarks are organised on the map.

- *Point in the direction*

  This step required the participants to recall the locations of the objects in the virtual environment. They must indicate the direction of the object based on what they recall from the previous step in the virtual environment. The score will be determined by whether the correct or incorrect direction was selected.

- *Route navigation*

  At this point, the participants had to navigate to the object's location by following the directions and taking the shortest path. This step is more interesting and difficult because the participants must process their mental representation of the entire map in order to plan and execute the shortest route to the targeted object. Scores will be assigned based on the correct object selected and reaching the object's location.

On the basis of all three of the aforementioned concepts, this experiment was conducted with autistic people, particularly for the designation of the tasks as listed in Section 6.7.4, in order to measure their levels of spatial knowledge and how they can be improved with the assistance of haptic technology. Furthermore, a specific experimental comparison was performed by comparing the parameters with those of other applications. The objective of this experiment is to conduct a comparative analysis of six different applications, including the HBVE application, with the aim of investigating whether the use of the HBVE application leads to enhanced spatial abilities in autistic people in comparison to the other five applications (Fornasari et al., 2013; Sophie E Lind et al., 2013; M. Ring et al., 2018; Umesawa et al., 2020; J. Zhao et al., 2022)

6.7.2 Participants

This experiment was conducted with the same group of autistic people (participants) as in the previous experiments. There were twenty participants recruited from Pondoku centre and Fitrah Academy, whose average age ranged from 9 to 27 years, with the mean age of the sample size of 17.05 years and SD = 5.949. The participants confirmed and reported that they have uncommon spatial learning with cognitive mapping skills and are not familiar with the implemented urban virtual environment for this study.

6.7.3 Experimental Apparatus and Environment

Based on the previous experiments, the MYO Armband was used as a haptic wearable interface device (refer to Figure 6.50), with a standard Windows-based LCD screen computer with Intel's Core(TM) 15-3570 CPU @3.40GHz. An urban modal of a HBVE was used to conduct this experimental study to study the spatial learning and cognitive mapping skills of participants. This environment is designed and presented in both egocentric and allocentric representations, or reference frames (refer to Figure 6.77). The starting location of both egocentric and allocentric representations is always in the centre of the environment to reduce the amount of disorientation experienced by autistic users. Additionally, autistic users are limited to moving in only one direction while navigating the environment. In the case of the egocentric representation, the autistic user will have the ability to view things from a first-person perspective. It indicates that the LCD screen on the computer is representing how they see things from their viewpoint. On the other hand, when it comes to allocentric representation, the autistic user will have direct exposure to a view that provides a top-down survey perspective. The location of this autistic user within the environment is represented by a direction icon in the form of a red arrow.

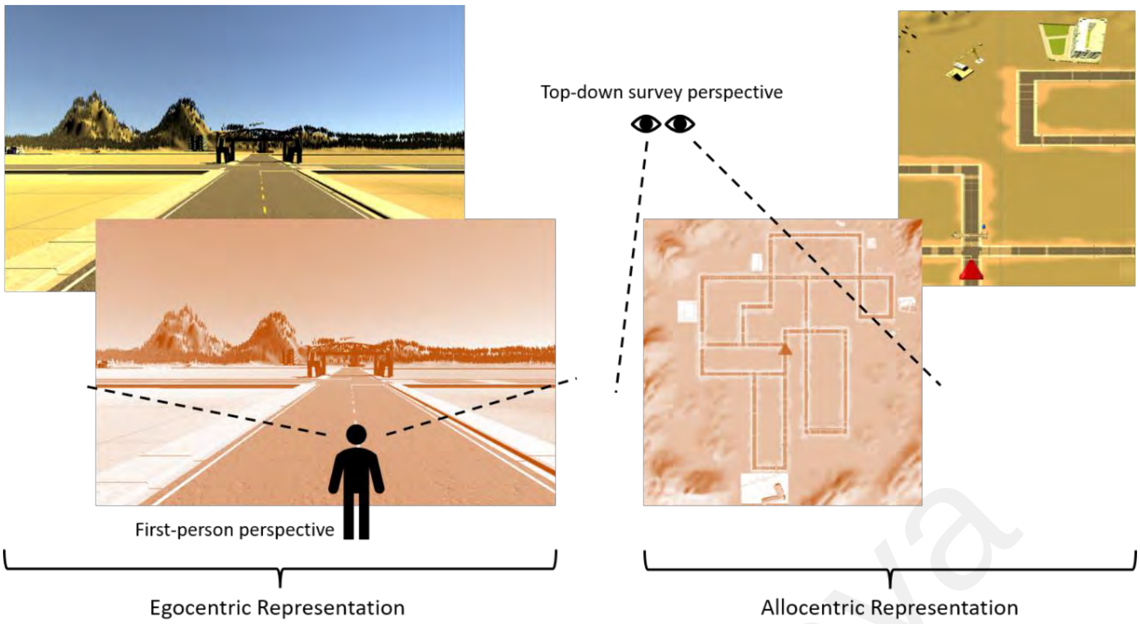


Figure 6.77: Overall perceptual factor performance

6.7.4 Spatial Awareness and Cognitive Mapping Task

This experiment focused on the following two types of tasks to determine the effectiveness of spatial learning and cognitive mapping skills through haptic technology in participants:

(1) Cognitive mapping test: Participants were provided with the locations of the ten object landmarks (including the cognitive maps as clues (refer to Figure 6.44) and the AHSON algorithm as support) and asked to process and store the information they saw that related to the object's landmarks through their mental model. These locations of the object's landmarks were not shared with participants during the partial learning and post-learning stages, except for the pre-learning stage.

(2) Spatial awareness: Participants were asked to recall those spatial information objects' landmarks information) they processed and stored from the previous test by identifying the target objects as specified in the tasks list (refer to Figure 6.44) through navigation in the HBVE application. This test started at the center of the urban virtual environment.

(3) Allocentric and Egocentric: Participants were asked to recall those spatial information objects' landmarks information) they processed and stored from the previous test by identifying the target objects as specified in the tasks list (refer to Figure 6.44) through navigation in the HBVE application. This test started at the center of the urban virtual environment.

6.7.5 Procedure

All the participants took part in each specified task (refer to sections 6.7.4) and were observed separately. The experiments were conducted based on the following steps:

(1) Participants were asked to become familiar with the MYO Armband haptic interface and with the virtual environment concepts and features.

(2) Participants were asked to become familiar with the anonymous urban-based haptic virtual environment with the MYO Armband haptic interface before the actual practise and test began.

(3) Participants were asked to acquire, store, and recall information about ten object landmark locations (cognitive mapping task).

(4) Participants were asked to identify the target object landmark through navigation (a spatial awareness task).

This experiment has four stages: (1) exploration with HBVE stage; (2) pre-learning (baseline) stage; (3) partial learning (intervention) stage; and (4) post-learning (maintenance and generalization) stages. Each participant was given a maximum of five minutes to complete each of the tasks. As underlined previously in the experimental steps (1 and 2), for the exploration with the HBVE stage, each of the participants provided knowledge about the virtual environment and features involved, and also introduced the haptic interface (MYO Armband) features and the way to control and manipulate them in HBVE. Apart from that, they were required to explore the urban-based virtual environment to become familiar with objects and locations in their surroundings. After exploring and familiarising with the virtual environment and haptic interface, the rest of the experimental stages were conducted based on the spatial learning and cognitive mapping tasks. During the pre-learning stage, participants were asked to complete spatial learning and cognitive tasks with the help of cognitive maps and the AHSON algorithm. Meanwhile, during the partial learning stage, the participants were required to test again with the same tasks but without cognitive map clues and AHSON algorithm support. In the event that the participant had difficulties recalling the spatial information, the participants were provided with support through cognitive map clues and AHSON algorithm support by reduction of their gained scores for it. Finally, at the post-learning stage, with the same environment and tasks, the autistic people participants were tested without cognitive map clues and AHSON algorithm support to studies on their ability to maintain their knowledge of spatial learning and cognitive mapping skills.

6.7.6 Data Measurement and Analysis

Four different experiments have been conducted in order to demonstrate the effectiveness of spatial learning and cognitive mapping among autistic people with the wearable MYO Armband haptic device. The experiment objective is to analyse the performance of participants in terms of wayfinding through landmarks with the proposed algorithm as an assistive technology to identify the targeted object or locations. The independent and dependent variables used for conducting the analysis are as:

(1) **Independent variables:** number of trials, virtual environment;

(2) **Dependent variables:** number of object landmarks or targeted object identified correctly; time taken to complete the task, number of times AHSON algorithm provided assisted to complete task

Furthermore, the following objective of this research is to assess the efficacy of the HBVE application within the context of the proposed HBVE-framework. This will be achieved through a comparative analysis with other existing applications. The independent and dependent variables used for the first analysis are as follows, with the t-Test and risk value analysis:

(1) **Independent variables:** type of tasks, the virtual environment;

(2) **Dependent variables:** time taken to complete the task, number of targeted completed, pointing the direction, time taken to reach the target, and recognition of landmark image.

Also, for the analysis of the experimental data, a t-Test was used at a 0.05 level of significance.

6.7.6.1 Data Measurement

Before starting this evaluation, the study collected measurements of the characteristics and levels of participants' experiences. This study collected spatial awareness and cognitive mapping information based on participants' navigation performance, spatial orientation and knowledge, cognitive mapping skills, and allocentric and egocentric skills measure:

(a) ***Navigation Performance Measures***

The following sub-sections show the list of variables considered in the navigation performance measures:

- *Time taken to complete route task*

  The participant's total time taken to complete the route tasks in each session for the following learning levels: pre-learning (baseline: three sessions); partial learning (intervention: three sessions); and post-learning (maintenance: three sessions). The maximum time allowed to complete each session is 90 seconds.

