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VR systems for memory assessment and depth perception

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I dedicate this work to my darling daughter Doménica, who is the sweetest and most loving being that God has given me. Darling daughter, I want you to know that you are and will be forever my life. You have been strength and motivation to achieve the goals raised. I will always be there to support you in difficult times, and also to share your joys and triumphs. I hope and wish that your world will be limited only by your imagination, creativity, and perseverance. God bless you always with health and happiness.

With love for you, Mom!

Abstract

The evolution of Virtual Reality (VR) technology has contributed in all fields, including psychology. This evolution involves improvements in hardware and software allowing more immersive experiences. In a VR environment users can perceive the sensation of "presence" and feel "immersed". These sensations are possible using VR devices as Head-Mounted Displays (HMDs). Nowadays, the development of the HMDs has focused on improving their technical features to offer full immersion in VR environments.

In psychology, VR environments are regarded as a research tool because they allow the use of a range of new paradigms that are not possible to employ in a real environment. There are some applications for assessing spatial memory that use basic methods of human-computer interaction. However, VR systems that incorporate stereoscopy and physical movement have not yet been exploited in psychology.

In this thesis, a novel VR system combining immersive, interactive and motion features was developed. This system was used for the assessment of the spatial memory and the evaluation of depth perception. For this system, a virtual maze task was designed and implemented. The cognitive task comprised three phases: habituation, learning, and testing. In this system, two different types of interaction were also integrated: a locomotion-based interaction pedaling a fixed bicycle (active physical condition), and a stationary interaction using a gamepad (inactive physical condition). This system also integrated two types of display systems. One of them used the Oculus Rift-DK2 HMD, which provides full immersion, tracking system and visualization technology based on motion cues. The other used a large stereo screen, which allows the projection of the virtual environment onto a big rear-projection stereoscopic screen, and participants can view the 3D by wearing a pair of polarized glasses.

Two studies were designed to determine the efficacy of the VR system using physical movement and immersion regard to the cognitive task performance, ease of use, interaction types, satisfaction, and their 3D perceptions between two display systems.

The first study assessed the spatial short-term memory using Oculus Rift-

DK2 HMD and two types of interaction: active physical condition and inactive physical condition. A total of 89 adults between 20 and 35 years old participated in this study. From the results, we observed that there were statistically significant differences between both conditions. The participants who performed the inactive physical condition got better performance than participants who performed the active physical condition. However, there were no statistically significant differences in satisfaction and interaction scores between both conditions. The performance on the task correlated with the performance on other classical neuropsychological tests, revealing a verisimilitude between them.

The second study involved participants who had and who had not stereopsis. The Lang Stereotest was used to check stereopsis. This study assessed the depth perception by comparing two display systems (Oculus Rift-DK2 and large stereo screen). A total of 59 adults between 23 and 30 years old participated in the study. The participants performed the task using the inactive physical condition. The results showed that the different features of the display system did not influence the performance on the task between the participants with and without stereopsis. Statistically significant differences were found in favor of the HMD between the two conditions and between the two groups of participants regard to depth perception. The participants who did not have stereopsis and could not perceive the depth when they used other display systems (e.g. CAVE or autostereoscopic screens) and when they were checked with the Lang Stereotest; however, they had the illusion of depth perception when they used the Oculus Rift-DK2 HMD. The study suggests that for the people who did not have stereopsis, the head tracking largely influences the 3D experience.

The statistical results of both studies have proven that the VR system developed for this research is an appropriate tool to assess the spatial short-term memory and the depth perception. Therefore, the VR systems that combine full immersion, interaction and movement can be a helpful tool for the assessment of human cognitive processes as the memory.

General conclusions from these studies have been extracted:

- The VR technology and immersion provided by current HMDs as the Oculus Rift-DK2 are appropriate tools for psychological applications, in particular, the assessment of spatial short-term memory.
- A VR system like the one presented in this thesis could be used as a tool to assess or train adults in skills related to spatial short-term memory.

- The two types of interaction (active physical condition and inactive physical condition) used for navigation within the virtual maze could be helpful to use with different collectives.

- The Oculus Rift-DK2 HMD allows that the users without stereopsis can perceive the depth perception of 3D objects and have rich 3D experiences.

Resumen

La evolución de la tecnología de Realidad Virtual (RV) ha contribuido en todos los campos, incluyendo la psicología. Esta evolución implica mejoras tanto en hardware como en software, que permiten experiencias más inmersivas. En un entorno de RV los usuarios pueden percibir la sensación de "presencia" y sentirse "inmersos". Estas sensaciones son posibles utilizando dispositivos de RV como los cascos de realidad virtual (HMDs). Hoy en día, el desarrollo de los HMDs se ha centrado en mejorar sus características técnicas para ofrecer inmersión total en entornos de RV.

En psicología, los entornos de RV se consideran una herramienta de investigación porque permiten el uso de nuevos paradigmas que no son posibles en un entorno real. Hay algunas aplicaciones para evaluar la memoria espacial que utilizan métodos básicos de interacción. Sin embargo, sistemas de RV que incorporen estereoscopía y movimiento físico todavía no se han explotado en psicología.

En esta tesis, se ha desarrollado un nuevo sistema de RV que combina características inmersivas, interactivas y de movimiento. El sistema de RV se ha utilizado para la evaluación de la memoria espacial y la evaluación de la percepción de profundidad. Para este sistema, se diseñó e implementó una tarea en un laberinto virtual. La tarea cognitiva constó de tres fases: habituación, aprendizaje y prueba. En este sistema también se integraron dos tipos diferentes de interacción: una basada en locomoción que consistió en pedalear en una bicicleta fija (condición física activa) y otra estacionaria usando un gamepad (condición física inactiva). Este sistema también integró dos tipos de visualización. Uno de ellos usó el Oculus Rift-DK2 HMD, que proporciona inmersión completa, sistema de seguimiento y tecnología de visualización basada en señales de movimiento. El otro utiliza una gran pantalla estéreo, que permite proyectar el entorno virtual sobre la misma, utilizando para ello proyección trasera, y los participantes pueden ver el 3D usando un par de gafas polarizadas.

Se diseñaron dos estudios para determinar la eficacia del sistema de RV utilizando movimiento físico e inmersión en relación con el rendimiento de la tarea cognitiva, la facilidad de uso, los tipos de interacción, la satisfacción y sus percepciones 3D entre los dos sistemas de visualización.

El primer estudio evaluó la memoria espacial a corto plazo usando un Oculus Rift-DK2 HMD y dos tipos de interacción: condición física activa y condición física inactiva. Participaron en el estudio un total de 89 adultos entre 20 y 35 años. A partir de los resultados, se observó que existían diferencias estadísticamente significativas entre ambas condiciones. Los participantes que utilizaron la condición física inactiva obtuvieron mejor rendimiento que los que utilizaron la tarea en la condición física activa. Sin embargo, no se encontraron diferencias estadísticamente significativas en las puntuaciones de satisfacción e interacción entre ambas condiciones. El desempeño en la tarea correlacionó con el desempeño en las pruebas neuropsicológicas clásicas, revelando la verosimilitud entre ellas.

El segundo estudio incluyó participantes con y sin estereopsis. Se utilizó el Estereotest de Lang para comprobar la estereopsis. Este estudio evaluó la percepción de profundidad comparando dos sistemas de visualización (Oculus Rift-DK2 y gran pantalla estéreo). Un total de 59 adultos de entre 23 y 30 años participaron en el estudio. Los participantes realizaron la tarea usando la condición física inactiva. Los resultados mostraron que las diferentes características del sistema de visualización no influyeron en el rendimiento en la tarea entre los participantes con y sin estereopsis. Se encontraron diferencias estadísticamente significativas a favor del HMD entre las dos condiciones y entre los dos grupos de participantes respecto a la percepción de profundidad. Los participantes que no tenían estereopsis y no podían percibir la profundidad cuando utilizaban otros sistemas de visualización (por ejemplo, CAVE o pantallas auto-estereoscópicas) y tampoco cuando fueron evaluados con el Estereotest de Lang; sin embargo, dichos participantes tuvieron la ilusión de percepción de profundidad cuando utilizaron el Oculus Rift-DK2 HMD. El estudio sugiere que para las personas que no tienen estereopsis, el seguimiento de la cabeza influye en gran medida en la experiencia 3D.

Los resultados estadísticos de ambos estudios han demostrado que el sistema de RV desarrollado para esta tesis es una herramienta apropiada para evaluar la memoria espacial a corto plazo y la percepción de profundidad. Por lo tanto, los sistemas de RV que combinan inmersión total, interacción y movimiento pueden ser una herramienta útil para la evaluación de procesos cognitivos humanos como la memoria.

De estos estudios se han extraído las siguientes conclusiones generales:

- La tecnología de RV y la inmersión proporcionada por los actuales HMDs como el Oculus Rift-DK2 son herramientas adecuadas para aplicaciones

psicológicas, en particular, la evaluación de la memoria espacial a corto plazo.

- Un sistema de RV como el presentado en esta tesis podría ser utilizado como herramienta para evaluar o entrenar adultos en habilidades relacionadas con la memoria espacial a corto plazo.
- Los dos tipos de interacción (condición física activa y condición física inactiva) utilizados para la navegación en el laberinto virtual podrían ser útiles para su uso con diferentes colectivos.
- El Oculus Rift-DK2 HMD permite que los usuarios sin estereopsis puedan percibir la percepción de profundidad de objetos 3D y tener ricas experiencias 3D.

Resum

L'evolució de la tecnologia de Realitat Virtual (RV) ha contribuït en tots els camps, incloent la psicologia. Aquesta evolució implica millores en el maquinari i el programari que permeten experiències més immersives. En un entorn de RV, els usuaris poden percebre la sensació de "presència" i sentir-se "immersos". Aquestes sensacions són possibles utilitzant dispositius de RV com els cascos de realitat virtual (HMDs). Avui dia, el desenvolupament dels HMDs s'ha centrat a millorar les seves característiques tècniques per oferir immersió plena en entorns de RV.

En la psicologia, els entorns de RV es consideren com eines de recerca perquè permeten l'ús d'una gamma de nous paradigmes que no es possible emprar en un entorn real. Hi ha algunes aplicacions per avaluar la memòria espacial que utilitzen mètodes bàsics d'interacció. Tanmateix, sistemes de RV que incorporen estereoscòpia i moviment físic no s'han explotat en psicologia.

En aquesta tesi, s'ha desenvolupat un sistema de RV novell que combina immersiò, interacciò i moviment. El sistema s'ha utilitzat per a l'avaluació de la memòria espacial i l'avaluació de percepció de profunditat. Per aquest sistema, s'ha dissenyat i implementat una tasca en un laberint virtual. La tasca cognitiva va comprendre tres fases: habituació, aprenentatge, i prova. En aquest sistema, dos tipus diferents d'interacció s'han integrat: una interacció basada en locomoció pedalejant una bicicleta fixa (condició física activa), i l'altra una interacció estacionària usant un gamepad (condició física inactiva). Aquest sistema també va integrar dos tipus de sistemes de pantalla. Un d'ells va utilitzar l'Oculus Rift-DK2 HMD, el qual proporciona immersió plena, sistema de seguiment i tecnologia de visualització basada en senyals de moviment. L'altre va utilitzar una gran pantalla estereoscòpica, la qual permet la projecció de l'entorn virtual, i els participants poden veure portant unes ulleres polaritzades.

Dos estudis van ser dissenyats per determinar l'eficàcia del sistema de RV que utilitza immersió i moviment físic en relació amb el rendiment de la tasca cognitiva, facilitat d'ús, tipus d'interacció, satisfacció, i les percepcions 3D entre els dos sistemes de pantalla.

El primer estudi va avaluar la memoria a curt termini i espacial utilitzant un Oculus Rift-DK2 HMD i dos tipus d'interacció: condició física activa i condició física inactiva. Un total de 89 adults entre 20 i 35 anys van participar en aquest estudi. Dels resultats, vam observar que hi havia diferències estadísticament significatives entre les dues condicions. Els participants que van utilitzar la condició física inactiva van obtenir millor rendiment que els participants que van utilitzar la condició física activa. Tanmateix, no hi havia diferències estadísticament significatives dins satisfacció i puntuacions d'interacció entre les dues condicions. El rendiment de la tasca va correlacionar amb el rendiment en les proves neuropsicològiques clàssiques, revelant verosimilitud entre elles.