- *Time taken to view the map*

  The participant's total time taken to view the projected map during the navigation in the virtual environment.

- *Distance travelled*

  The participant's total three-dimensional "Euclidean" distance travelled during the navigation from one location to another location or object in the virtual environment with the measured value based on Unity's internal measurement support.

- *Number of routes completed*

  The participant's total number of routes taken to reach their desired location or targeted object during the navigation in the virtual environment within the specified time limit is 90 seconds.

(b) ***Spatial Orientation and Knowledge Measures***

The following sub-sections show the list of variables considered in spatial orientation and knowledge measures:

- *Translation of landmark image*

  During the navigation in the virtual environment, the participants were able to view five landmark images and requested that they indicate the location of the landmark image in the virtual environment.

- *Estimation of route duration*

  During the navigation in the virtual environment, the participants requested an estimate of the time it would take to travel and reach the target landmark location if they decided to navigate directly to the targeted location.

(c) ***Cognitive Mapping Skills Measure***

The following sub-sections show the list of variables considered in the cognitive mapping skills measure:

- *Estimation of distance*

  The participant was tasked with estimating the relative "Euclidean" distances between one location and another location of an object in the virtual environment.

- *Reconstruct the location map*

  The participants had to construct the location from memory by placing objects or landmarks in the appropriate locations on an empty map.

- *Pointing the direction*

  The participants had to indicate in which direction the remembered object was situated within the virtual environment.

- *Route selection*

  The participants were tasked with making their way to the location of the object in the virtual environment using the route that was chosen. The distance travelled can be broken down into three categories: short and long.

(d) ***Allocentric and Egocentric Skills Measure***

- *Recognition of landmark image*

  During the navigation in the virtual environment, the participants were able to view five landmark images and requested that they indicate the location of the landmark image in the virtual environment.

- *Time taken to reach the target object or landmark*

  Time taken to complete route tasks in each session, broken down by pre-learning (three sessions), partial learning (three sessions), and post-learning conditions (maintenance: three sessions). Each session must be completed within 90 seconds.

- *Adding a new object or landmark*

  The capability of the participant to find the location of the object or landmark even after it has been added with a new object or landmark may have an impact on or influence the route selection while the participant is navigating in a virtual environment.

- *Recognition of Route (Shortest route)*

  A participant's total "Euclidean" distance travelled while moving from one location or object in the virtual environment to another is calculated using Unity's built-in measurement support. One of the purposes of this measurement is to determine whether or not the participants are still able to locate the shortest route after a new object or landmark has been introduced.

6.7.6.2 Data Analysis

The data collected from each participant was based on their performance in the three tasks. The data derived from each participant to measure the variables such as time taken to complete, number of routes completed, and distance travelled from one location to another location was based on mean values. At the same time, this study also collected information related to participant scores to measure the spatial orientation and knowledge skills among autistic people. The MANCOVAs analysis is used to evaluate participants' performance in developing and improving spatial learning and cognitive mapping skills during virtual navigation across all three stages of learning (pre, partial, and post-learning). The Alpha value was set at 0.05. res for measuring the spatial orientation and knowledge skills among autistic people.

6.7.7 Results

The results show the effectiveness of a HBVE in autistic people for transferring the spatial knowledge and cognitive mapping skills presented at three different levels: pre-learning (baseline), partial learning (intervention), and post-learning (maintenance). During the post-learning stage, all the navigation assistance is excluded.

6.7.7.1 Pre-learning (Baseline)

Spatial Awareness: The results relate to the spatial learning task in the HBVE. The results are presented based on these three measures: navigation performance, spatial orientation and knowledge, and allocentric and egocentric. There are significant effects on the participants' performance with the provided navigation assistance, such as landmarks and the autonomous AHSON algorithm, and these can be seen in Table 6.33 for all the performance measures. Participants with navigation assistance showed less time taken to complete tasks and to view the map. Furthermore, due to the navigation assistance, the distance travelled during the navigation was very small, and this also indirectly increased the number of routes that could be completed during the navigation in a HBVE. For the spatial orientation and knowledge, the participants show significant results for both the translation of landmark images and the estimation of route duration when most of the participants are still dependent on the navigation assistance, which completely influences the participants' spatial knowledge (refer to Figure 6.78 and 6.79).

Cognitive Mapping: Performance in the cognitive mapping task was based on mean and standard deviation values to estimate how accurate the participants were able to recall the landmarks and route after each of the sessions conducted, and these results are presented in Table 6.33. Even though the participants had assistance with navigation while they were navigating the virtual environment, the results showed that cognitive mapping had a moderately significant effect on their performance. The findings also showed that every one of the participants had an accurate sense of the distances between the location of an object and other locations. This demonstrates that the Euclidean distance is demonstrating significant effects, although to a smaller extent. In addition, in order to provide evidence in support of this result, the task of reconstructing the location of the objects on the map and pointing the direction showed that the participants remembered the location of the objects, even though they were still at the beginning of the learning and exploration level. In the meantime, during the route navigation task, the results show that there was an average distance covered because the majority of the participants travelled a long route (refer to Figure 6.80).

Allocentric and Egocentric: The egocentric and allocentric tasks do not show significant differences for all four measures (recognition of the landmark image, time taken to reach the target object or landmark, adding a new object or landmark, and route traveled) (refer to Figure 6.81). *D*ue to the early of learning stage, participants mostly spend their time to either to process and encode information about the location of an object or its attributes to other objects, or process their self-perspective to location of the object or landmark.

Table 6.33: MANCOVA results for the effects of performance measures for the pre-learning, partial learning, and post-learning sessions

Measures	*Pre-learning (Baseline)*		*Partial learning (Intervention)*		*Post-learning (Maintenance)*			
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***p***
Navigation Performance								
Time taken to complete route task	*0:01:55*	*0:02:04*	*0:01:00*	*0:01:04*	*0:00:35*	*0:00:28*	*73.229*	*.001*
Time taken to view the map	*0:00:10*	*0:00:26*	*0:00:04*	*0:00:07*	*0:00:02*	*0:00:03*	*19.985*	*.001*
Distance travelled	*744.70057*	*727.31542*	*539.25543*	*345.45649*	*298.97377*	*227.59263*	*63.977*	*.001*
Movement Speed	*1.93807*	*2.51552*	*4.06960*	*5.50320*	*7.03583*	*4.88132*	*97.607*	*.001*
Number of routes completed	*0.31000*	*0.46327*	*0.61333*	*0.48780*	*0.91000*	*0.28666*	*151.482*	*.001*
Spatial Orientation and Knowledge								
Translation of landmark image	*0.23152*	*0.42575*	*0.37428*	*0.48536*	*0.58402*	*0.49438*	*40.565*	*.001*
Estimation of route duration	*0:00:27*	*0:00:57*	*0:00:13*	*0:00:22*	*0:00:05*	*0:00:07*	*28.567*	*.001*
Cognitive Mapping Skills								
Estimation of distance	*527.54313*	*494.57481*	*516.26230*	*307.75262*	*436.63953*	*246.77125*	*5.521*	*.004*
Reconstruct the location map	*0.16353*	*0.37029*	*0.32648*	*0.46979*	*0.51616*	*0.50074*	*44.484*	*.001*
Pointing the direction	*0.13436*	*0.34050*	*0.22557*	*0.41938*	*0.42003*	*0.49438*	*35.880*	*.001*
Route selection	*0.15857*	*0.36409*	*0.33667*	*0.47336*	*0.49595*	*0.50082*	*42.867*	*.001*
Allocentric and Egocentric								
Recognition of landmark image	*0.22955*	*0.41938*	*0.37333*	*0.48450*	*0.59242*	*0.49203*	*46.963*	*.001*
Time taken to reach the target	*0:01:55*	*0:02:04*	*0:01:00*	*0:01:04*	*0:00:35*	*0:00:28*	*73.229*	*.001*
Adding a new object or landmark	*0.14718*	*0.35436*	*0.32159*	*0.46853*	*0.51669*	*0.50056*	*51.747*	*.001*
Recognition of Route (Shortest route)	*0.19362*	*0.39557*	*0.30228*	*0.46046*	*0.52808*	*0.50012*	*41.969*	*.001*