El segon estudi va implicar participants que van tenir i que van haver-hi no estereopsis. L'estèreo test de Lang va ser usat per a verificar la estereopsis. Aquest estudi va avaluar la percepció de profunditat comparant dos sistemes de pantalla (un Oculus Rift-DK2 i una gran pantalla estèreo). Un total de 59 adults entre 23 i 30 anys van participar en l'estudi. Els participants realitzen la tasca utilitzant la condició física inactiva. Els resultats van mostrar que les diferents característiques del sistema de pantalla no va influir en el rendiment en la tasca entre els participants qui tenien i els qui no tenien estereopsis. Diferències estadísticament significatives van ser trobades a favor del HMD entre les dues condicions i entre els dos grups de participants. Els participants que no van tenir estereopsis i no podien percebre la profunditat quan van utilitzar altres sistemes de pantalla (per example CAVE o pantalles autostereoscòpiques) i quan van ser avaluats amb l'estèreo test de Lang; tanmateix, van tenir la il·lusió de percepció de profunditat quan van utilitzar l'Oculus Rift-DK2 HMD. L'estudi suggereix que per les persones que no van tenir estereopsis, el seguiment del cap influeix en gran mesura en l'experiència 3D.

Els resultats estadístics dels dos estudis han provat que el sistema de RV desenvolupat per aquesta recerca és una eina apropiada per avaluar la memoria espacial a curt termini i la percepció de profunditat. Per això, els sistemes de RV que combinen immersió plena, interacció i moviment poden ser una eina útil per la avaluació de processos cognitius humans com la memòria

Les conclusions generals que s'han extret d'aquests estudis, són les següents:

- La tecnologia de RV i la immersió proporcionada pels HMDs com l'Oculus Rift-DK2 són eines apropiades per aplicacions psicològiques, en particular, la avaluació de memoria espacial a curt termini.
- Un sistema de RV com el presentat en aquesta tesi podria ser utilitzat com a eina per avaluar o entrenar adults en habilitats relacionades amb la memoria espacial a curt termini.

- Els dos tipus d'interacció (condició física activa i condició física inactiva) utilitzats per navegació dins del laberint virtual podrien ser útils per al seu ús amb diferent collectius.
- L'Oculus Rift-DK2 HMD permet que els usuaris que no tenen estereopsis puguen percebre la percepció de profunditat dels objectes 3D i tenir riques experiències 3D.

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Eternally grateful. God's blessings!

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Definitions and Acronyms

In this thesis, several technical terms have been used. The list of definitions and acronyms is in alphabetical order.

Head-Mounted Display (HMD): is a display device that can be worn on the user's head, provided with one or two optical displays in correspondence of one or two eyes and a head-tracking system (Saggio and Ferrari 2012; Velger 1998).

Human-Computer Interaction (HCI): is a discipline that studies how the people interact with computers, and it is concerned with the design, evaluation, and implementation of interactive computer systems so the user can carry out activities productively and safely (Preece and Rombach 1994; Sharma 2016).

Immersion: is a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences (Witmer and Singer 1998).

Latency: is the time delay between action and result. In the case of the 3D tracker, latency is the time between the change in object position/orientation and the time the sensor detects this change (Burdea and Coiffet 2003).

Locomotion: means of travel restricted to self-propulsion. Motion interfaces can be subdivided into those for passive transport (inertial and non-inertial displays) and those for active transport (locomotion interfaces) (Blade and Padgett 2002).

Presence: is a subjective phenomenon such as the sensation of being in a virtual environment (Slater and Wilbur 1997).

Stereopsis: refers to the depth perception through visual information that is obtained from the two eyes of an individual with normally developed binocular vision (Howard and Rogers 1995).

Short-term Memory: is a structural model of memory that allows retaining the information for a short time until that information is processed and becomes part of a more durable memory, which is called long-term memory (Baddeley and Hitch 1974).

Traditional Methods: refer to the set of classical psychological tests used in this thesis, which focus on understand the person's cognitive status.

Virtual Environment (VE): model of reality with which a human can interact, getting information from the model by ordinary human senses such as sight, sound, and touch and/or controlling the model using ordinary human actions such as position and/or motion of body parts and voice. Usually virtual environment and virtual reality are used synonymously, but some authors reserve VE for an artificial environment that the user interacts with (Hale and Stanney 2014).

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1

Introduction

> *"We all have dreams. But in order to make dreams come into reality, it takes an awful lot of determination, dedication, self-discipline, and effort."*
>
> Jesse Owens

This chapter aims at guiding the reader through the contents of this document. Thus, section 1.1 presents the motivation that has originated this thesis. Section 1.2 shows the main objectives of the thesis, and section 1.3 shows a guide about the organization of this thesis.

1.1 Motivation

The advances in technology have opened up new opportunities for the development of applications for a broad range of domains to solve real-world problems. Interactive technologies, and notably Virtual Reality (VR) have achieved a significant development of many applications which have been helpful in different fields. According to some experts, VR has the potential to become one of the top breakthrough technologies of the next decade (The Farm 51 2015; Markets and Markets 2016). The VR market is expected to grow from USD 1.37 billions in 2015 to USD 33.90 billions in 2022, with an annual growth rate of 57.84% between 2016 and 2022 (Markets and Markets 2016). Several studies on VR have explored the creation of different environments which aim to provide participants the sense of "presence", which can be described as immersion and intuitive interaction (Bowman, Gabbard, and Hix 2002; Chertoff, Goldiez, and LaViola 2010).

For providing an immersive visual effect, various stereoscopic display systems have already been used: Head-Mounted Displays (HMDs) that isolate the field of view of each eye physically by small display screens, and render the two perspectives onto the two screens individually; Large stereo screens (LSSs) that create an illusion of 3D depth leading to immersive perception; CAVEs that are specially constructed rooms with projections on multiple walls and possibly floor and/or ceiling to provide immersion.

The current state of HMDs is optimal for developers to create not only applications in which users can enjoy incredible experiences, but also to develop applications for therapeutic or educational purposes. Most of the current HMDs offer full immersion. For example, the Oculus Rift DK2 is a lightweight HMD, which offers an extended field of view of 110 degrees, stereoscopic vision, and fast head tracking. The Oculus Rift has already been used as a visualization device for different purposes (Tecchia et al. 2014; Tan et al. 2015; Kawamura and Kijima 2016). The Oculus Rift have been compared with other display systems. Young et al. (2014) compared the Oculus Rift and Nvis SX60 HMD, which differ in resolution, the field of view, and inertial properties, among other factors. Their findings showed that the Oculus Rift consistently outperformed the Nvis SX60 HMD. A study carried out by Hoffman et al. (2014) showed that the Oculus Rift can elicit a strong illusion of presence.

Some VR systems use locomotion-based interaction, including walking (Nescher, Huang, and Kunz 2014), cycling (Bolton et al. 2014), and other complex types of locomotion (Moen 2007). For example, the VR system developed by Jeong et al. (2005) integrated HMDs with stationary bicycles for improving the sense of balance using a virtual bicycle simulator. Other work with locomotion was a mountain climbing game using the Oculus Rift. In this game, the player attempts to ascend the highest peaks of each continent (Dufour et al. 2014). Other types of virtual environments used classic devices for navigation, like mouse, keyboard, joysticks or gamepads. Participants usually remain stationary while interacting with these environments (Waller et al. 2007). Some virtual environments have combined HMD and gamepads. For example, Juan et al. (2009) developed an acrophobic environment that was visualized using HMD and a CAVE for treating phobias. The user was able to walk around the virtual room using a gamepad, while the user's head movements were followed with a tracker.

Nowadays, VR applications applied to behavioral sciences are becoming very useful tools and may provide advantages over traditional methods (Rose and Foreman 1999). Several authors have pointed out the potential that the development of virtual environments has for therapies that require repetitive training or physical exercises (Juan and Pérez 2009; Krichevets et al. 1995), assessment in psychology (Foreman 2010), or learning (Martín-SanJosé et al. 2017).

In psychology, virtual environments provide advantages in terms of the interface flexibility, the virtual experience, and the opportune online monitoring of performance (Foreman 2010). Related to this, the spatial cognition and spatial orientation are crucial for adapting to new environments and getting from one point to another (Lin, Chen, and Lou 2014). There are some applications for assessing spatial memory in humans (Sturz and Bodily 2010; Lin et al. 2012). These applications introduce the users into an environment in which they can move and interact by using traditional devices (e.g., computer screens, mouses, or keyboards) (Koening et al. 2011; Cánovas, García, and Cimadevilla 2011; Cimadevilla et al. 2011).

Studies on memory have often been employed in the context of virtual learning situations, with the use of input devices and free choice of displacements as the equivalent of a concurrent spatial task (Sandamas, Foreman, and Coulson 2009). For example, in a previous work of our group (Rodríguez-Andrés et al. 2016), a VR environment with a large stereo screen and natural interaction was developed to evaluate spatial memory in children. That study compared two types of interaction: a gamepad and a steering wheel (with a Wii Remote$^{\text{TM}}$control). The results of that study showed correlations between the virtual system and traditional methods. Also, our group has been pioneer in the use of Augmented Reality (AR) for the assessment of spatial memory in children, demonstrating new forms of displacement that enable movement in a controlled space (Juan et al. 2014). In that work (Juan et al. 2014), our group showed the advantages of using AR for the assessment of spatial memory in children. That application was a valid tool for assessing the spatial short-term memory ecologically, and the results with the AR application correlated with the results obtained with traditional methods.

VR systems that incorporate both HMDs and physical movements for the assessment of spatial short-term memory have not yet been developed. Therefore, in this thesis, a new immersive VR system is developed to assess spatial short-term memory in adults. This system integrates a virtual maze, involving physical movements and immersion. The VR system uses two types of display systems (Oculus Rift-DK2 HMD and large stereo screen). For the interaction was included a locomotion-based mechanism (riding and pedalling a real bicycle) and a fixed condition (sitting using a gamepad). Thus, the VR system contributes to the real-time assessment of a participant's spatial short-term memory in a manner that more closely resembles human functional abilities.

In addition, stereopsis or binocular depth perception is the visual ability to perceive the world in three dimensions and the distance of an object (Snowden, Thompson, and Troscianko 2012; Hershenson 1999). Also, it quantifies the relationship between disparity and the perceived depth when a scene is viewed with both eyes by someone with normal binocular vision (Snowden, Thompson, and Troscianko 2012). The literature suggests that stereopsis is an advantage in certain tasks, especially in the comprehension of complex visual presentations and those requiring good hand-eye coordination (Fielder and Moseley 1996). However, the impaired depth perception is a deficit associated with abnormal spatial vision or amblyopia under ordinary (binocular) viewing conditions. This impairment could have a substantial impact on visuomotor tasks and limit career options for adults with amblyopia. (Webber and Wood 2005; Hershenson 1999; Levi, Knill, and Bavelier 2015). There are works that show various approaches to treat amblyopia and suggest several promising new approaches to recovering stereopsis (Levi, Knill, and Bavelier 2015; Li et al. 2011). For example, a study involving adults who were stereoblind or stereoanomalous showed a substantial recovery of their stereopsis after perceptual learning (Ding and Levi 2011). In other study, adults who were stereo-deficient were trained in a natural visuomotor task (a VR environment) (Vedamurthy et al. 2016). They concluded that "some adults deprived of normal binocular vision and insensitive to the disparity information can, with appropriate experience, recover access to more reliable stereoscopic information". All these previous works indicate that human adults could also recover or acquire stereopsis in adulthood.

Furthermore, an observation made on the subject of Virtual and Augmented Reality of the Master's Degree in Artificial Intelligence, Pattern Recognition and Digital Imaging motivated the study about the assessment of depth perception in people without stereopsis. The students who had not stereopsis (checked using the Lang Stereotest I) had not the perception of depth when they used VR devices such as a CAVE, a large stereo screen and even with autostereoscopic displays. However, the same students had the sensation of depth using the Oculus Rift. Therefore, in this thesis a study was designed to corroborate or not if the users that do not have stereopsis could have a statistically richer 3D experience using current HMDs.

1.2 Scientific goals and research hypotheses

The main objective of this thesis has been to develop and test an immersive VR system to assess the spatial short-term memory and depth perception. This assessment focuses on different performance measures such as data collected with the VR system, data obtained with the traditional methods applied in psychology, and questionnaires defined for this type of evaluations. Also, other aspects were evaluated such as stereopsis of users, satisfaction, presence, and interaction.

To achieve this objective, the following activities were carried out:

1. An immersive virtual environment was designed based on the Cincinnati Water Maze (Arias, Méndez, and Arias 2014). The maze had walls, pathways, and included a virtual bicycle. The bicycle was depicted as a first-person avatar.

2. A Virtual Maze Task was designed and implemented. This virtual task is based on egocentric orientation (Kelly and McNamara 2008). The user learns one's body position in space for orientation (i.e., idiothetic information). The cognitive task comprised three phases: habituation, learning, and testing.