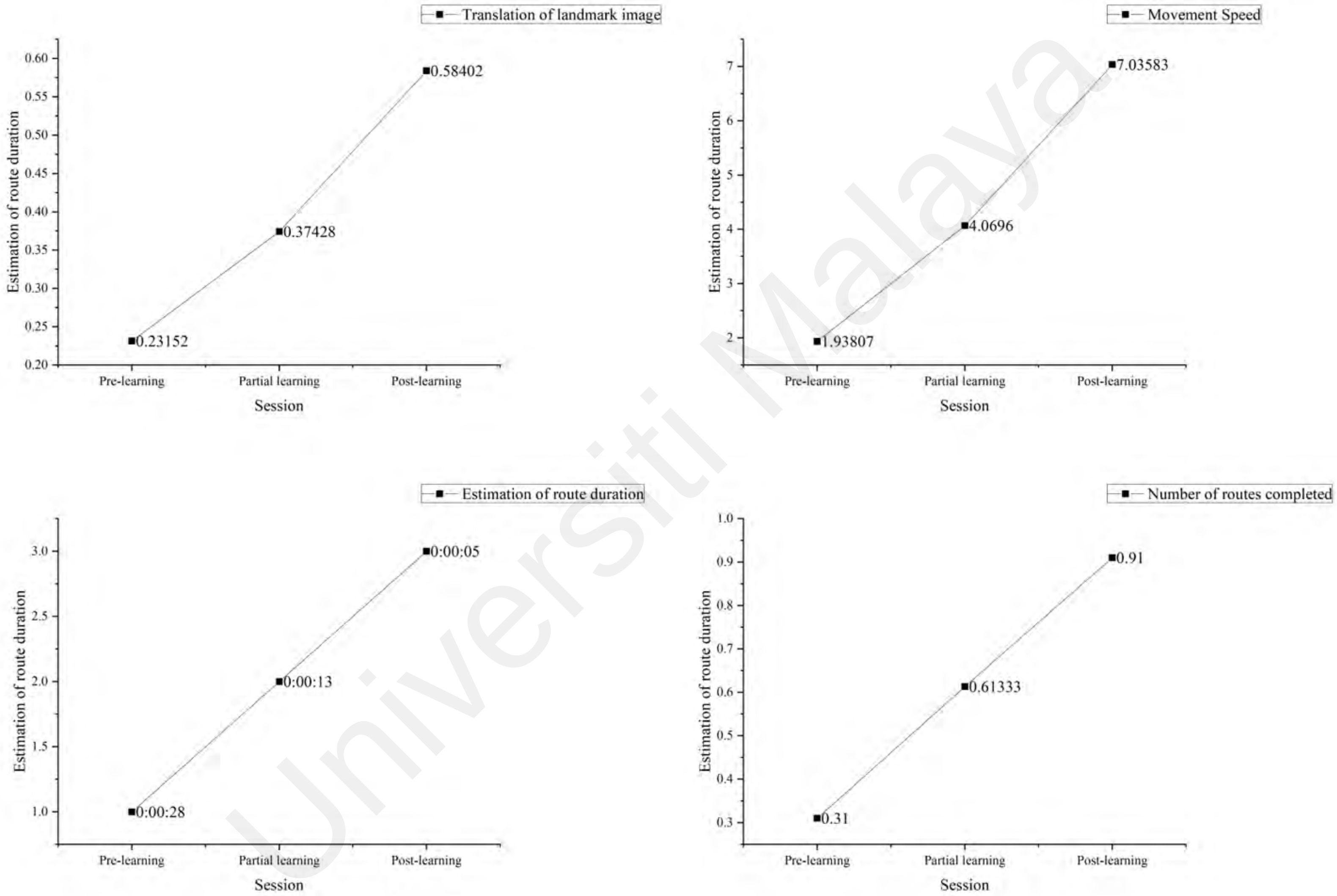


Figure 6.78: Overall spatial learning performance in autistic people (1)

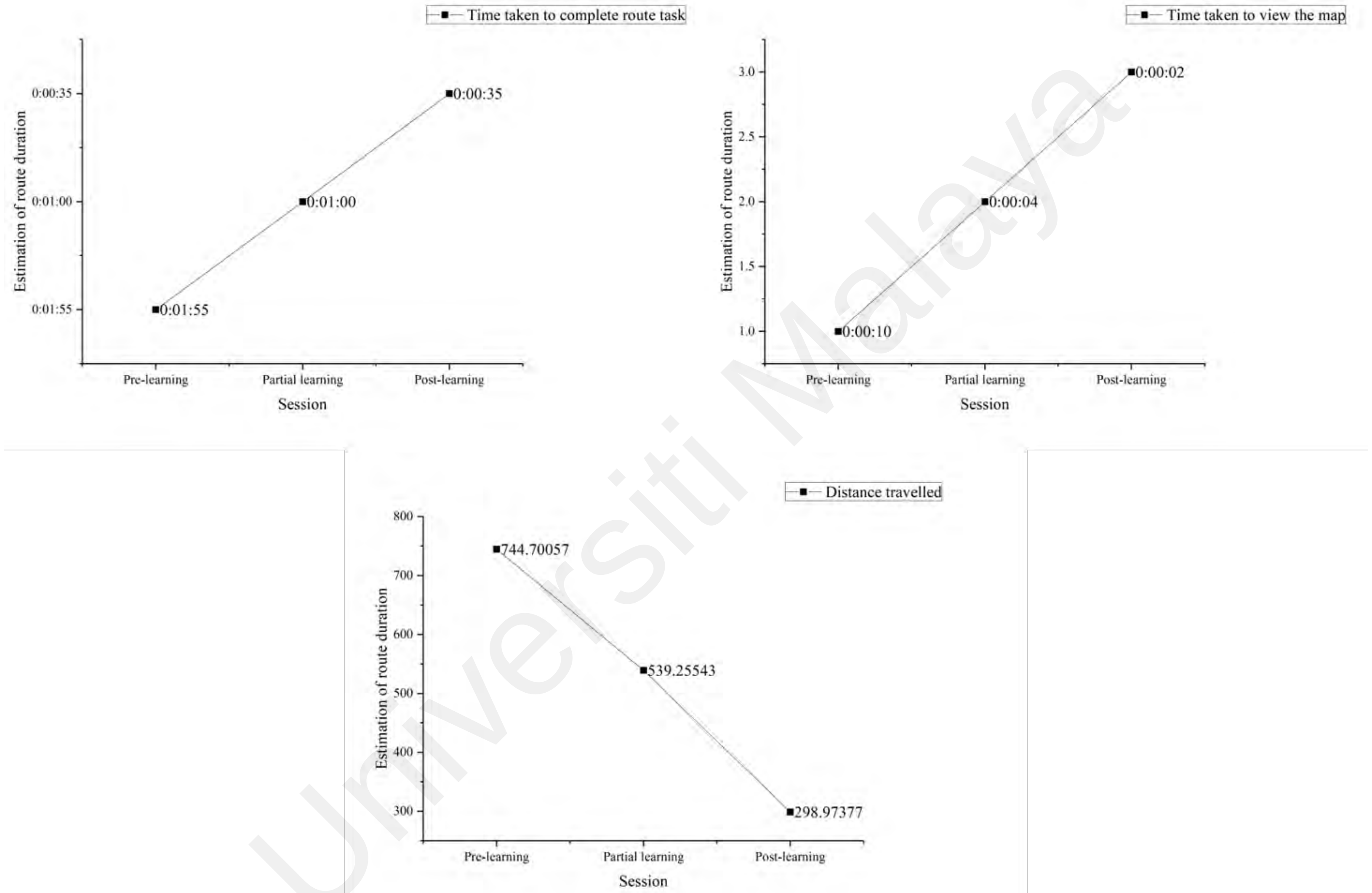


Figure 6.79: Overall spatial learning performance in autistic people (2)

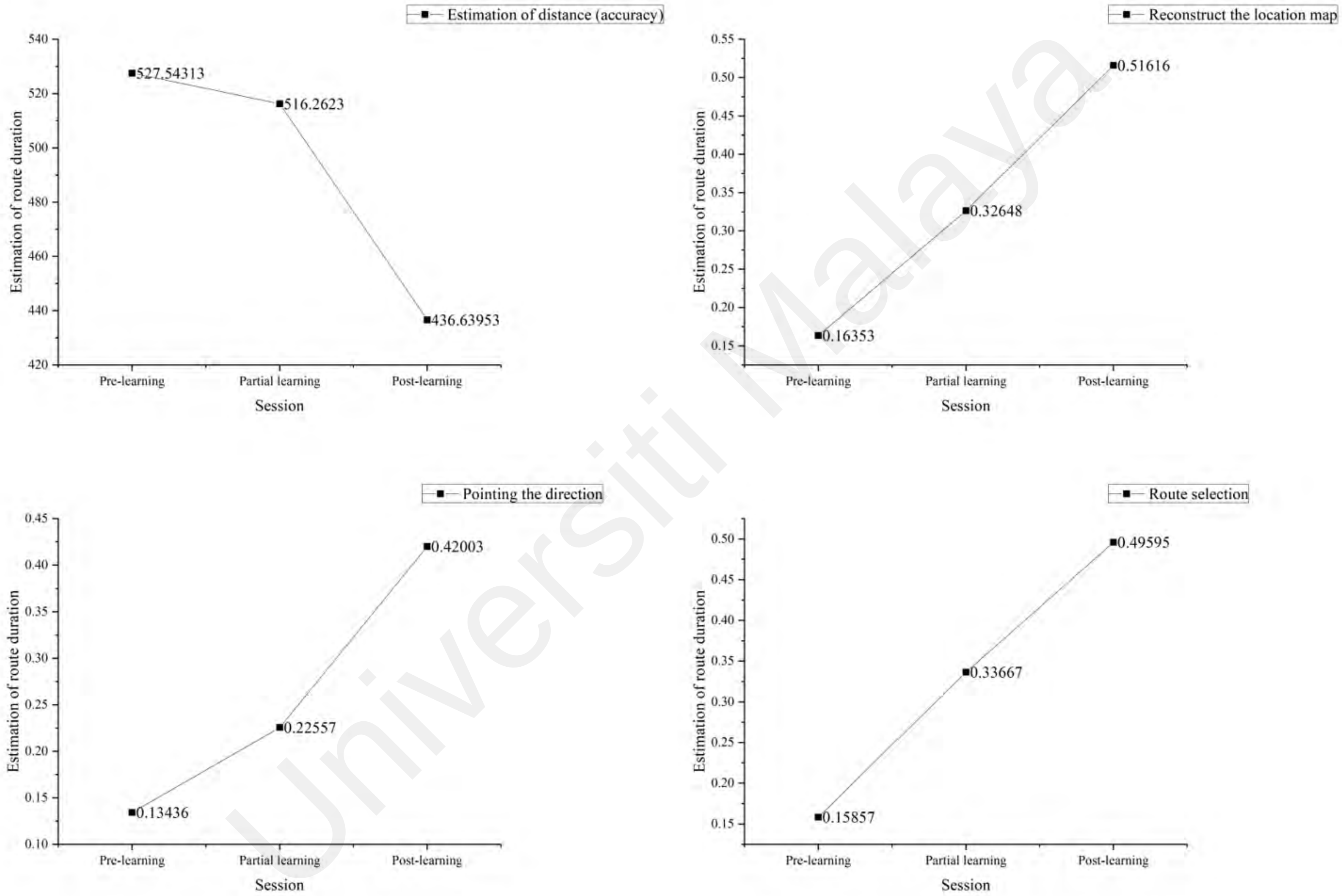
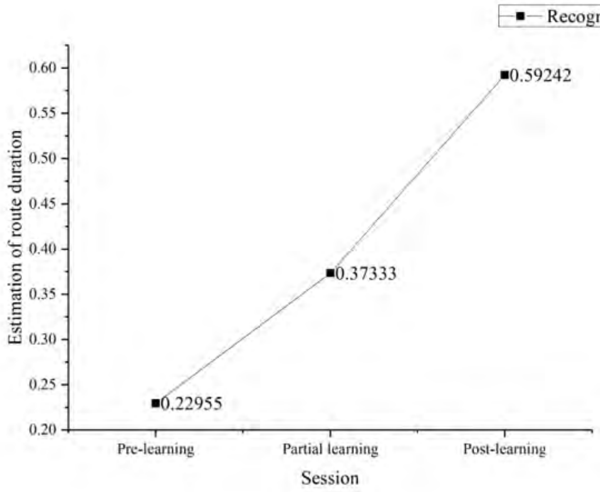
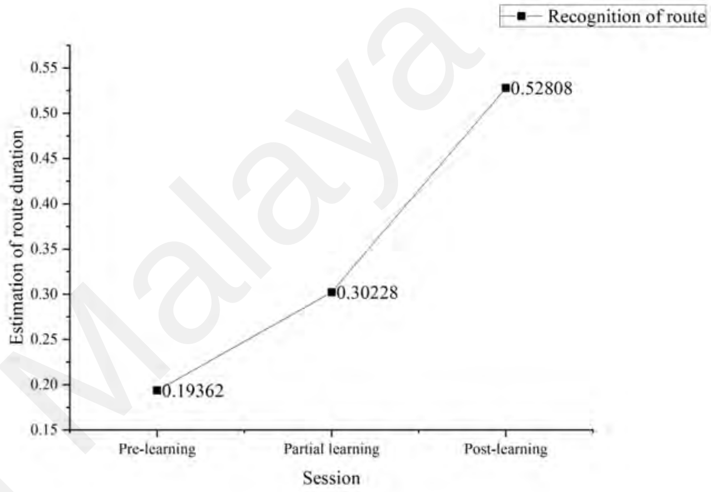


Figure 6.80: Overall cognitive mapping performance in autistic people





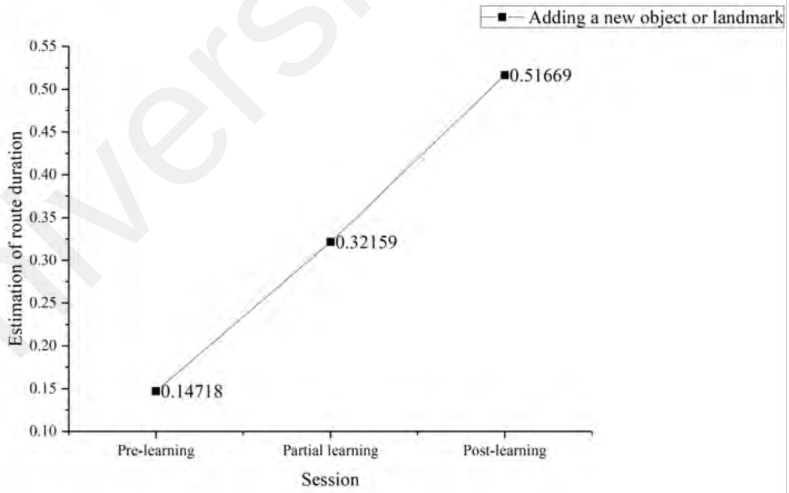


Figure 6.81: Overall allocentric and egocentric performance in autistic people

6.7.7.2 Partial-learning (Intervention)

Spatial Awareness: In partial-learning, the results are based on three sessions for each of the participants (refer to Figure 6.78 and 6.79). Similar to the pre-learning stage, this stage used the same measures: navigation performance, and spatial orientation and knowledge. For all the performance measures in the first four partial learning stages, there were moderate significant effects compared to the previous learning stages. This was due to most participants' failure to completely utilise the navigation assistance, while they were keener to use their gained spatial knowledge from the recall method to recognise the landmarks or location of the virtual object. Table 6.33 shows that there is a slightly higher time taken to complete the task and to view the map when compared to the pre-learning stage. Apart from this, there has also been an increase in the distance travelled during the navigation compared to the pre-learning stage. Due to most of the participants' desire not to use navigation assistance frequently, there has been a decrease in the number of routes completed. Meanwhile, for spatial orientation and knowledge, the participants show moderately significant results for both the translation of landmark images and the estimation of route duration. These results were completely impacted after the second session in the partial learning stage, where the performance measure shows highly significant effects. The participants show good improvement by spending less time completing the task and viewing the map. In addition, the participants also showed improvements in terms of distance travelled where the distance travelled from one location to another location was decreased, and the participants were able to complete more routes compared with previous sessions without navigation assistance. Due to the high effects on navigation performance after the second session in the partial learning stage, the participants also show high performance effects in terms of spatial orientation and knowledge, where both the translation of landmark images and the estimation of route duration show highly significant results.

Cognitive Mapping: For the cognitive mapping performance, the results show a moderately significant effect in the first two sessions, but dramatically, this result shows highly significant results after the second session for cognitive mapping without navigation assistance (refer to Figure 6.80). In the beginning, there were only moderately significant differences in indicating Euclidean distance, reconstructing the location of objects on the map, and pointing the direction of object location tasks. However, these moderately significant differences became highly significant only after the second session in partial learning, and it also demonstrates a dramatic and highly significant difference when compared to pre-learning performance. In addition, because of the underestimation of Euclidean distances in the first two sessions, the difference between all of the sessions in partial learning was only moderately significant. However, taking into account the relatively small sample size, this difference between all of the sessions in partial learning is likely to become significantly larger if more participants are included. In addition, the route navigation task performed significantly better in partial learning compared to the pre-learning stage. This was because the majority of participants chose a short route in the final session, even though they mostly selected long routes in the first two sessions.

Allocentric and Egocentric: A result of moderate significance was found across all four measures for the egocentric as well as the allocentric conditions (refer to Figure 6.81). Anyhow, the egocentric condition is showing an increased amount of improvement in comparison to the allocentric condition for all three measures, particularly after the fourth session. This is probably due to continued practise and learning from the previous session, which resulted in the participants having a good knowledge of self-direction and distances based on the formation of their cognitive map to the targeted object or landmark. Event thought allocentric shows low significant compared to egocentric on the same learning stage, but when it comes to comparison in between pre-learning and partial learning in terms of identifying the object or landmarks, there is still significantly showing some increased improvement event thought highly time taken to reach to the targeted object or landmark. In addition, the participant shows moderate significance especially in egocentric when there has newly added object or landmark in the virtual environment, and this also impacts the participants' route travelled, where there has reported slightly most of the participants navigate in the shortest route. However, this performance is slightly less significant in the allocentric condition compared to the egocentric.

6.7.7.3 Post-learning (Maintenance)

Spatial Awareness: In terms of the navigation performance, there was a significant effect with no major difference when compared to the last three sessions from the partial-learning stage for the time taken to complete route tasks, time taken to view the map, the distance taken to travel to reach the desired location and the total number of routes completed even though the participants were not provided with navigation assistance. Table 6.27 shows there has been a decrease in terms of time taken to complete route tasks, view the map, and the distance travelled. This indirectly increases the total number of routes completed. Meanwhile, for the spatial orientation and knowledge measures, the results show that there are highly significant results for both the translation of landmark images and the estimation of route duration due to the continuous spatial knowledge from the past sessions (refer to Figure 6.78 and 6.79).

Cognitive Mapping: In terms of the performance of cognitive mapping, the participants were able to maintain a high level of significance even when they were not given any assistance with navigation (refer to Figure 6.80). Despite the fact that the high significant differences between each session are only visible in small portions or on a small scale, the participants have shown significant improvement in their ability to maintain the number of results for Euclidean distance, reconstruct the location of objects on the map, and point in the direction of where the objects are located over the course of the last three sessions that have been conducted as part of this learning stage. This is as a consequence of the high significance that was reported in the task of reconstructing the location of objects, in which the participant was able to remember or recall the location of the objects after many attempts in all of the previous navigation sessions, regardless of whether they originated from pre-learning or partial learning. Post-learning has been reported to have the same level of high significance as prior learning, with only a minor difference. In addition, when it came to the navigation of the route, the majority of the participants had selected the shorter route at this learning stage for all three sessions as opposed to the partial learning option. This was because they were already familiar with the route and the landmarks.