3. In the VR system were incorporated two types of interaction. The first included a locomotion-based mechanism (riding and pedaling a real bicycle) by using a speed sensor, cadence sensor, and an accelerometer. The second consisted of a fixed condition (sitting using a gamepad).

4. For the visualization of the virtual maze an Oculus Rift-DK2 HMD and a large stereo screen were integrated in the VR system using Unity, Oculus SDK, and libraries developed.

5. To develop this immersive VR system a set of techniques and tools were applied to produce real-time interaction and simulation, which allow perceiving the sense of presence through sensorial channels, visual and aural; offering the user a virtual experience as if it was real.

Two different studies were carried out:

1. **Assessment of the spatial short-term memory (Study 1).**

   The objective of this study was to test the capability of the VR system to assess spatial short-term memory in healthy adults involving physical movement and immersion. Also, the participants' performance on the virtual task and traditional neuropsychological tests were evaluated and compared.

   The first of our hypotheses (H1) of this study is that the VR system could evaluate spatial short-term memory and spatial orientation in adults like the traditional procedures applied in psychology. The second hypothesis (H2) is that there would be no statistically significant difference in the score of the task between gender. The third hypothesis (H3) is that there would be no statistically significant difference for the score of the task between the two types of interaction. The fourth hypothesis (H4) is that there would be no statistically significant differences in the satisfaction and interaction of the task between the two types of interaction.

   Some reasons that support these hypotheses are the following:

   (a) The performance on the virtual maze task and classical neuropsychological tests would obtain significant correlations because our virtual task also involves sustained attentional demands and higher working memory capacity similar to procedures applied in psychology.

   (b) The physical movement is directly related to the vestibular system, and this would have a positive influence on spatial memory.

2. **Assessment of 3D experiences using VR devices for people with stereo-deficiencies (Study 2).**

   The objective of this study was to compare two display systems between people who had and had not stereopsis, based on the same virtual task and the same device of interaction (gamepad). The hypothesis (H5) of this study was that the users that had not stereopsis would have a statistically richer 3D experience with the HMD than with a large stereo screen. Thus, for testing the hypothesis of this study was compared the Oculus Rift-DK2 HMD with a large stereo screen that included the use of polarized glasses. However, other HMDs or different visualization systems could also be used (e.g., CAVE or autostereoscopic displays).

The reasons that support this hypothesis are the following:

(a) The field of view of current HMDs is much more similar to the human eye than other VR devices or display systems.

(b) The inclusion of head tracking, low latency, and the motion parallax cue in the Oculus Rift-DK2 HMD play an important role in stereoscopy.

1.3 Organization of the thesis

This section provides the organization of the thesis. The chapters are structured as follows:

- **Chapter 1**. Introduces the thesis, including the motivation, the scientific goals, the research hypotheses, the studies carried out, and the organization of the document.
- **Chapter 2**. Shows a brief description of human memory and its assessment, human factors related to the use of VR devices, and finally, the most relevant literature about Virtual Reality, display systems, VR systems and VEs.
- **Chapter 3**. Describes in general, the design and development of the immersive VR system.
- **Chapter 4** Describes the first study of the thesis, that consisted of the assessment of spatial short-term memory in humans, by comparing the participants' performance in the task and traditional neuropsychological tests.
- **Chapter 5**. Describes the second study of the thesis, that consisted of the assessment of the visual perception between people who had and had not stereopsis, by comparing between two types of display systems.
- **Chapter 6**. This chapter summarizes the work with the general conclusions, future works and lists the publications derived from this thesis.
- **Appendice A**. Shows the questionnaires that have been used in this thesis.

CHAPTER

II

2

Background and literature review

> *"Technique always develops from the primitive via the complicated towards the simple."*
>
> `Antoine De Saint Exuoéry`

2.1 Introduction

This chapter briefly describes the topics involved in this thesis, the technology employed in the development of the VR system and the studies carried out. First, general notions about human memory and assessment are described. Second, human factors related to the use of VR devices and VR displays are briefly described, such as vestibular system, visual perception, and stereopsis. Finally, some fundamentals about Virtual Reality that make virtual experience possible are described, such as architecture, and components of VR systems, display systems, virtual environments, stationary and locomotion interfaces.

2.2 Virtual Reality

The development and growth of Virtual Reality has occurred thanks to academic research, to the invention of new input and output devices, and mostly to affordability. Some applications and visions existed in the past like the flight simulators (Kennedy et al. 1989). Currently, several areas are using this technology to solve real-world problems such as the entertainment industry (Barab, Gresalfi, and Ingram-Goble 2010), the automotive industry (Novák-Marcinčin, Kuzmiaková, and Beloushy 2009), engineering (Kalawsky 1993), medicine (Moorthy et al. 2003), physiotherapy (Dascal et al. 2017), education (Peña and Tobias 2014), exhibition of collections and artworks (Carrozzino and Bergamasco 2010), and assessment of psychological processes (Parsons et al. 2013).

According to the literature reviewed, VR has received numerous definitions. In this thesis the following have been considered:

> “Virtual reality involves a fundamental shift from traditional conceptions of computer applications as software running on machines populating our desktops, towards a space in which the user can enter, interact and be completely immersed” (Bryson 1996).

> “Virtual reality is a user interface technology that provides an immersive and realistic, three-dimensional computer simulated world” (LaViola 2000).

> “Virtual reality is the use of computers and human-computer interfaces to create the effect of a three dimensional world containing

> interactive objects with a strong sense of three dimensional presence" (Blade and Padgett 2002).
>
> "The virtual reality technology field focuses on spatial multi sensory representation, interaction, and presence, combined with real-time simulation techniques and high level management of the handled virtual environments" (Blach 2008).
>
> "Virtual reality is a computer generated simulation of three-dimensional objects or environments with seemingly real, direct, or physical user interaction" (Dionisio, III, and Gilbert 2013).

According to these definitions and additional references (Bamodu and Ye 2013b; Muhanna 2015), we can summarize which, the virtual reality combines technological and computer advances such as computer graphics, image processing, pattern recognition, artificial intelligence, networking, sound systems and other similar ones to produce computer simulation and interaction. It also applies a series of techniques and tools to develop an immersive visual environment, to provide users with a perception of being present through sensorial channels like visual, aural, haptic and others, which allow living a virtual experience as if it was real. Additionally, VR includes components real-time interaction and simulation through the novel devices of input and output.

Virtual Reality continues developing thanks to its usefulness and benefits in many application fields. This trend is expected to continue in the future with the advance of technology into several areas; e.g., simulators for aircraft cockpits and vehicles (Wan et al. 2011), movement analysis for sports and rehabilitation (Bideau et al. 2010), scene representation for archaeological sites and museums (Champion, Bishop, and Dave 2012), skill training for surgery operation and engineering repair (Cramer et al. 2004), treatment of phobias (Juan and Calatrava 2011), evaluation of psychological processes (Parsons and Rizzo 2008), data visualization for scientific research and industry design (Grey 2002; Henry and Polys 2010), as well as entertainment (Zyda 2005).

2.3 Display systems

Since the 1960s, different devices or systems have been used to display a virtual environment as shown in Figure 2.1. The types of displays that can be used to view the virtual environments range from desktop to fully immersive. The type of interaction devices for the navigation within virtual environments range from hand-held devices through to motion tracking systems. Several types of display systems have been distinguished:

- Desktop displays (monitors or TVs)
- Wall-sized displays (single wall of a room, large stereo screen, large curved screen)
- Surround-screen displays (CAVEs with four sides)
- Head-mounted displays (different types of HMDs)

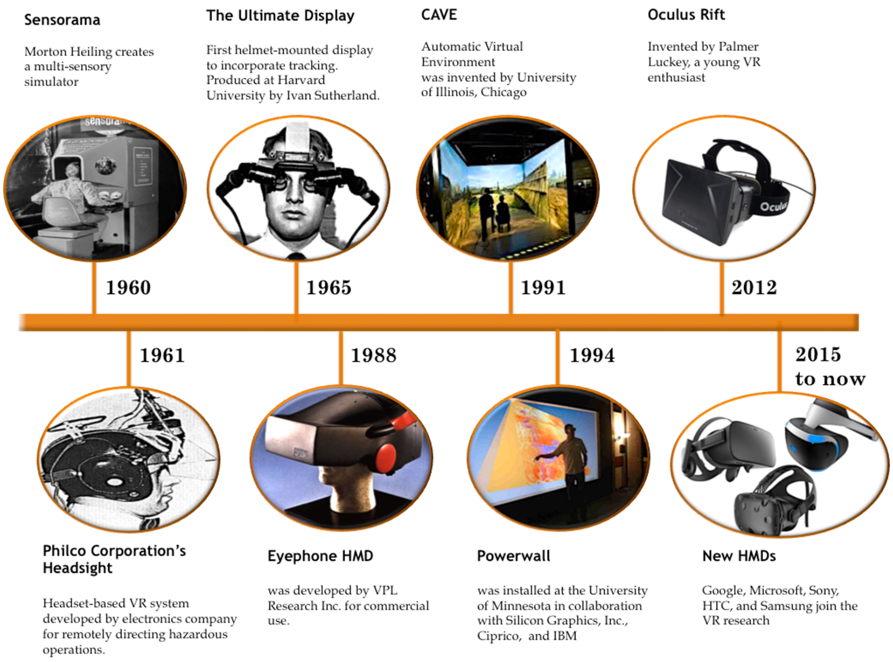

Figure 2.1: Evolution of the display systems.

2.3.1 Head-Mounted Displays

The Head-Mounted Displays are the type of display that is most commonly associated with the phrase "virtual reality". The manufacture of a vast number of HMDs models became an increasingly available device to experience virtual reality. These devices are made with different types of materials (cardboard, plastic, and others) to guarantee user comfort and affordable prices. For example, Google Cardboard only require an Android or iOS Smartphone to run games or videos and enjoy the experience. Other current models bring more quality to the virtual experience such as Oculus Rift, Samsung Gear VR, HTC Vive, PlayStation VR or Vituix Omni.

The *Oculus Rift* is considered the origin of a new trend in the development of Virtual Reality, regarding visualization devices as helmets and HMDs. Oculus Rift connects by cable and requires additional hardware (NVIDIA GeForce GTX 970 graphics card, AMD Radeon R9 290 or higher, and at least 4 GB of RAM, an HDMI 1.4 port or DisplayPort 1.2 or higher. This may seem like a disadvantage compared to other HMDs, but these characteristics, for the moment, guarantee a smooth experience and offer a real immersion. Several versions of this device have been developed, as shown in Figure 2.2. These are some alternatives offered now, but there are sure to be other devices that will bring even more immersive experiences.

Figure 2.2: Oculus Rift's versions.

The Oculus Rift-DK2 HMD has been used as a visualization device for different purposes. For example, Space Rift is a VR game that taught children about the solar system by allowing them to explore it in a virtual environment (Peña and Tobias 2014). Space Rift was tested with fifth-grade students. The students described the game as enjoyable and immersive, although they had problems distinguishing some of the images due to lack of sharpness. Other studies have compared different versions of the same virtual environment using the Oculus Rift. For example, two different virtual roller coasters were compared, each with different levels of fidelity (Davis, Nesbitt, and Nalivaiko 2015). They found that the more realistic roller coaster with higher levels of visual flow had a significantly greater chance of inducing cybersickness. The Oculus Rift-DK2 HMD was used to watch movies in which two conditions were considered: the observer condition, in which the participant was observing the scene as in traditional movies; and the actor condition, in which the participant was observing from the perspective of one of the actors and he/she became part of the plot (Van den Boom et al. 2015). They only found differences between the two conditions with regard to spatial presence in favour of the actor condition.

The Oculus Rift has also been compared with different visualization systems. For example, the Oculus Rift and a high-cost Nvis SX60 HMD were compared, which differ in resolution, field of view, and inertial properties, among other factors (Young et al. 2014). They also assessed simulator sickness and presence. The findings showed that the Oculus Rift consistently outperformed the Nvis SX60 HMD, but some people were more subject to simulator sickness with the Oculus Rift. A nVisor MH60V HMD, the Oculus Rift DK1, and Samsung Gear VR were used to learn anatomy with students of medical disciplines (Buń et al. 2015). Twenty students from the Poznan University of Technology participated in a study concerning perception. The participants were asked to select the preferred HMD and interaction method. Most of them chose the Gear VR in combination with Kinect and the gamepad as the preferred solution. Tan et al. (2015) presented a study involving 10 participants that played a first-person shooter game using the Oculus Rift and a traditional desktop computer-monitor. They concluded that the participants had heightened experiences, a richer engagement with passive game elements, a higher degree of flow, and a deeper immersion with the Oculus Rift than on a traditional desktop computer-monitor. However, they also mentioned the problems of cybersickness and lack of control. Gutiérrez-Maldonado et al. (2015) developed a VR system to train diagnostic skills for eating disorders and compared two visualization systems (Oculus Rift DK1 vs. a laptop with a stereoscopic 15.6-inch screen). In this study, fifty-two undergraduate students participated. No differences were found in either effectiveness or usability with regard to skills training in psychopathological exploration of eating disorders through virtual simulations.