Allocentric and Egocentric: At this stage, the both allocentric and egocentric shows high significant improvement compared to previous learning stage (refer to Figure 6.81). Furthermore, events thought egocentric on this same stage show more improvement compared to allocentric, but overall, for all the measures in the recognition of landmark images, time taken to reach the target object or landmark, adding a new object or landmark, and route traveled, there is a slight improvement, as can be seen in Table 6.33.

6.7.7.4 Comparison of the parameters between five applications and the proposed framework-based HBVE application

This section provides a comparison of six distinct types of haptic-based virtual environments, including the newly developed application specifically designed for this study, which is based on the proposed HBVE-Framework. The details of this comparison can be found in Table 6.34. The analysis considered the theoretical instability of these factors, and the findings were interpreted using a predefined set of parameters (see Table 6.34). In a range of experiments involving HBVE applications, it has been demonstrated that these parameters can contribute to the understanding of users' spatial abilities in reaching the desired location. On modest effect size, the HBVE application exhibits a 12.2% reduction in time compared to the other three applications. Furthermore, the HBVE application demonstrates a 7.1% increase in the number of targeted objects or locations reached and 37.1% increase in pointing the direction compared to the other two applications. This improvement can be attributed to the incorporation of an automated route navigation feature in the HBVE application, which serves as an alternative means of navigation assistance when locating the desired object or location. In contrast, the duration required to reach the target was found to be 24.1% lower, and the accuracy of landmark image recognition by the HBVE application was observed to be 4.8% higher in comparison to the other two applications when participants relied on both allocentric and egocentric.

Table 6.34: Comparison of the parameters between five applications and the proposed framework-based HBVE application

Benchmark parameters: Demographics	**Urban Environment**	**RF System**	**Morris Water Maze**	**Memory Island**	**VR-Training**	**HBVE**	
Number of Participants	16	17	26	27	22	20	
Age	9.56 (2.16)	20.9 (3.70)	38.81 (11.81)	34.64 (12.97)	3.45 (3.50)	16.35 (5.31)	
Gender:							
Male	14	14	23	21	19	16	
Female	2	3	3	6	3	4	
Task Name	Navigation- Urban Environment	Touch-Target Positioning	Spatial Navigation Task	Memory Island Navigation Task	Look for Bags, Maps, Bananas, etc	Spatial Awareness and Cognitive Mapping Task	
Benchmark parameters: Measures	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	**Effect Size d | v**
Spatial Orientation and Knowledge: Time taken to complete the task	68.28 (60.72)	-	33.22 (26.58)	96.71 (43.09)	-	0.58 (0.47)	2.131 | 0.73
Spatial Orientation and Knowledge: Number of targeted completed	7.56 (2.10)	-	-	0.84 (0.22)	-	0.90 (0.29)	3.903 | 0.89
Cognitive Mapping: Pointing the direction	-	-	-	0.78 (0.24)	29.86 (9.47)	0.42 (0.49)	4.318 | 0.91
Allocentric and Egocentric: Time taken to reach the target	-	14.88 (0.02)	31.86 (28.01)	-	-	0.58 (0.47)	2.298 | 0.75
Allocentric and Egocentric: Recognition of landmark image	-	0.62 (0.55)	-	-	-	0.59 (0.49)	0.058 | 0.03

6.7.8 Discussion

The objective of this study has been achieved, and this can be seen from the dramatic improvement from the pre-learning until the post-learning stage. The navigation knowledge gained from the pre-learning stage with the navigation assistance, either the AHSON algorithm or navigation map, increased the individual spatial knowledge, and this can be proven by better performance in the post-learning stage. Although navigation assistance was present and used at all three stages, its use decreased at the partial and post-learning stages due to the individual's familiarity with their surroundings. In addition to supporting the previous statement, it was reported that the overall time taken to complete each of the sub-tasks decreased from the pre-learning to the post-learning stage, even though there was a slightly increased overall time taken at the first two sessions of partial-learning for most of the participants. This is due to the intention of the participants to find their route to the desired location without the use of any navigation assistance, but anyhow, the performance of the participants manages to return to normal with no difference from pre-learning to partial-learning stage. There is a possibility that cognitive mapping skills will be decreased if continuous navigation assistance is provided for all three stages where the participants may stop to require and recall the destination landmark. But if the study looked closely into the performance of each individual during the navigation, as reported earlier, the total time taken, the distance travelled, and also the number of times the AHSON algorithm and navigation map were used to complete each task decreased after the third session of partial-learning, meaning that the participants were able to recall the landmark and its location more quickly and were able to find the desired location within a minimum amount of time. This proves that the navigation assistance did not have an adverse impact on the participants in terms of improving their cognitive mapping skills, while it helped as additional knowledge to find their desired location. Since the contrast value between less total time taken to complete the task and the AHSON navigation assistant programmed as will be move slowly compared navigation without any navigation assistance, and the dramatic drop of use the navigation map, can be proven enough that the autistic people used their cognitive mapping skills to navigate to their desired location.

In addition, the knowledge acquired with a high degree of improvement from reconstructing the location of objects on the map, pointing the direction of object location, and estimating the distance shows that autistic people are able to form their cognitive mapping with the goal of finding the shorter route while navigating. Distance estimation has a high significance of estimated distances with accurate distances reported, indicating better representation of relative distance between objects or locations in a cognitive map in post-learning compared to the previous two learning stages. The finding demonstrates that autistic people may accurately estimate distances between locations or objects in an HBVE (Avraam et al., 2019; Candini et al., 2020; Candini et al., 2019; Edgin & Pennington, 2005; Giovannini et al., 2009; Iyer et al., 2017; Pellicano et al., 2011; Sheppard et al., 2016; Soulières et al., 2010). This ability may indicate a potential for cognitive map formation in controlled environments. However, additional investigation or research is required to determine whether these distance estimate abilities remain consistent in real-world environments where there are significant differences in sensory and cognitive demands. This better performance on distance estimation by participants is an indication of cognitive map formation. This measurement was not specifically stated on the maps, which typically provide an overview-like representation. Furthermore, this measurement takes into consideration a representation that might enable an allocentric rather than an egocentric perspective. In addition, the participants were seeking to find the shortest routes between locations or objects, and some of them considered slightly different routes to be the shortest. However, the difference in length between these routes was minimal, and the findings of this study indicate that such differences did not have a significant impact on the estimations of travel distance. At the same time, this slight difference is most likely influenced by a large-scale environment with a different perspective during navigation.

The steps to reconstruct location maps indicate that the participants are equally capable of determining routes between locations or objects from their cognitive maps. The participants performed well in terms of reconstructing the location map, indicating that they were familiar with the routes between locations or objects. Even though their ability to reconstruct the location's routes after exploring using HBVE significantly decreases during pre-learning, it has greatly improved during partial-learning and post-learning due to their previous experience. This demonstrates that the participants have a solid route and survey knowledge of the cognitive map. This is because this study reveals that autistic people are capable of utilizing visual-spatial cues, such as landmarks and the visual characteristics of turns, to encode and remember turn-by-turn information within a navigational context. This implies that individuals are able to retrieve past routes by mentally reconstructing the route's appearance using cues from landmarks and subsequently choosing the correct route to navigate and successfully arrive at their intended destination. In the context of survey knowledge, individuals with autism possess the capacity to accurately estimate directions, indicating a generally intact ability to construct cognitive maps. In further understanding, it may be stated that autistic people may encounter challenges when it comes to reconstructing routes. This could potentially result in impairments in their ability to acquire and remember route information. Additionally, if they have difficulty with representing and reconstructing cognitive maps, it is plausible that they may also have impairments in their acquisition and retention of survey knowledge (Yingying et al., 2021). Moreover, to correctly reconstruct distance while reconstructing the location map, using information from the body's relative position or remembering a sequence of distances may have been enough. Therefore, route knowledge may be significant to performing well on this step.

Meanwhile, even though the participants were given the AHSON algorithm, they did not perform well at the pointing the direction step during the pre-learning stage. Moreover, the participants made mistakes in pointing the direction because of the presence of additional landmarks or objects, and this increased the complexity. However, during the partial learning and post-learning, most people had an equally correct feeling of directions between landmarks or objects, even with the existence of new landmarks or objects. This is probably due to multiple attempts and experience with the routes and the minimal support of the AHSON algorithm, especially during partial learning. Also, during these two periods of partial learning and post-learning, the participants mostly took the shortest routes, since they could see the locations and plan the route with the help of a reconstructed location map.

During the route navigation step, this study found that most of the participants were generally good navigators, even though they had a small significant improvement on their navigation abilities during the pre-learning stage, which was likely due to the unfamiliar environment, even though they had acquired and become familiar with the map in the beginning and had fewer experiences. The constant improvement shown during partial learning and post-learning demonstrates that their good navigation abilities may be reflected in better performance on the reconstruct location map and pointing in the direction steps. The results of pointing in the appropriate direction and route selection indicate autistic participants accurately reformed (re-formation) cognitive mapping, particularly during post-learning, compared to the other two previous learning stages, which are most likely related to repetition of spatial experiences.