2.4 VR systems

A VR system has three major features: presence, interaction and imagination (Burdea and Coiffet 2003). *Presence* is the feeling of being present or being a part of a virtual world. It is the result of the stimulation of the VR system on human senses (visual, aural, haptic, and smell). *Interaction* is a means of communicating between the VR system and user. Its features must be effectiveness, real time reaction and human participation. *Imagination* would be the thought of the system designer to execute a particular goal (Burdea and Coiffet 2003; Zhou and Deng 2009; Isdale 1998).

The VR systems can be classified into 4 categories. These are, no-immersive, semi-immersive, full-immersive and distributed-VR (Blackledge, Barrett, and Coyle 2010; Bamodu and Ye 2013a; Bamodu and Ye 2013b; Isdale 1998; Muhanna 2015).

- **No-Immersive VR system** is the least immersive and least expensive of the VR systems. It allows users to interact with a 3D environment through a stereo display monitor and glasses, others common use as keyboard and mouse.
- **Full-Immersive VR system** usually the most expensive, but gives the highest level of immersion and realism; its components include HMD, tracking devices, data gloves and others, which give the user the feeling of being part of the virtual environment.
- **Semi-Immersive VR system**, provides high level of immersion, while keeping the simplicity of the desktop VR or utilizing some physical model. Example of such system includes the CAVE, augmented reality system or applications for driving or flying simulators.
- **Distributed-VR** exists as a result of rapid development of the internet. Its goal is to remove the problem of distance, allowing people from many different locations to participate and interact in the same virtual world through the help of the internet and other networks.

The stereoscopy technology is used for different purposes and in different works has been compared. For example, Patrick et al. (2000) carried out a study to compare differences in spatial knowledge learned in a virtual environment using three display systems: HMD, large projection screen, and desktop monitor. They found no significant difference between the HMD and the large projection screen conditions. But, screen and monitor conditions were significantly different. Their results suggested that a large projection screen may be a useful display device in spatial cognitive learning in a virtual environment like a HMD. Also, Carrozzino and Bergamasco (2010) have used two setups, a "full-immersive" featuring a CAVE system and an exoskeleton, and another "immersive" featuring a stereo powerwall with a large desktop haptic device. They have shown that this technology, thanks to its compelling features, might motivate to the public to have cultural experiences, especially young people.

2.4.1 Architecture of the VR systems

A VR system is made up of hardware and software (see Figure 2.3). The components of the hardware are the VR engine or computer system, input and output devices. The software includes application software and database. The application software is a collection of tools and software for modeling, designing, developing and maintaining VR applications. The database is a repository where the information is stored.

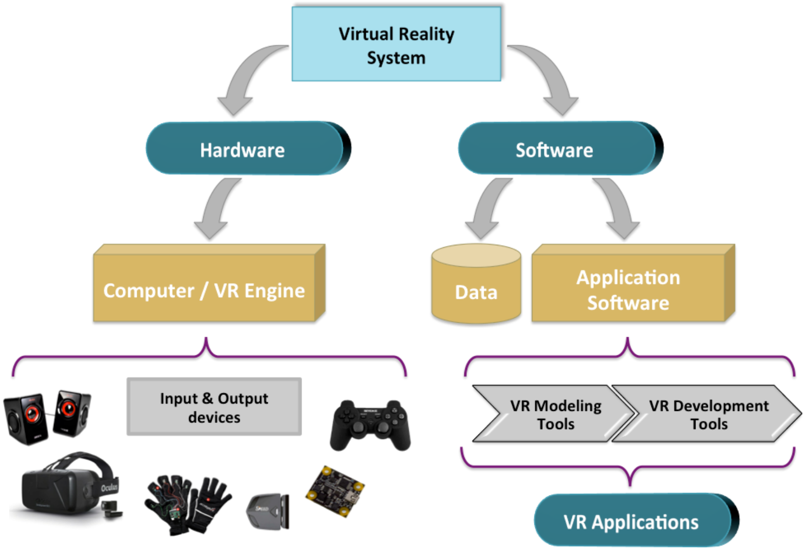

Figure 2.3: Architecture of a VR system.

One of the primary goals of a VR system is to achieve a high degree of “reality” when a person experience immersion into a virtual world. For this purpose some technical aspects must be considered: (a) Interaction with the virtual environment must be immersive and intuitive; (b) Rendering must be done in real-time and without perceptible lag; (c) The behavior of an object must be natural and simulated in real time. Furthermore, a VR system must employ visually-coupled devices, such as a HMD, shutter glasses or stereographic glasses, that are worn by the user. These allow separate images to be projected to the use’s left and right eye and thereby creating an illusion of 3D.

2.4.2 Components of the VR system

The components of a VR system are grouped into the following modules: visualization, navigation, devices handler, communication, specific application, and physically-based simulation (see Figure 2.4). Below is a description of these components:

The visualization module

This module represents the visual and graphic side of a virtual world. It is “visible” to the users and helpful in the interaction. There are some packages that allow creating, designing, managing and rendering virtual environments, such as Unity, Open GL, Blender, 3DS Max, Cinema 4D, VRML, and others.

Currently, there are numerous software techniques and graphic utilities to create 3D images, with powerful rendering techniques such as shading, shadowing, and texturing applied to them to increase the realism of images. These techniques allow the creation of a variety of virtual environments. A virtual environment was defined by Barfield (2010) as a representation of a computer model, which can be experienced interactively and manipulated by the user.

A VR system may use a multitude of display systems to visualize a virtual environment. Examples of display systems are traditional desktop monitors, HMDs, large wall-mounted displays, or CAVEs with various numbers of sides. These display types represent the array of technologies for creating immersive experiences that range from “looking at” a virtual 3D world to “being in” that virtual world (Shneiderman et al. 2010).

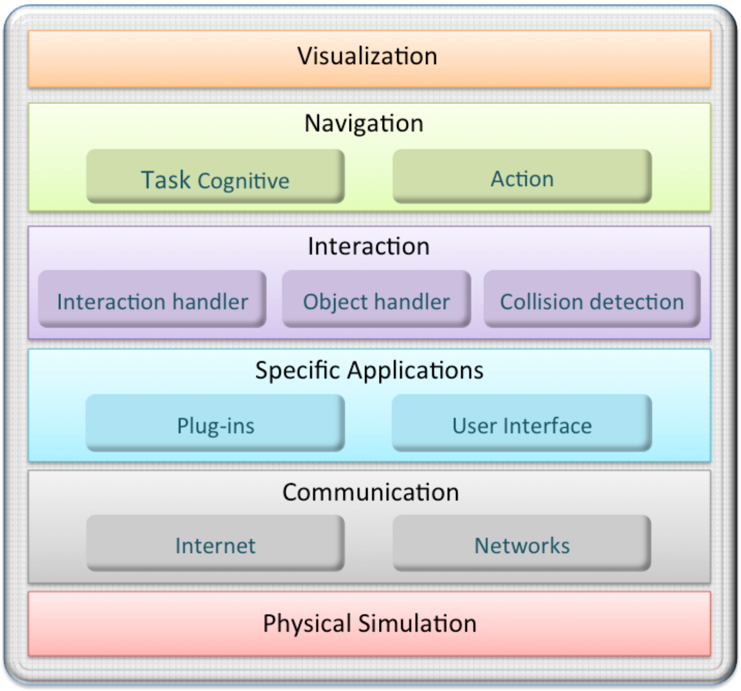

Figure 2.4: Components of a VR system.

The navigation module

This module is accomplished by using position tracking with an interaction device that allows a potentially high degree of "reality" in the virtual world. This module is probably a fundamental interaction technique in VEs. Most navigation modes are distinguished for the ways they control the position of the object or avatar.

The navigation comprises two components:

- *A cognitive task,* the user must build a mental map of the environment. This mental map is always updating during locomotion; the navigation technique and constraints have an impact on the user's ease to build the map. Depending on the application, the cognitive task can be more or less difficult; for instance, when navigating through vast terrains or cities, a map can be very helpful for the cognitive task.
- *An action,* it provides input to the computer to perform the locomotion by transforming the viewpoint in the desired direction. It consists of the execution of events such as selection, grasping, creating and destroying objects, observing and reminding objects, text input, listening to music or instructions, etc.

Depending on the application, the locomotion component of navigation can be significant by itself, e.g., in training firefighters, pilots, soldiers, surgeons, or memory of routes and objects in VEs. It is important so that navigation is as natural as possible. One or more coordinates can be defined so that the avatar's translation is fixed at a particular value, e.g., the height or the path. This feature can be used to keep the virtual user's position at eye level to increase a natural feeling into VEs, for example in a city or a maze virtual.

The interaction module

This module is an architecture which allows flexible configuration of the hardware. This module includes the object handler, collision detection, and interaction handler. It is also responsible for detecting collisions among objects in the scene graph. Additionally, postures of the body, head, and hand or gestures plus orientation are configured. This module includes the technological interface of the virtual environments that are VR displays such as a HMD for viewing stereoscopic images, a spatial tracker for locating the position of the head or hands, equipment to spatial sound, and equipment to provide tactile and force feedback to the virtual environment user; i.e., all output and input devices.

The application-specific module

This module includes plug-ins, which provide some application-specific behavior or functionality, or an on-line interface to other applications through sensors. Also, the user interface includes, virtual buttons and menus, object selection, sound, voices, body movements and other interaction techniques. VR system must load at run-time.

The communication module

This module is responsible for the communication between two or more users through the internet and other networks, as to guarantee the functionality and interaction of several users in the same environment virtual.

The physical simulation module

This module is based on computer simulation, the model of an actual or theoretical real system is designed, executing the model on a computer, and analyzing the execution output (Fishwick 1996). Almost all modules should be able to run concurrently to each other. This is particularly necessary for real-time critical modules such as the visualization, physical simulation, collision detection, and devices manager module. These actions bring the virtual environment to "life".

2.5 Virtual environments

Virtual environments (VEs) allow users to see, hear, and feel three-dimensional virtual objects, as well as explore and interact with virtual worlds. This technology has already been used for several years in military training (Knerr 2006), flight simulators (Kennedy et al. 1989), driving simulators (Maguire, Nannery, and Spiers 2006) and other activities (Riecke et al. 2010). More recently, the technology has begun to find applications in medicine (Qian et al. 2015), education (Lindgren, Moshell, and Hughes 2014), psychology (Parsons et al. 2013), engineering (Novák-Marcinčin, Kuzmiaková, and Beloushy 2009), and entertainment (Barab, Gresalfi, and Ingram-Goble 2010).

The virtual environment is usually generated using a HMD. These devices have a spatial tracker for identifying the head position, two image sources and optic projection units (one for each eye), which generates a binocular virtual display providing a 3D or stereoscopic scene (Barfield and Furness III 1995). Since HMDs can provide the user with 3D stimuli, the user may feel a sense of “presence”, i.e. that they are actually “inhabiting” a new place rather than merely looking at a picture. The participant feels “immersed” and the original environment seems to disappear from his or her awareness (Slater and Wilbur 1997). Although HMDs have existed for nearly half a century (Sutherland 1968), they have only recently become commercially available and affordable to a broad population.

The HMD can create an immersive visual environment, but additional equipment is needed to provide sound and tactile or force feedback, which makes the experience feel more natural. This way, participants can interact with the environment by viewing images, hearing sounds, touching virtual objects and transferring mechanical energy to the virtual environment (Barfield and Furness III 1995).

In most of the VR systems combining HMDs with joysticks, mouses, gamepads, or other traditional controllers, the users are sitting, standing, or walking, while they navigate through the virtual environment. Studies as these have determined two types of interfaces to navigation within of virtual environments (stationary and locomotion).