Furthermore, there is a possibility that the process of spatial learning was delayed due to the use of a haptic device as a navigation control (Barker, 2019; Lobo et al., 2019). Due to the complex design with limited processing capabilities, it can delay the participants' interaction between the virtual objects and also require the participants, especially non-experienced haptic device participants, to become familiar with the haptic device before completely engaging with the virtual environment (Dawei et al., 2013; Keeter, 2020; W. Wu et al., 2017). Even though these reasons can impact participants' performance in terms of spatial learning, the current result showed that the impact was detected at a low level since the time taken and distance travelled only showed a little bit higher in both pre-learning and partial learning, but in post-learning there was good improvement in terms of time taken and distance travelled. This shows that there has been improvement in terms of spatial learning at post-learning even though it's impacted the first two learning stages.

Additionally, one of the objectives of this research is to investigate the capabilities of autistic people to use egocentric and allocentric perspectives while facing the challenges of spatial learning. Even difficulties with spatial learning will be consistent with autistic people's abilities in the formation of cognitive maps (Buckley & Seery, 2016; Golledge, 1999; Johns, 2003). The emphasis placed on egocentric and allocentric representations served as the basis for the conclusion that was reached after considering the findings. According to the findings, it demonstrates that the allocentric representation used in this study is more complex than the egocentric representation. This can have an effect on the participant, leading them to select a longer route and requiring them to spend more time trying to find the object or landmark. However, applying the egocentric representation, or, to look at it another way, the formation of a self-perspective of the surrounding environment, is typically a more challenging and complicated action, particularly for autistic people. Anyhow, the fact that this study shows that allocentric representation was more difficult and complex for all of the learning stages is proven by the low significant improvement recorded for the partial learning event that the autistic participants experienced and learned during the pre-learning stage. It should come as no surprise that no differences were discovered between any of the four measures used to assess pre-learning performance from egocentric or allocentric perspectives.

Moreover, these measurements cannot be considered independent of one another, and therefore, they cannot be said to indicate a difference at this stage. In addition, the self-perspective view in the virtual environment probably makes the egocentric task more realistic with a replica of the real environment when it comes to navigating and pointing the target, and this indirectly provides autistic participants with a better opportunity to improve (Ahmadpoor & Shahab, 2019; Akamatsu et al., 1995; Bouyer et al., 2017; Steinicke et al., 2006). Furthermore, this test investigated the use of cognitive mapping formation through allocentric representation, which is a common challenge for autistic people when it comes to navigation (Carpenter et al., 2002; Cho, 2017a; Ramloll & Mowat, 2001; Wen et al., 2011). This allocentric method is dependent on the autistic participant's ability to remember, recall, and recognise landmarks or objects that are present in the environment in order to reach the object that is being targeted (Carpenter et al., 2002; Johns, 2003; H. Zhang et al., 2014a). In general, at this stage, autistic participants will attempt to move in the same absolute direction or location even if navigational support offers the suggestion of a different route, in particular the AHSON algorithm that was introduced in this research. Furthermore, the results showed that allocentric recognition of a landmark or object and adding with a new object or landmark improved significantly more at the partial learning stage than at the pre-learning stage. This was the case even though the amount of time it took to get to the target object or landmark was extended, which indirectly influenced the performance of autistic people when it came to adapting the allocentric representation.

Anyhow, in partial learning, both egocentric and allocentric skills required slightly more time than was necessary compared to the pre-learning stage, and this had an indirect impact on the ability to recognise landmarks or objects and the route travelled. It means that during partial learning, slightly the majority of autistic participants used a shortest route to travel, in contrast to pre-learning, which used a long route to travel. This was due to the participants' ability to remember and recall the object or landmark via its characteristic or attributes, and this was not an exception for a newly added object or landmark (Amon et al., 2018; Johns, 2003; Thorndyke & Hayes-Roth, 1982). The results also show that practising egocentrism was more difficult at certain points, particularly in real-world environments. This is because when the participant moved from his or her current location, the object's location or position also moved; this is unnatural and does not occur in real environments because objects or landmarks such as buildings remain in the same place in real environments (Miniaci & De Leonibus, 2018; Ramloll & Mowat, 2001).

However, both egocentric and allocentric practitioners performed well during the partial learning, which indicated that their spatial awareness in relation to the environment is sufficiently robust to perform the task. In the meantime, during the post-learning stage, both the allocentric and egocentric representations show a higher level of significant improvement in comparison to the stage of partial learning. It's possible that allocentric demands were easier to meet for autistic people than egocentric ones. It means that participants were required to walk or move around the environment and understand the objects' relations and attributes to one another. The act of mentally manipulating objects from a fixed point of view could be considered allocentric (Cho, 2017a; Johns, 2003; Wen et al., 2011). The egocentric representation, on the other hand, requires participants to understand how a self-perspective is involved in the representation of an object in an environment. Autistic people who are egocentric can imagine things from a different point of view in their surroundings. Autistic people might be capable of overcoming their challenges if they were placed in an environment with certain attributes. Allocentric and egocentric differences may have resulted from differences in the individual, the complexity of the task when newly added with an object or landmark, and also when the route tasks themselves are more complex. In addition, the application of these two types of representation in a real environment with an unfamiliar setting may result in a different level of complexity. Autistic people appear to have unaffected performance in egocentric spatial navigation, which is where they might find benefit from the AHSON direction and cognitive map clue, particularly during the pre-learning stage. On the other hand, autistic people have difficulty with allocentric spatial navigation, which is evidenced by the fact that it takes them more time to reach a targeted object while they are navigating. Furthermore, these results could be different for each individual due to memory, manipulation of spatial information, and the individual's own ability in cognitive map formation to acquire knowledge in their route or path selections. This is because memory and ability in cognitive map formation are both influenced by the individual (Cho, 2017a; Wen et al., 2011; H. Zhang et al., 2014a).

Additionally, there are three issues that should be emphasized within the context of this study. The first aspect to consider is the existence of diversity in navigational skills, which can manifest at various levels and originate from diverse sources. Proficiency in one component process does not necessarily guarantee proficiency at a subsequent level. This study revealed that a significant proportion of the participants with autism demonstrated proficiency in recalling and indicating the spatial orientations of objects within a virtual environment, particularly during the pre-learning and partial learning phases. However, they exhibited difficulties in accurately following directions and selecting the most efficient route to reach the desired object location. Consequently, this approach will mitigate the tendency to assume that actions witnessed in a single context will automatically transfer to another. In addition, this study also discovered that further exploration should be conducted to look into the complexity of navigational aspects. Further research in the field of autism has the potential to contribute to the establishment of equitable standards for behavior across autistic people. This further exploration could also yield advantages by understanding navigational research in other developmental disorders. Neuropsychological studies pertaining to topographical disorientation can contribute to the understanding of navigational impairments observed in autistic people. Finally, this study has determined that the current research has general scientific challenges that must be resolved prior to making substantial claims about navigation abilities in autistic people. The presence of diverse participant age ranges, sample characteristics, and variations in navigational and spatial learning abilities poses challenges when attempting to compare the three distinct learning stages in autistic people.

Finally, a comparative analysis was conducted to evaluate the efficacy of the HBVE application utilised in this study in improving spatial learning abilities in autistic people in comparison to five other applications. The objective was to identify the most optimal application for improving spatial learning outcomes in this population. The application known as HBVE exhibited a notable improvement in enhancing spatial knowledge, as evidenced by its better performance. However, it is important to consider that this comparison may be influenced by other factors, including variations in the number of participants, age groups, and types of tasks involved. Furthermore, it is imperative for the HBVE application to consider additional variables in subsequent analyses, such as the inclusion of new objects or landmarks, the assessment of distance estimation, and the selection of optimal routes. These considerations will enable a more comprehensive evaluation of the HBVE application's efficacy in enhancing spatial cognition among autistic people relative to alternative applications. In general, the HBVE application, developed according to the proposed HBVE-Framework in this study, demonstrates effective performance in enhancing spatial knowledge among autistic people, as shown by the conducted comparison with other applications.

6.8 Summary

This chapter introduced a novel HBVE application developed to assist autistic people develop or improve their spatial learning and cognitive mapping skills. This chapter begins by developing an HBVE application based on the proposed HBVE-framework and taking into account the suggested components from the case study conducted with the expert group. The developed HBVE application was then used to evaluate the effectiveness of the application with a haptic interface in five different aspects. The first aspect is to assess the acceptance of the proposed application by an expert's group with the modified heuristic evaluation according to this research domain. According to the results of this assessment, the majority of the experts agreed with all of the features and elements used in the proposed application.

Meanwhile, the following aspect is to assess the effectiveness of the AHSON algorithm as a navigational support element for autistic people in finding the direction of the targeted objects or landmarks without getting lost during navigation. Two different methods are used to evaluate the proposed algorithm. The first comes from the performance of autistic people in terms of wayfinding with and without the AHSON algorithm. The second method is based on the signal generated by autistic people while they are determining their direction, which is studied in two different positions: pitch and yaw. Both methods showed positive significance and correlation, indicating that using the AHSON algorithm improved wayfinding in autistic people without getting lost in direction.

The next aspect is to assess the efficacy of haptic feedback in autistic people by using vibration to provide a sense of touch during interaction with virtual objects. This assessment was carried out using two distinct methods. The first method is based on individual perception and employs two types of sensory profiles (SSP2 and ASSP) to investigate the individual's behavioural responses during haptic interaction with virtual objects. Meanwhile, the second method is based on touch sensory patterns and employs signals generated by both the 9-axis IMU sensors and the haptic device's EMG sensors. The results of both methods revealed that touch sensitivity and haptic feedback were present in autistic people during interaction with virtual objects via haptic devices.