2.5.1 Stationary interfaces with VEs

There types of virtual environments that are based on classic device combinations for navigation, like mouse and keyboard, or devices like joysticks and gamepads. Participants usually remain stationary while interacting with these environments (Waller et al. 2007). Using these devices involves intuitive commands and does not require any pre-training (Jung et al. 2014). Studies have combined HMDs and gamepads with virtual environments. For example, in a study by Riecke et al. (2010), an HMD (NVIS NVisor SX) was used with a wireless joystick (Logitech Freedom 2.4) to experiment with different navigation strategies. Horizontal translations and rotations in the virtual environment were controlled, respectively, by joystick deflections and rotations. Their results suggested that such a navigation system can capture full-body rotations.

2.5.2 Locomotion interfaces with VEs

A locomotion interface is a mechanism to create a sense of physical movement within a virtual environment. Physical movement uses the motion of the user's body to travel through the VE. Examples include walking, riding a stationary bicycle, or walking in place on a virtual conveyor belt while the body is maintained localized in the real world (Van Dam et al. 2000).

Locomotion-based interactions play a strong role in social and cognitive developments (Clearfield 2011), which is related to attention, perception, learning, memory, thinking and language (Pashler and Yantis 2002). Therefore virtual environments involving these types of interactions can reveal valuable cognitive information such as the effects of exercise on spatial tasks (Herting and Nagel 2012), spatial abilities (Waller 2005) and spatial cognition (Lin et al. 2012). Virtual environments may also be well suited to the assessment of learning, since they can test the ability to learn and react to a new environment by executing a series of actions (such as moving within the environment or shifting objects) to attaining a goal (Munro et al. 2002). Therefore virtual environments may complement traditional formats of human performance assessment.

In this type of interfaces (physical movement) are identify two important tasks:

- Orientation of the viewpoint in the VE.
- Movement of the viewpoint in the VE.

Proprioceptive and vestibular feedback during locomotion physical is of particular importance for navigation. (Usoh et al. 1999; Ware and Slipp 1991; Witmer et al. 1996). In this context, Juan et al. (2009) in their research on treating phobias, developed an acrophobic environment that was visualized using a HMD and a CAVE. The user was able to walk around the virtual room using a gamepad (Logitech WingMan Cordless Rumblepad), while the user's head movements were followed with an MTx tracker (Xsens Motion Technologies). Their results showed that the environment provoked anxiety and induced a sense of presence in non-acrophobic participants.

Virtual environments, which may or may not involve HMDs, are a new type of human-computer interface that allow users to interact with 3D environments (Kalawsky 1993) through body movements (Waller and Hodgson 2013). Virtual environment technologies can track only head or whole-body rotation, so additional devices, such as treadmills or bicycles, are needed to track translational movement through the simulated space. Such multi-tracking virtual environment set-ups are still in the prototype stages of development, but they already show potential as research tools (Durlach and Mavor 1995).

Numerous studies have examined whole-body, locomotion-based interactions of participants with virtual environments using treadmills and exercise bicycles (Souman et al. 2010). Most of these studies have focused on assessing aspects of physical activity. One study compared spatial awareness and ability to navigate while walking around flat terrain or terrain with small or large hills (Jackoski et al. 2015). Participants wore an Oculus Rift-DK2 HMD. The results suggested that spatial awareness improved as the terrain became more uneven. In another study (Xu, Jeong, and Mulligan 2009), participants wore an eMagin z800 HMD and exercised on a stationary bike, which was synchronized with a computer monitor for the evaluator. The characteristics of the trail changed depending on the participant's cycling speed. The results showed that this virtual exercise environment made exercising more enjoyable; participants enjoyed gauging their progress and performance. Another study compared the user navigation performance on the Torus Treadmill with performance using a joystick-based interface. Their results showed that performance was significantly better in the walk mode than in the visual turn mode (Iwata and Yoshida 1999). A bicycle simulator study in which participants pedalled and navigated through a virtual city was performed to examine the effects of altering the friction coefficient (Veen and Distler 1998). A virtual environment generated on a Cybermind Visette Pro HMD was used to assess rugby players' ability to detect deceptive movements (Bideau et al. 2010): experience level was found to influence how much participants picked up on sophisticated perceptual information about the direction in which a player was going to run.

Virtual environments with HMDs have also been applied to studies of teaching and learning. For example, one study illustrated the ability of the Oculus Rift-DK1 HMD to support learning and training (Tecchia et al. 2014). This display augments the virtual space with real-time 3D rendering of the user's hands and body. This helps users feel present in a virtual environment, manipulate virtual objects with their own hands and walk around naturally. The preliminary results from that study suggest that this form of virtual self-representation may substantially improve learning and training processes. Virtual environments to analyze and support learning also overlap with the entertainment industry: for example, Titans of Space uses Oculus and HTC Vive HMDs to provide a guided tour of the solar system (Peña and Tobias 2014).

2.6 Human Memory

Memory is the ability to retain and to evoke events of the past, through neurobiological processes of storage and retrieval of information, it is necessary for learning and thinking (Baddeley 1997; Ballesteros Jiménez 1999). Memory is not a single process. Memory and learning can not be separated because learning must be recorded in memory to use at a later time when necessary. There are different types of memories in the human brain: the sensorial memory (visual, auditory, olfactory, etc.), short-term memory (maintenance memory and working memory) and long-term or permanent memory (episodic, semantic, autobiographical) (Atkinson and Shiffrin 1968). A general scheme of the types of human memory can be seen in Figure 2.5.

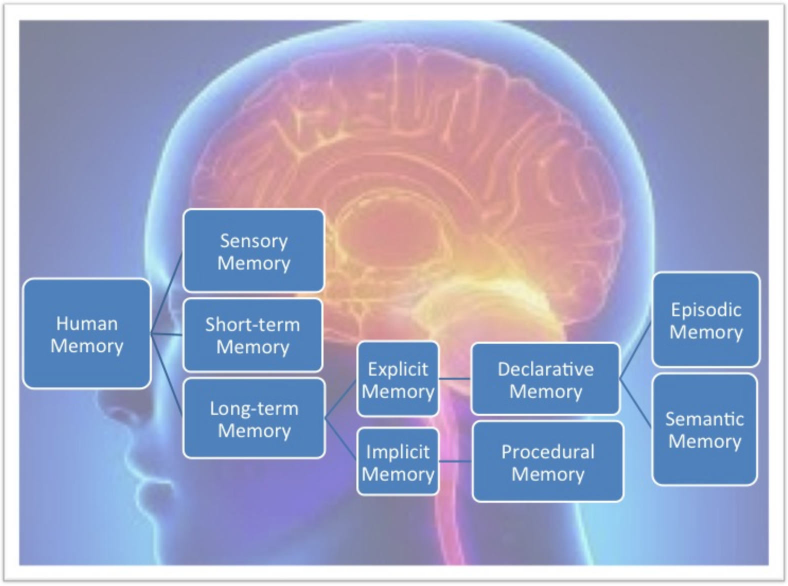

Figure 2.5: Scheme of the types of human memory by Luke Mastin (2010).

2.6.1 Short-term memory

Short-term memory is the capacity of keeping a small amount of information in mind for a short period of time. The structural model of memory is like a store that allows retaining the information for a short time (usually a few seconds) until that information is processed and becomes part of a more permanent memory, which is called long-term memory. This type of memory allows other cognitive functions such as repetition, learning, language comprehension or reasoning tasks (Baddeley and Hitch 1974). Short-term memory is evaluated using tests that require the retention of a small amount of information for very short periods of time.

2.6.2 Spatial memory

Spatial memory is a system involved in the temporary retention of information related to the spatial location of elements. It is an important cognitive skill for survival. This memory is related to a wide range of cognitive abilities that humans have. According to Bisby and Burgess (2016) "the storage and retrieval of information within the brain that is needed both to plan a route to the desired location and to remember where an object is located or where an event occurred. Finding one's way around an environment and remembering where things are within it are crucial everyday processes that rely on spatial memory".

2.7 Assessment of memory

Several methods, tests, and techniques are used to assess memory. These are helpful to determine the core components of person's psychological or mental health problems, personality, intellectual coefficient, or cognitive processes as memory and learning. The process of assessment also helps to identify not just weaknesses of a person, but also their strengths (Baddeley 1997; Nadel et al. 2000; Anderson and Bower 2014). Traditionally, paper and pencil tests and computerized tests have been used for the assessment of cognitive skills. However, computer-based environments, especially VR systems for neuropsychological assessment, represent a major advance for the assessment of cognitive skills in a more ecological way. Ecological validity refers to the degree to which test results relate to real-life performance (Chaytor and Schmitter-Edgecombe 2003).

The neuropsychological assessment of individual cognitive skills improves our understanding of individual differences in behavior and helps us to detect pathology (Lezak 1995). Also, the use of VR applications in psychology offers several benefits, for example, learning and spatial cognition, movements flexibility in virtual space, the opportunity to reproduce the virtual experience and ease of monitoring user's performance on-line.

Some authors highlighted the possibility of using VR measures for neuropsychological assessment in research applications as well as in clinical practice (Negut et al. 2016). The neuropsychological assessment of individual cognitive skills improves our understanding of individual differences in behavior and helps us to detect pathology (Lezak 1995). The study of Juan et al. (2014) showed the advantages of using an Augmented Reality application for the assessment of spatial memory in children. Their study focused on the assessment of short-term memory like this one, which can be defined as the capacity for holding a small amount of information in mind in an active state for a short period of time. The children who participated in the study were satisfied with the application and considered that it was easy to use. In addition, the application developed by the study, was a valid tool for assessing the spatial short-term memory ecologically (Juan et al. 2014). In other study Rodríguez-Andrés et al. (2016) have used a virtual reality environment with a large stereo screen includes natural interaction to evaluate spatial memory in children. That study compared two types of interaction: a gamepad and a steering wheel (with a Wii Remote^{TM}control). Their results showed correlations between the system and traditional methods. These works suggest the effectiveness of using different types of display systems and VEs to assess the memory in children.

With regard to ecological validity, Canty et al. (2014) evaluated the sensitivity, convergent validity and ecological validity of a virtual reality task for assessing prospective memory (i.e., the Virtual Reality Shopping Task). The task was tested with patients who have suffered a traumatic brain injury. They developed a VR shopping center and used a laptop screen to visualize the environment. Their results showed that the task was sensitive and ecologically measured the time and events based on prospective memory ability in patients with post-traumatic brain injury. That work allowed them to prove the benefits of using VR in the assessment and rehabilitation of memory in individuals with traumatic brain injury. Plancher et al. (2012) used a laptop to present a three-dimensional view of two urban environments inspired by Paris. In addition, a soundtrack of typical city noises (cars, people, etc.) were added to give the participants the feeling of being immersed in each environment. The participants were seated on a chair, and the virtual environment was projected 150 cm in front of them. The environment was explored by means of a virtual car using a real steering wheel, a gas pedal and a brake pedal. The results demonstrated that complex virtual environments may provide tools to reflect subjective cognitive deficits in pathological aging. The study also demonstrated the feasibility of using VR technology to study the episodic memory deficits of patients with amnesic mild cognitive impairment and Alzheimer's disease.

Although most studies use conventional monitors for showing the virtual environment, Parsons and Rizzo (2008) used a HMD eMagic Z800 to assess and compare the psychometric properties between the virtual environment and paper-and-pencil measures. They created a Virtual Reality Cognitive Performance Assessment Test. Their test focused on neurocognitive testing using a virtual city to assess recall of targets delivered within the city. Their findings revealed that there were significant correlations between the total memory score of their test and the classical learning and memory tests. In this line, Nori et al. (2015) developed a VR test based on the WalCT, which is a test for assessing memory for sequences of steps within a real setting (Piccardi et al. 2008). That test aimed to assess human navigational ability. They used a HMD eMargin z800, and a graphic Workstation HP. Participants had to learn 8-step sequences, which were shown by an avatar. Their results showed that there were no differences between the real version and the virtual version of the same test. They also indicated that the virtual test was a good tool for studying the brain networks involved in sequential topographical learning. A practical on-line demonstration was used to enhance comprehension among psychology students on a virtual scanning task of the short-term memory (Kahan and Mathis 2007).

In this thesis, several traditional neuropsychological tests to assess short-term spatial memory have been used, as described below.

- *The Corsi Blocks Task (CBT)* is used to assess visuospatial short-term memory. Two versions of this test were used to assess the visual and spatial short-term memory: Forward (CBTF) and Backward (CBTB) (Kessels et al. 2000).

- *Test of Memory Assessment and Learning (TOMAL)* has a battery of subtests. Two verbal subtests were used: Digits Forward (DF) to assess the recall of a sequence of numbers, and Digits Backward (DB) to recall a sequence of numbers, but in reverse order (Reynolds and Bigler 1994).

- *The Random Walker Test (RWT)* is a paper-pencil test to assess the left-right orientation ability. Two subtests were used RWTS with score and RWTT with time (Uchiyama, Mitsuishi, and Ohno 2009).