The next aspect is to assess the efficacy of real-time rendering interaction in the HBVE application among autistic people. This assessment was based on three different testbeds that used the haptic interaction taxonomy: navigation and object interaction, selection and manipulation, and detection of stiffness. During this assessment, all the external aspects, such as user and environmental factors, have been taken into consideration. The findings are organised into three stages: pre-learning (baseline), partial-learning (intervention), and post-learning (maintenance). The findings revealed that when compared to traditional communication or physical virtual control (mouse and keyboard) interaction methods, people dramatically improved their interaction with HBVE via haptic virtual control (haptic interface) until they reached a mature level, resulting in more realistic interaction and manipulation with virtual objects.

Finally, the effectiveness of haptic technology in assisting autistic people by improving their spatial learning and cognitive mapping skills is being assessed. This assessment is based on two types of tasks: cognitive mapping and spatial awareness. Similar to the previous aspects of evaluation, this aspect also analysed and presented results based on three different stages: pre-learning, partial-learning, and post-learning, which showed dramatically improved results from each of the stages until the participants showed the full range of gained skills. Overall, with the addition of haptic feedback as a sense of touch, this HBVE application can be used to develop or improve spatial awareness and cognitive mapping skills in autistic people.

CHAPTER 7: CONCLUSION

This research focuses on subjects that are related to real-time interaction through HBVE with autistic people in terms of developing spatial knowledge and cognitive skills. This research investigates the issues related to the design of HBVE applications from the perspective of haptic modality (haptic feedback) as a sense of touch and for identifying objects, and from the perspective of using haptic interface (device) as technology to obtain spatial knowledge and cognitive skills among autistic people. This chapter presents a restatement of the research problem and follows with research objectives to explain the purpose of this research. Meanwhile, in the following sections, this research focuses on the research contribution, the implications of the research, the limitations of the research, and at the end of the section, it presents the future direction of this research.

7.1 Restatement of the Research Objective

This section provides the restatement of the research objective that was stated in the previous section by reviewing the outcomes of each study carried out.

7.1.1 Research Objective 1: *To investigate elements related to autism, spatial cognitive mapping skills and haptic interaction that constitute a haptic based spatial learning environment for autistic people to create their spatial awareness.*

This chapter sets out to investigate the elements related to autism, spatial cognition mapping, and haptic interaction (haptic sensation and modality) that induce a HBVE in autistic people to develop and improve their spatial awareness and learning skills. The investigation is guided by a systematic review (SLR), which is then followed by a narrative or traditional literature review.

7.1.2 Research Objective 2: *To construct a new algorithm-design-framework based on haptic technology and spatial learning and cognitive mapping elements.*

This objective describes the process of construction of a new autonomous algorithm for spatial orientation and navigation for autistic people based on haptic technology (haptic sensor) and spatial cognition mapping elements. This algorithm is proposed to solve the difficulties faced by autistic people during navigation in HBVE: sensory acquisition in the HBVE (lost the sensors during navigation through haptic sensors), and the issue with the inability of autistic people to understand their surroundings during navigation in an unfamiliar VE due to their impairment in the formation of mental maps of new or unfamiliar HBVE. Due to these difficulties, this chapter implemented an autonomous algorithm based on the spatial orientation and navigation concept, where it's able to guide and move independently and acquire spatial knowledge by identifying objects and obstacles in the HBVE with the haptic technology (sensors) assistive. An experimental evaluation was conducted to determine the significance of the proposed algorithm and how well the difficulties faced by autistic people during the navigation process in the HBVE application are addressed. The findings show that the proposed algorithm is able to process and transfer the IMU sensors within eclipse zone circulations by calculating the angular position, accelerometer, and velocity of the autistic people during the navigation in HBVE with the combination of landmarks or objects' attributes data as a cognitive map to identify objects or landmarks to reach their desired location. Overall, this proposed algorithm achieved the fundamental requirements of the design by resolving the difficulties faced by autistic people during the navigation in HBVE, even though this proposed algorithm was imperfect in terms of time to complete the assigned tasks in HBVE by comparing within the expected timing.

7.1.3 Research Objective 3: *To develop a simulation of a real-time haptic technology environment to demonstrate the logical view of the proposed algorithm-design-framework.*

This objective is intended to design and develop a simulation of a real-time HBVE for autistic people. This proposed simulation was developed based on the component that was identified during the component identification process. The proposed simulation was evaluated using an applicability test to discover the usability problem and make adjustments to the current HBVE application to address the identified problem. The existing set of applicability dimensions were adjusted in accordance with this research objective and were utilised to conduct the evaluation in order to improve the simulation.

7.1.4 Research Objective 4: *To conduct an experimental study to analyze spatial awareness and cognitive mapping skills among autistic people in the proposed real-time haptic technology environment.*

This objective was achieved based on performing experimental evaluations. Four different types of experimental evaluations have been conducted in order to determine the effectiveness of the proposed simulation in improving spatial learning and cognitive mapping skills among autistic people through haptic devices. This study began with an evaluation of the proposed autonomous algorithm to determine whether or not it is capable of assisting a autistic people in reaching the desired location. The second experimental evaluation was conducted to determine the presence of touch sensation in autistic people, and it was carried out on the basis of analysing their behavioural responses (Sensory Profile – SSP) and touch sensory patterns (Adolescent/Adult Sensory Profile – AASP). Whereas, a third experimental evaluation was initiated to determine whether haptic devices are effective in terms of real-time interaction with the virtual environment by adopting a set of different taxonomic levels of haptic interaction. An evaluation of how haptic technology can assist in the improvement of spatial learning and cognitive mapping skills among autistic people was conducted as a final experimental evaluation in this research. After conducting an experimental evaluation, it was determined that using haptic devices, autistic people experienced significant improvements in terms of spatial learning and cognitive mapping skills.

7.2 Restatement of the Research Question

This section provides the restatement of the research question that was stated in the previous section by reviewing the outcomes of each study carried out.

7.2.1 Research Question 1: *What is the fundamental understanding of autistic people and their spatial knowledge and cognitive mapping?*

This research question was based on the first objective of this research, and it demonstrated how autistic people can be defined or manifest in various ways, such as anomalies in social interaction or communication or uneven cognitive capacities, through a review of relevant narrative-based literature on autistic people and the fundamental principles of spatial learning and cognitive mapping and their differences. Furthermore, a literature review provides information on the most common indications and symptoms of autism experienced by both children and adults. Additionally, it provides knowledge about the concepts of spatial learning and cognitive mapping. Also highlighted was the use of haptic modalities as instructional approaches for the development of spatial cognition in autistic people. All of these inquiries were thoroughly detailed in chapters 2, 3, and 4.

7.2.2 Research Question 2: *What role does haptic technology play in the development of haptic-based virtual environments for learning purpose?*

Furthermore, as noted in 7.2.1, this research question was narrowed based on the first research objective, with a focus on the element of haptic interaction. The study also looks at how haptic technology played a role in the HBVE application for learning purposes.

Furthermore, this study highlighted the various applications of haptic technology that can be found in modern practise. The type of haptic interface that has been used in the past or is currently being used in an HBVE application is also highlighted, such as the MYO Armband, which can be used as a low-cost haptic interface for interaction. Furthermore, the most effective haptic interface among those defined was also defined for the purpose of promoting spatial learning for people with autism. This study also highlighted the various real-time haptic rendering interaction techniques available, such as the virtual hand and virtual pointer, for user interaction and manipulation, as well as the most effective in terms of spatial awareness and learning. Furthermore, the narrative review emphasised which taxonomies of haptic interaction tasks are used in HBVE applications such as motor control and perception, which are currently used or designed in accordance with interaction techniques such as navigation, selection, and manipulation in this thesis. It was also mentioned which taxonomy is preferable for teaching spatial awareness to autistic people. This study also sought to investigate the relationship between the virtual environment and haptic technology, as well as how they interact. Essentially, this was demonstrated through research into the availability of different types of virtual reality systems, such as immersive and non-immersive environments for haptic interaction. Because non-immersive environments are more comfortable and adaptable for autistic people, this study also used a non-immersive based environment for haptic interaction. This study also included a systematic review of sensory modalities in autistic people. The systematic review focused on what causes this haptic sensory modality impairment in autistic people as well as whether the haptic interface delivered via virtual environments helps autistic people perform more efficiently.

7.2.3 Research Question 3: *How would the autonomous assistive algorithm assist autistic people with wayfinding in HBVE?*

This research question was specified to underline the second objective of this research. This study aims to propose and construct a new algorithm as a component of the proposed HBVE-Framework to assist autistic people with navigation in HBVE applications. Based on the quantitative analysis of participant performance and the generated signal pattern analysis of the effectiveness of the proposed AHSON algorithm, it is possible to conclude that this AHSON algorithm assists participants in moving autonomously across virtual environments using haptic sensors and enables participants to re-orient their navigation route in a virtual environment to reach their desired location or object. Furthermore, a positive correlation has been identified between the existence of the AHSON algorithm and wayfinding performance, particularly in terms of the number of objects identified and the time required to reach the targeted object. Furthermore, the comparison results between the AHSON algorithm and other algorithms show that the AHSON algorithm performs better in terms of avoiding disorientation during wayfinding. These were organised in this research's chapters 4 and 5.

7.2.4 Research Question 4: *How were the main and sub-components effectively identified and organised in the model structure and also usable to design the HBVE application?*

This research question was developed or specified in order to fulfil the third objective, which was discussed in Chapter 6. In terms of the proposed HBVE-Framework, this research came to the conclusion that only relevant components were found and included after multiple filtering through expert responses. This was done to meet the main goal of this thesis, and adding a newly formed component as the AHSON algorithm gave this HBVE-Framework an extra advantage that made it better than other similar frameworks. The use of an MVC-based framework structure that is completely relevant to this thesis's objective, as well as its acceptance by the majority of experts in this thesis. Furthermore, the experts agreed that the inclusion of all of the framework's components and structure meets the requirements of ISO/IEC 25010 and the criteria's expectations. Furthermore, the selected components successfully produced an HBVE application for this thesis in order to conduct a relevant experimental evaluation in order to meet the research objective. The experts also acknowledged that the proposed HBVE-Framework can be used as a guideline to develop an HBVE application for autistic people to improve their spatial learning and cognitive mapping skills.

7.2.5 Research Question 5: *How does a simulation of a haptic based virtual environment developed and tested?*

This research question was focused on meeting the third objective, as stated in 7.2.4, and it was also discussed in Chapter 6. The goal of this study was also to develop a simulation of a real-time haptic technology environment in order to demonstrate the logical view of the proposed algorithm and the HBVE-Framework. This thesis accomplished its goal by developing an HBVE application based on the components suggested by the HBVE-Framework usability and expert evaluation. The application was built around three distinct modules: the pattern of the controller, the pattern of the view, and the pattern of the model. Furthermore, the newly improved components such as "Data Repository" and the proposed AHSON algorithm component are implemented at respective patterns in the application development. Furthermore, the developed HBVE application was tested at two levels: unit testing, integration testing, system testing, and usability testing to demonstrate that it met the requirements and performed better than other similar applications. All of the testing results demonstrated that this HBVE application addressed the proposed framework component objectives.

7.2.6 Research Question 6: *Does the use of haptic technology improve spatial learning and cognitive mapping skills via HBVE among autistic people?*

Finally, in order to meet the fourth objective, this research question was formulated, which was discussed in Chapter 6. A part of the experimental evaluation of the AHSON algorithm with autistic people revealed that the proposed algorithm improved autistic people's abilities in finding the targeted location or object. In the meantime, multiple experimental evaluations were carried out in this study to determine the effectiveness of haptic technology in improving spatial learning and cognitive mapping skills among autistic people using the developed HBVE application. The use of a haptic device to create or improve a haptic sensory sensation among autistic people during interaction with virtual objects was evaluated at the start of the experimental evaluation. This evaluation also demonstrated that the outcome of this evaluation demonstrated an optimistic significant sensation-based signal detection for autistic people. In addition to this experimental evaluation, real-time rendering interactions with virtual objects produced satisfactory and improved results in autistic people. Finally, this study found that the HBVE application improves spatial learning and cognitive mapping skills among autistic people from the baseline to the maintenance stage.

7.3 Research Contributions

The results demonstrate that the proposed HBVE-Framework has progressed into a reference framework structure for choosing the optimum component to build an HBVE application, and that this will enable us to produce a better version of the HBVE application in the future. Subsequent research revealed that the primary goal of this research was attained through the development of an HBVE application to improve spatial learning and cognitive skills in autistic people. This research also introduced an autonomous algorithm to assist autistic people in identifying the right direction to reach their desired target without losing their orientation. Moreover, based on experimental evaluation, it has been shown that, in addition to improving spatial awareness and cognitive skills, haptic technology can also improve tactile sensory information among autistic people while interacting with virtual objects.

7.4 Discussion of Findings in Relation to Current Concerns and Challenges

Based on the findings of this research, the following concerns and challenges have been identified:

7.4.1 Contextualization of the Findings

This research investigated the efficacy of haptic-based virtual environments (HBVE) in enhancing spatial learning and cognitive mapping in HFA autistic people, aged 9 to 27 years. The study included participants from urban areas in Selangor and Negeri Sembilan, Malaysia, with a male-to-female ratio of 4:1. The purpose of the research was to examine and determine the potential benefits of haptic feedback in relation to navigation, sensory processing, interaction, and support in exploring spatial information.

7.4.2 The Comparison with Smith's Research

Smith offers a crucial viewpoint regarding the difficulties faced in research concerning autistic people, with a specific emphasis on the necessity for diverse samples of participants (Smith, 2015). This research aligns with the author's concerns about the disparities in the quality and quantity of participants, as well as the potential risks of overgeneralizing solutions too broadly to autistic people (Smith, 2015).

7.4.3 Addressing the Issue of Inconsistent Participant Quality and Quantity

This study specifically examined individuals with HFA and addressed the difficulties mentioned by Smith regarding the inconsistency in participant quality. By limiting the sample to high-functioning individuals and focusing on urban areas in Selangor and Negeri Sembilan, Malaysia, this research may not provide a comprehensive understanding of the spatial learning abilities and challenges that exist among the larger autistic population. This issue highlights Smith's criticism that research focused on technology interventions for autism generally lacks varied and representative samples (Smith, 2015). As a result, the findings may not fully reflect the needs of all autistic people.

7.4.4 Concerns about Over-generalization

In addition to Smith's concern, there is a significant risk of forming broad generalizations about the efficacy of haptic technology based on our research findings. Although this research observed enhancements in spatial learning across the participants in its experiments, it would be erroneous to extrapolate these findings to imply a consistent advantage across all environments and subgroups within the autism spectrum. The author advocates for a logical viewpoint, suggesting that behaviours observed in a particular environment or subgroup of autistic people should not be automatically believed to be applicable to the entire autism spectrum.

Therefore, future research is necessary to address these issues, and this will be elaborated on in the section on future research directions.

7.5 Extended Considerations of Research Limitations

Based on the findings of this research, the following limitations have been identified as requiring special attention in future development:

7.5.1 Training Environment

This research has concentrated on the outdoor urban environment, perhaps as a training environment to practise and improve their spatial learning and cognitive skills, and it has not taken into consideration the indoor environment as a training environment.

7.5.2 Specialized for Autistic people

The proposed HBVE application was developed with the goal of improving spatial learning and cognitive skills in autistic people, as well as developing touch sensory information for autistic people who have deficits in touch and intend to feel the virtual object during the interaction. So, the suggested HBVE application is limited to autistic people who need to enhance their spatial learning and cognitive mapping skills while also experiencing the feeling of touching virtual objects throughout their interactions with it.

7.5.3 Single hand interaction and Manipulation

The research was carried out using a single MYO armband wearable device, which limited the degree of freedom for control during the interaction with virtual objects. Furthermore, autistic people must be forced to move their forearm (from the current haptic position) in different directions according to the activities or commands. This has the potential to have significant consequences for the ergonomics of interacting with the proposed HBVE application.

7.6 Future Research Directions

This research was carried out with the purpose of enhancing spatial awareness and haptic sensations in autistic people. Experiments have demonstrated that the use of wearable haptic devices can assist autistic people in processing spatial information in their surroundings, particularly during virtual environment navigation. Meanwhile, haptic feedback provides a sensory sensation for autistic people, allowing him or her to feel the virtual object while interacting with it or performing manipulation tasks. In order to achieve greater effectiveness among autistic people, it is recommended that further research be conducted using a combination of different types of sensory feedback, such as visual feedback and audio feedback, in addition to haptic feedback in haptic technology and spatial cognition implementation. Furthermore, the tasks that were engaged during the spatial visualisation and rotation tests, such as the object force pushing interaction task, were made less difficult to accomplish. Therefore, it is suggested that more complicated interaction and manipulation tasks be devised for participants. This research only looked at vibrotactile feedback, but there are many other types of haptic feedback available, such as electrotactile feedback, ultrasound tactile feedback, and thermal feedback, which can benefit both parties by allowing autistic people to experiment with different technology in terms of receiving sensory feedback, or by allowing experts or researchers to better understand how autistic people perceive different types of sensory feedback and how it can enhance their spatial awareness in a more efficient way. This study concentrated on egocentric and ecocentric metaphors for interaction and manipulation, which covered those sub-components that were common and widely used in HBVE development but left out some important sub-components, such as automatic scaling. Consequently, this research can be further improved by investigating how those ignored sub-components of metaphor can improve the performance of autistic people while they are dealing with complex tasks such as hole-peg tasks. In a real-environment situation, immersive virtual environment (IVE) technology is a significant and effective tool for studying people's perspectives. The outcomes of this investigation could thus be advanced by conducting experiments with immersive technology, which would provide autistic people with an intense feeling of being present in an IVE that is comparable to a real-environment setting. Apart from this, there are several designed haptic devices with a degree of freedom (DOF), such as the Phantom Omni, Novint Falcon, and Force Dimension Sigma 7, that are incorporated with high detection of tactile sensors to measure forces applied by autistic people during interaction with a virtual environment. Therefore, in addition to utilising the low cost of the MYO armband haptic device, this research can be evaluated by using other sets of haptic devices as a mediated communication platform to highlight undiscovered benefits in terms of executing more complex interaction and manipulation tasks while at the same time improving spatial learning and cognitive skills among autistic people. Furthermore, in accordance with the perspective presented by the author Smith, it is recommended that this study broaden its sample to encompass a broader range of autism spectrum disorders, levels of intellectual functioning, and geographic regions (Smith, 2015). Despite the fact that this research has concentrated on the urban environment as a training environment for autistic people to practise and improve their spatial learning, it has only addressed the outdoor environment and neglected the indoor environment, where autistic people must practise and become familiar with the indoor environment in order to be safer from any unwanted incidents. Therefore, this research must improve and develop the current HBVE application in order to increase the awareness of autistic people about their surroundings.

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