2.8 Human factors

The word “factors” in “human factors” is occasionally equated with “limitations”. However, the human factors literature shows the effort to insight into e.g. the cognitive, sensory-motor, and perceptual aspects of human behavior that could instigate the design of an optimum performance between the “human and his machine”, viewed as one functional system (Soegaard and Dam, Rikke Friis 2016; Salvendy 2012). In consequence, the Human-Computer Interaction community emerged from the Human Factors community and other disciplines such as Cognitive Psychology/Science, and took a “contextual turn” towards a more humanistic and sociological accounts of meaning from the late 80s and onward. The focal point of the discipline is sensory-motor aspects of man-machine interaction regarding communicative and cognitive aspects (Carroll 1997). These aspects were initially not viewed, all was at a very physical, muscle-operated level, and focused on the problems of designing equipment operable by humans (Oppenheim and Shinar 2011).

Currently, human-computer interface devices are maturing. They are more easy to carry or wear, somewhat more accurate, and offer better performance. These devices include tracking as well as visual and the haptic/tactile rendering. From an interaction point of view, the Human-Computer Interface with virtual environments is still a field of active research. New intuitive, immersive metaphors, techniques, hardware and software have been created to improve interaction with virtual environments. The use of this technology is increasing; there is demand for tools for developing applications (Kim 2015; Oppenheim and Shinar 2011; Soegaard and Dam, Rikke Friis 2016). These applications are being very relevant for a broad range of domains. At present, applications are mainly offered to the entertainment industry, however, in other disciplines, Virtual Reality is becoming a useful tool (e.g., Psychology, Medicine, Education, Architecture, Art, Designed, and Security).

Despite all these advances, the integration of some human factors with existing technology infrastructure has not yet been solved in a satisfactory manner. One of these factors is the symptoms of sickness that a user can feel after use VR devices such as HMDs, active shutter glasses, CAVEs (Cave Automatic Virtual Environments), large screens and others. On the other hand, some people do not have stereopsis; they have difficulty to see the 3D objects and depth in the real world, and therefore it is much harder to see a virtual object using VR devices. Stereopsis is a topic that also was studied in this thesis because some individuals cannot perceive the depth perception when they use VR devices such as CAVE, large stereo screen and even with autostereoscopic displays.

2.8.1 Vestibular system

In real life, the vestibular and visual systems receive stimuli from the real environment. However, in VR, vestibular information may not be present or be influenced by optical flow patterns that are characteristics of self motion (Hettinger and Riccio 1992). Therefore, the inclusion of the physical movements in applications for the assessment of spatial short-term memory is necessary to determine if it has a significant influence on spatial memory. Thus, in the first study of this thesis, the object was to determine if physical movement (directly related to the vestibular system) has a significant influence on spatial memory.

2.8.2 Stereopsis

Stereopsis refers to the depth perception through visual information that is obtained from the two eyes of an individual with normally developed binocular vision (Howard and Rogers 1995). The perception of depth is also possible with information visible from only one eye. In this case, the person uses differences in object size and motion parallax to have such perception (Howard and Rogers 2012). However, according to Barry (2009) the impression of depth cannot be as experienced as that obtained from binocular disparities. Furthermore, it is an important mechanism for seeing and assessing depth. It takes into account distances that depend on the use of both eyes together. In any scene with depth, our eyes receive slightly different images. Also, in daily life, many situations and actions are unnoticed. For example, stereoscopic vision produces conditions like pouring water from a jar to glass, catching a ball, parking a car or motorbike (calculating distances), and knowing how far or how near an object is (calculating depth), i.e., seeing the three-dimensional space. Moreover, stereopsis allows the brain to compare images of a scene of this type on the two retinas and to estimate relative depths with high accuracy. In people with normal vision, a sizeable minority seems to lack stereopsis (Howard and Rogers 1995). According to von Noorden and Campos (2002), not all people have the ability to perceive depth by stereoscopy. One current field of stereopsis applications is the design of stereoscopic imaging devices for VR systems (Mon-Williams, Warm, and Rushton 1993). In a VR system, two lightweight displays are carried on a helmet and viewed through lenses that magnify the images to create a binocular field. The display is coupled to the movements of the head to allow the viewer to look around the virtual environment (Howard and Rogers 1995).

Nowadays, many people do not know whether or not they have stereopsis problems. There are several tests for checking stereopsis. One of these tests is the Lang Stereotest, and it is based on pantographic presentation of random dot pattern. Therefore, no glasses are needed to recognize the stereoscopic images embedded in random dots on the test card. The only requirement is to place the card 40 centimeters in front of the subject. The Lang Stereotest is used to screen for stereovision deficiencies. This test combines two elements: random points and cylindrical grids (Lang 1983b; Lang 1983a). There are two types of cards in this test: Lang Stereotest I[1] (see Figure 2.6 (a)) and Lang Stereotest II[2] (see Figure 2.6 (b)).

The first card measures thick stereopsis. The second card measures fine stereopsis since it is composed of points that are finer. The Lang Stereotest I stereoscopically show a cat (1200”), a star (600”), and a car (550”). The Lang Stereotest II shows a monocular star and three objects stereoscopically (an elephant (600”) a truck (400”), and a moon (200”)). These tests have been designed to facilitate the analysis of stereopsis in young children, but it can also be applied to adults, as suggested by Brown et al. (2001). Those authors stated that the Lang Stereotest I is also suitable for assessing the vision of adults. In this thesis the Lang Stereotest I was used to measure stereopsis in adults.

2.8.3 Stereopsis recovery

Several previous works have focused on the idea of restoring stereopsis in adults. Two cases in which this recovering was described were experienced by Barry (2009) and Bridgeman (2014). Barry (2009) recovered from strabismus after visual therapy in adulthood. Bridgeman (2014) with stereo-deficiency, acquired stereopsis when watching a 3D movie. Besides these two personal experiences, other works have also been interested in stereopsis recovery. For example, Ding and Levi (2011) carried out a case study involving five adults who were stereoblind or stereoanomalous. After perceptual learning, the participants showed substantial recovery of stereopsis. They concluded that “some human adults deprived of normal binocular vision can recover stereopsis at least partially”. In the same year, Astle et al. (2011) carried out another case study involving two humans with anisometropic amblyopia whose stereopsis also improved after following a training course. Xi et al. (2014) carried out a case study involving 11 participants with anisometropic or ametropic amblyopia. Those participants were trained with anaglyphic textures with different disparities. They also experienced stereopsis improvement. Vedamurthy et al. (2016) trained adults who were stereo-blind or stereo-deficient using a natural visuomotor task (a Virtual Reality environment). They concluded that “some adults de-

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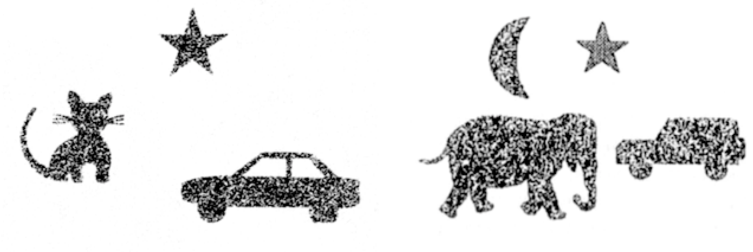
[1] Lang-Stereotest-I: `www.lang-stereotest.com/collections/products/products/stereotest-1`

[2] Lang-Stereotest-II:`www.lang-stereotest.com/collections/products/products/stereotestii`



(a) Lang Stereotest card I (b) Lang Stereotest card II

(c) View of the Stereotest

Figure 2.6: Lang Stereotest

prived of normal binocular vision and insensitive to the disparity information can, with appropriate experience, recover access to more reliable stereoscopic information”.

2.8.4 Visual perception

The visual perception refers to how we see the environment around us (its surfaces, layout, and their colors and textures). It also relates to where we are in the environment, whether or not we are moving, and where we are going. Besides, the visual perceptions helpful to decide what things are good for ..., or how to do everyday things (to thread a needle or drive an automobile) (Gibson 1984).

The natural vision depends on the eyes; the brain is the central organ that processes visual information. When the optical system has no constraints, deficiencies, or some abnormality, people can look around, walk up towards something interesting, and move around it so as to see it from all sides and go from one vista to another.

Perception comprises a series of processes that convert a physical phenomenon into information about our environment, through the stimulation of the perceptive organs (physical, physiological and psychological). Visual perception is of physical type and is related to the optical system. An optical element (for example a map) becomes information in the mind of the observer.

Stereoscopic perception can be achieved using new visualization and interaction techniques. It may provide a user with a higher sense of presence in virtual environments because of higher depth perception, leading to the greater comprehension of distance, as well as aspects related to it, e.g. ambient layout, obstacles perception, maneuver accuracy, etc. (Livatino and Privitera 2006).

For analyzing the benefits of stereoscopy, in previous works different depth cues, learning behaviors, etc. have been compared using one or two specific visualization technologies (Demiralp et al. 2006; Kasik et al. 2002). Nevertheless, depth perception and task performance may greatly vary for different display technologies, providing a user with a different sense of presence and interaction capabilities.

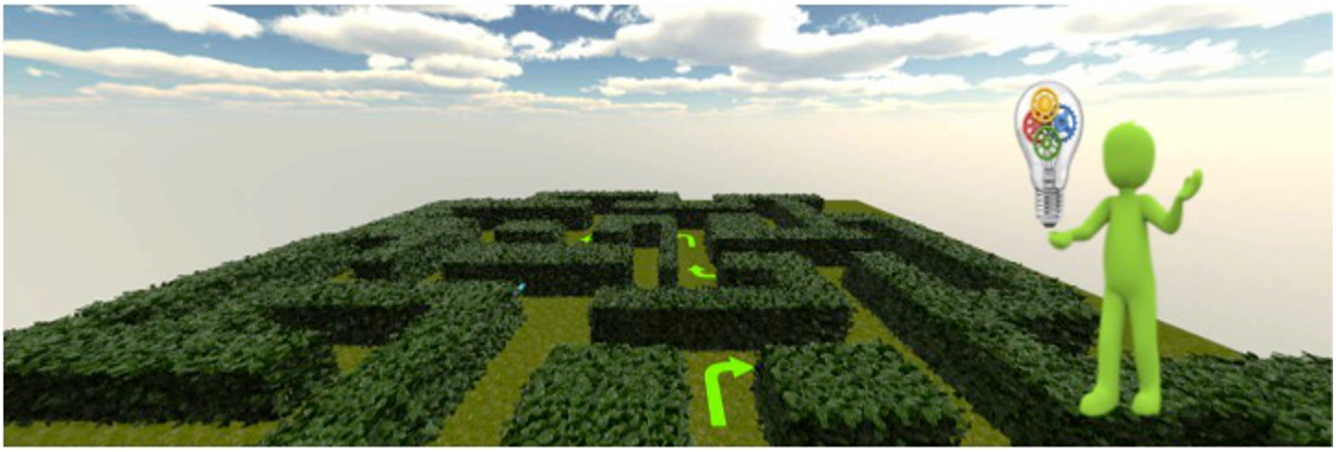
2.8.5 Users' perceptions

In this section, we focus on users' perceptions in which two different visualization devices have been compared. To our knowledge, no previous work has studied users' perceptions considering people with stereo-vision versus stereoblindness. However, some works have compared different versions of the same environment using HMDs. For example, Davis et al. (2015) used the Oculus Rift and compared two different virtual roller coasters, each with different levels of fidelity. They found that the more realistic roller coaster with higher levels of visual flow had a significantly greater chance of inducing cybersickness.

Also, previous works have compared HMDs with low and fully immersive VR systems and have quantified depth and size perception in virtual environments (Rolland, Gibson, and Ariely 1995). In contrast, in this thesis was compared an HMD with a partially immersive VR system.

CHAPTER

III



3

Development

“Virtual reality is the first step in a grand adventure into the landscape of the imagination”.

Frank Biocca, Taeyong Kim, and Mark R. Levy

3.1 Introduction

In this chapter, a detailed explanation of how was designed the VR system can be found. Next, information about the software and hardware are described. Finally, display systems and the types of interaction used are detailed.

3.2 Design of the VR system

The VR system consisted of a virtual environment, the task, display systems, and interaction devices. A scheme of the VR system can be seen in 3.1.

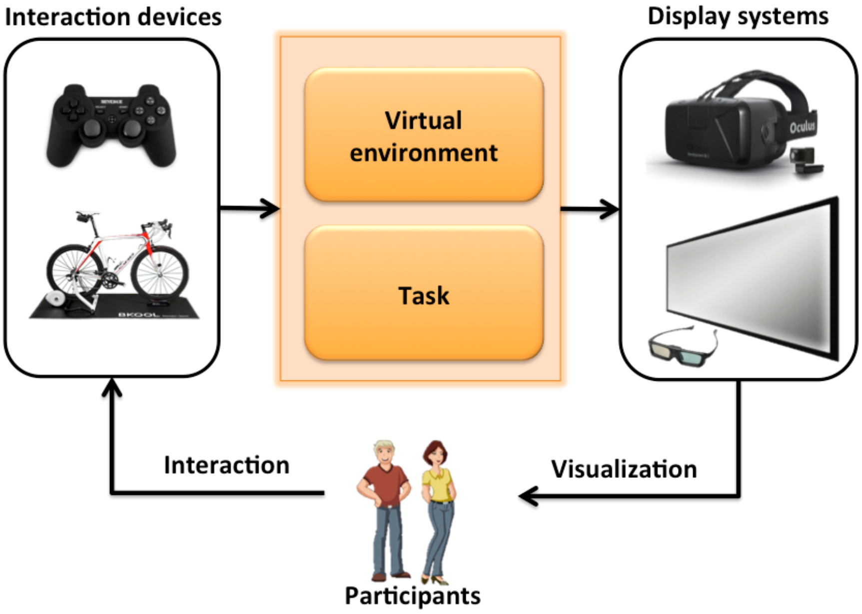


Figure 3.1: Scheme of the VR system

3.2.1 Virtual environment

The psychologist team of the CHILDMNEMOS project was in charge of the design of the virtual environment. The virtual environment was based on the Cincinnati Water Maze concept, which has been commonly used in laboratory studies of rats in order to assess short-term spatial memory (Arias, Méndez, and Arias 2014; see Figure 3.2).

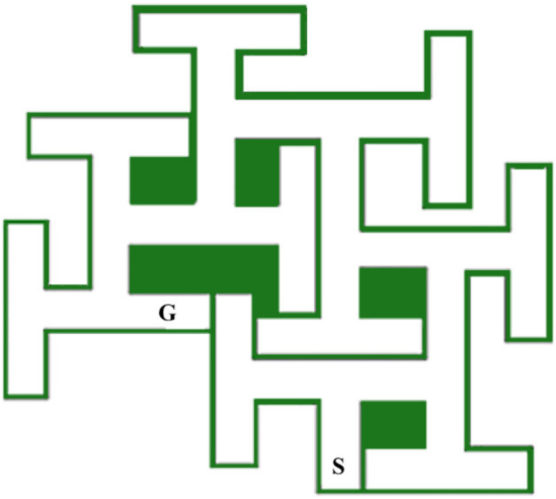


Figure 3.2: Schematic drawing of the Cincinnati Water Maze.

The advantages of using this maze to detect memory impairments in rats have been noted in Vorhees and Makris (2015). The original Cincinnati Water Maze has nine T-intersections. The virtual maze also has a route passing through nine T-intersections, and four of these Ts were modified to increase complexity. This virtual environment consists of hallways, a terrain with grass, and many walls of different lengths and two meters high filled with hedges (2 meters high) and pathways of grass (2 meters wide). The virtual maze can be seen in Figure 3.3. Also, at each intersection were defined detection zones to automatically placed back at the starting point the participant when chooses the wrong way. These zones allowed the participant to start the testing stage again.

Furthermore, several virtual objects were defined for the virtual environment: 3D animals, a 3D bicycle, green and yellow arrows.

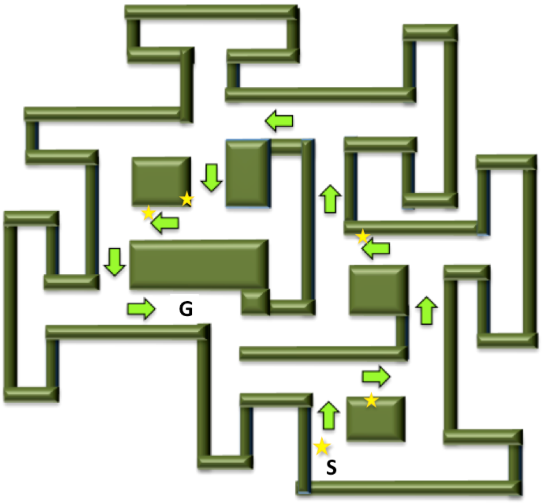


Figure 3.3: Scheme of the virtual maze, based on the Cincinnati Water Maze. Yellow starts indicate places of animals. Green arrows show the path. S = Start and G = Goal.

3D animals

The design of the virtual environment included four animals. They were placed on the route at different positions and at different heights, always on the right side of the path. The animals designed were a butterfly, a tortoise, a snail and a bird (see Figure 3.4).

(a) Butterfly (b) Snail (c) Tortoise (d) Bird

Figure 3.4: 3D animals

For example, the butterfly was placed at the second intersection, atop the wall; the snail was placed at the fourth intersection on the path. These animals were intended to help participants learn the route of the maze. The participant was able to move around the virtual maze while observing the environment, the sky, and animals (see Figure 3.5).

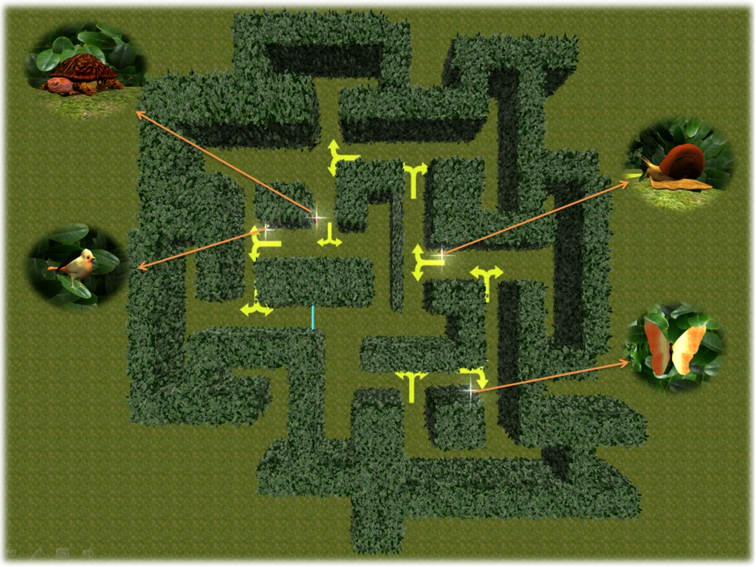


Figure 3.5: The virtual environment and location of 3D animals. Maze viewed from above.

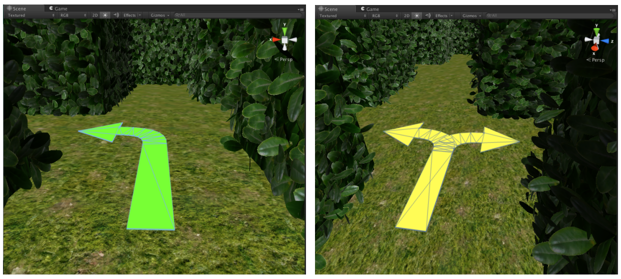
3D bicycle

A 3D bicycle as an avatar within the virtual environment was designed (see Figure 3.6). This bike represents the participant's point of view and personifies his/her movements in the maze. It allows that the participant could navigate the maze from a first-person perspective. Also, the participant could move around the virtual maze while he/she is observing the environment and animals. The handlebar of the 3D bicycle controls movements in the virtual maze so that the participant can turn right or left and only moves forward.

Figure 3.6: View of the 3D bicycle.

Arrows

A guiding technique based on directional arrows to enable helping in exploring the unfamiliar 3D environment was applied. The task of the exploring participant would be to find 3D objects on different places or paths without the spatial knowledge of this 3D environment.



(a) Green arrow (b) Yellow arrow

Figure 3.7: Arrows

The arrows models can be seen in 3.7. Two types of arrows were designed to suitably guide the participant, from the beginning of the path towards the end of the route. The green arrows were create to guide the participant from the beginning to the end of the maze. They must show options at each intersection for the participant to learn the route. Yellow, double-headed arrows were also designed. These arrows show possible turns when the participant was near an intersection. The yellow arrows were programed to disappear when the participant chose a path, and to reappear again at the next intersection.

3.2.2 Virtual Maze Task

The Virtual Maze Task is based on egocentric orientation. The user learns one's body position in space for orientation (i.e., idiothetic information). Kelly et al. (2008) also studied how egocentric experience, intrinsic structure, and extrinsic structure interact in a virtual environment. They found that the acquisition of spatial knowledge is similar to using virtual and real environments. Therefore, the Virtual Maze Task was designed to perform a cognitive task with two types of conditions of interaction (physical active and physical inactive) (see details in Section 3.3.4 Types of interactions). For the immersion and visualization were used two display systems (see Section 3.3.3 Display systems). The stages of this task were three stages: habituation, learning, and testing (see Figure 3.8).

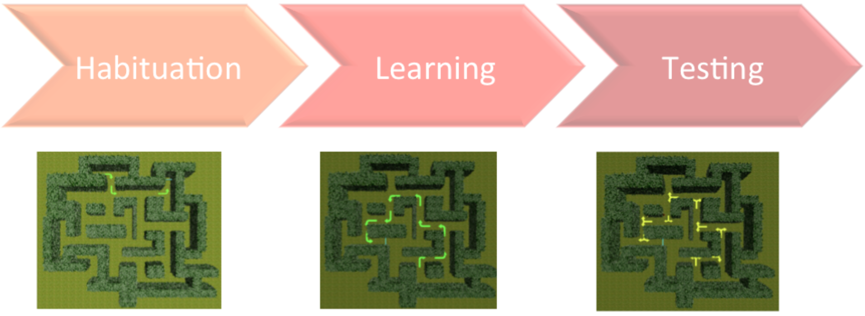


Figure 3.8: Stages of the virtual task.

- *The habituation stage* has an environment with a short route for approximately one minute. The path has four intersections and a straight road at the end. This is a trial stage to train participants to handle the system properly and to check that the HMD is properly positioned on their heads.

- *The learning stage* consists of an environment in which the participant follows another route with nine intersections and is guided by green arrows. The participant must learn the path.
- *The testing stage* has yellow arrows that show options at each intersection. The participant must remember and follow the same route that was followed in the learning stage. The participant was immersed in the virtual maze as if he/she was riding a bicycle. They could see the landscape and identify the animals to determine their positions. When the participants make a mistake in the choice of the direction, the system shows a warning message and they are automatically relocated back to the starting position. Each participant has five attempts to reach the end of the maze. The time increases with the number of attempts.

3.3 Development of the VR system

This section describes the software, hardware, displays systems and types of interaction used on the VR-system.

3.3.1 Software

For the development of the virtual environment was used Unity Edition Professional[1], version 4.6.0f3, as the game engine. 3D models of animals were taken from the De Espona 3D model library. The 3D animal models were edited in Blender 2.72 and GIMP 2.8.

For the VR system seven scenes were developed with Unity and programmed with C# and Javascript. The first four scenes can be seen by the monitor screen (see Figure 3.9). These scenes were designed to be filled out by the evaluator. The first scene allows the input of the participant's data as the birth date, gender and choose the type of interaction. Then, the VR system assigns a different code to each participant. According to the interaction type chosen, the second, third or fourth scene are displayed. These scenes have an option menu with buttons that load the VR scenes of each stage for the assessment of the task and/or to return.

The VR scenes contain the stages that the participant has to be carried out. (see Figure 3.10). The habituation stage correspond to the fifth scene. The sixth scene is the learning stage and the seventh scene is the test stage. When the participant finishes a stage, another menu is displayed allowing the

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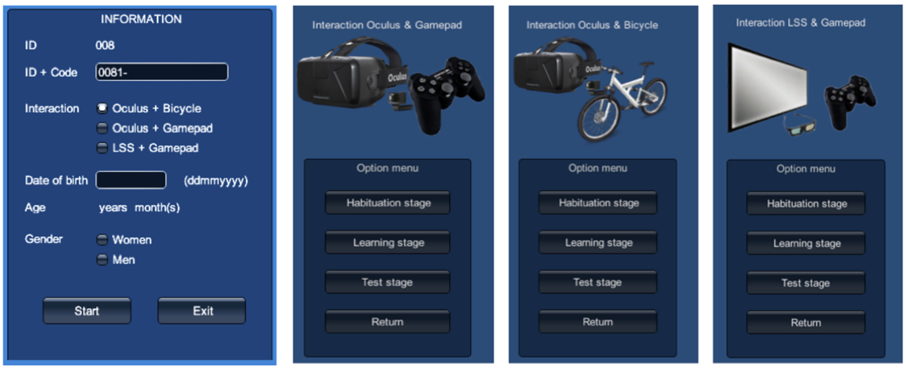
[1] Unity: `http://unity3d.com`



INFORMATION

ID 008

ID + Code 0081-

Interaction ● Oculus + Bicycle ○ Oculus + Gamepad ○ LSS + Gamepad

Date of birth ☐ (ddmmyyyy)

Age years month(s)

Gender ○ Women ○ Men

Figure 3.9: Scenes to be filled out by the evaluator.

participant to continue to the next stage until the task is complete. The VR scenes can be view through the HMD and the monitor screen.

Components

The VR system comprised the following components: the VM engine and the devices manager. This can be seen in Figure 3.11 and that is detailed as follow.

(a) VM engine

This component includes three modules:

- Task Engine, which manages the three phases of the task and the order of the scenes. This module was developed using C#.
- Graphic Engine, this manages visual maze rendering, collision detection, events in the task, bicycle animation, and voice messages. This was developed using Unity Edition Professional 4.6.0f3.
- Event Engine, this manages the events that occur within the virtual maze:
  - Collisions among items in the environment, such as the bicycle, walls, and animals. These algorithms were implemented using C#.
  - Bicycle movement, which in the locomotion-based condition, was based on the speed and gyro angle of the real bicycle. Four move-

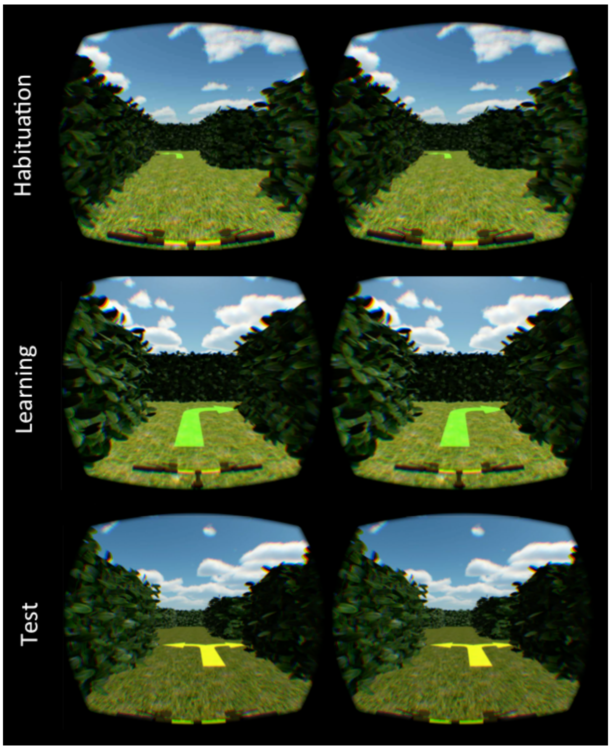


Figure 3.10: VR scenes to be filled out by the evaluator.

ments were possible: turning left, turning right, pedalling, and braking. These algorithms were developed using C# and JavaScript.

- Voice messages, delivered from loudspeakers to give context-specific instructions for task completion. This module was implemented using JavaScript.
- Recording of data such as time, attempts, head turning in text files (.txt). Recording was programmed using C#.
- Interactive Menu, which manages the running of the task and executing the scenes for each phase. It was developed with JavaScript and C#.

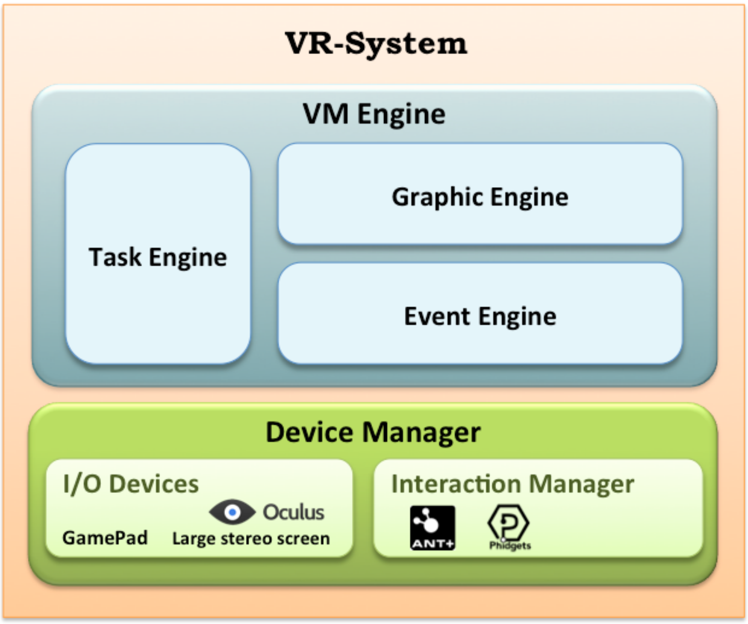


Figure 3.11: Components of the VR system

(b) Device manager

This includes two modules to ensure interfacing between the devices and software.

- Output-input devices
    - The Oculus Rift-DK2 HMD is one of the two output devices of the virtual maze. It features excellent resolution, high refresh rate, low persistence (so less motion blur), and positional tracking for low latency. This device includes an accelerometer, gyroscope, and magnetometer. The following manufacturer-supplied plug-ins were installed: Oculus SDK 0.4.2, Oculus Runtime, and Oculus Unity Integration Package. Installation of the Oculus Unity Integration Package features the following components: OVRMainMenu, OVRPlayerController, and OVRCameraController. The scripts required for the integration of the Oculus Rift-DK2 HMD with the virtual maze were programmed using C#. Oculus PC SDK 1.3 was installed to

  implement Asynchronous TimeWarp. These drivers and advanced hardware allowed us to reduce jitter and keep latency low.

  - The large stereo screen is the other output device of the virtual maze. A library was developed to create the 3D sensation using Unity. This library allowed the user to have the right point of view placing the two virtual cameras for simulating the two eyes of the user.

  - Gamepad is the input device of the virtual maze system set-up under the stationary condition. A scripting API from Unity was used to configure the gamepad and control the behavior of the virtual bicycle. The Controller Input Manager of Unity was used to integrate the gamepad with the virtual maze set-up.

- Interaction Manager

  This component controls the overall interaction logic and manages locomotion based interaction. This module acts as a middleware between the VM engine and the two sensors devices (accelerometer and speed sensor). Two modules process the interaction. The first module manages data from the speed sensor of the real bicycle, reflecting pedalling and movement of the rear wheel. The second module manages the data from the handlebar accelerometer, reflecting front wheel movement. Both modules were developed using C++.

3.3.2 Hardware

The Virtual Maze ran on an Intel Core i7 computer, 3.5 GHz processor with 16 GB RAM, an NVIDIA GeForce GTX-970 with a video card of 4GB, and Windows 8 Operating System. This computer was used for both studies. Two loudspeakers were also used to provide messages and instructions to the participants.

3.3.3 Display systems

In the study 1, an Oculus Rift-DK2 HMD was used for the visualization of the virtual maze. This device has a resolution of 960 × 1080 per eye, a field-of-view of 100 nominal, a weight of 0.32 kg, an optical frame rate of 75 Hz, head tracking, and positional tracking. This device also has an HDMI connector that needs to be plugged into the HDMI port of the graphics card of the computer. Video is sent to the Oculus Rift by this cable. This device also includes a

USB, which carries data and power to the device, and an audio jack 2.5 mm located on the side. In addition, this version includes an external IR camera that tracks the position of the participant's head in the 3D space. A detailed description can be found in (Desai et al. 2014).

Figure 3.12 shows a view of the virtual maze using the Oculus Rift-DK2 HMD.

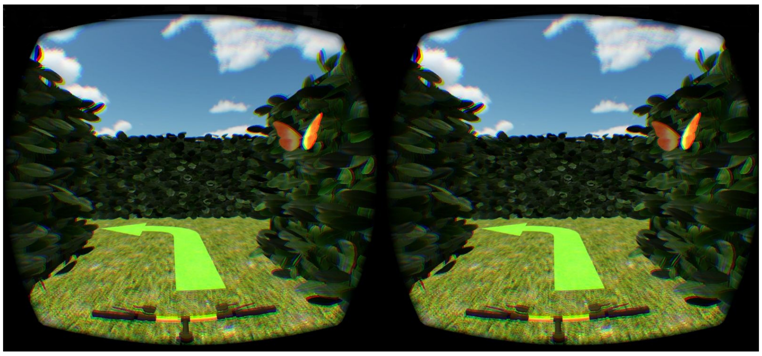


Figure 3.12: View of the virtual maze by Oculus Rift-DK2.

In the study 2, two types of display systems were used, an Oculus Rift-DK2 HMD and a large stereo screen. A large stereo screen is a high-resolution computer display. It should not be confused with normal projectors which simply display what is visible on a monitor onto a large screen. Figure 3.13 shows a representation of this room with the large stereo screen. The large stereo screen was installed in our University in a room that consists of two rear projectors, a wall dividing the areas with a translucent screen of 120-inch screen. The two projectors were placed in the projection area to project the two images onto the screen. These two images are polarized and a 3D image is created. These projectors could generate an image of 177 × 111 cm. at a throw distance of 140 cm. They produced a brightness of 3000 ANSI lumens and had a resolution of 1280 × 800 pixels. The participant must wear polarized 3D glasses to see the 3D image correctly.

A library was developed to create the 3D sensation. This library allowed the user to have the right point of view placing the two virtual cameras for simulating the two eyes of the user. The cameras are located at a standard intraocular distance (63 mm) (Dodgson 2004) and at a field of view of 60°. This value for the field of view was calculated from the real dimensions of the screen and the distance between the participant and the screen. This condition did not include head tracking.

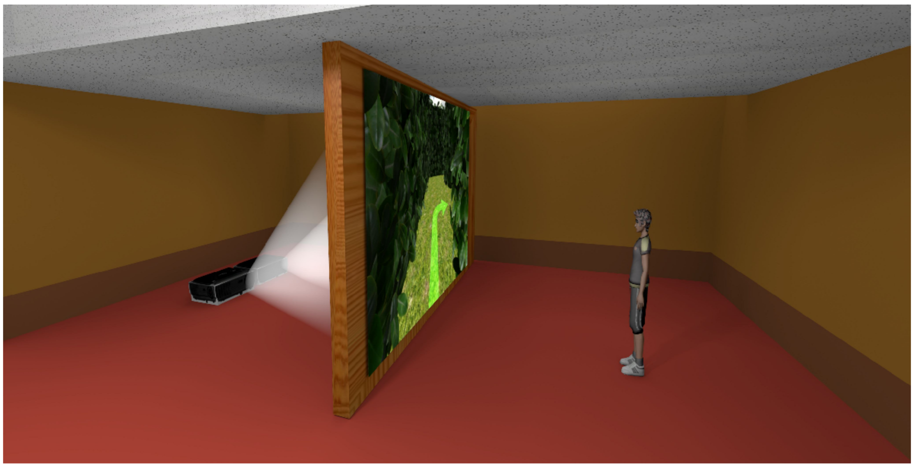


Figure 3.13: Testing room for the large stereo screen condition

3.3.4 Types of interaction

Two types of interaction interfaces were defined: stationary and locomotion. The participants must navigate the virtual maze using the corresponding interface. Participants completed the virtual maze task under two different experimental conditions, reflecting different types of interaction with the virtual environment: locomotion-based interaction (riding on a bicycle), and stationary interaction (sitting using a gamepad).

(a) Stationary

This type of interaction consisted of using a gamepad while the participant was seated on a chair (physical inactive condition) (see Figure 3.14). The participant was also able to move forward and to turn right or left by using the controller on the gamepad. The participant only had to stop moving the controller on the gamepad to stop the 3D bicycle.

In the stationary condition, the participant navigated the virtual maze while sitting in a chair and holding an AB-Move BG Revenge gamepad with both hands. The participant input interactions (move forward, turn left, turright), and the commands were relayed to the virtual environment via Bluetooth. To stop the virtual bicycle, the participant simply stopped moving the left stick control. This type of interaction was used in the two studies carried out in this thesis. The gamepad was integrated into the system thanks to the

Figure 3.14: Stationary interface (physical inactive condition)

Figure 3.15: Gamepad used to navigation.

controller *Input Manager* of Unity, which enabled functions and personalized the use of the device in the two visualization systems. The collision of objects in the environment was controlled to avoid the participants from colliding with the walls (see Figure 3.15).

(b) Locomotion

The second type of interaction consisted of a physical bicycle (physical active condition). The participant controled the navigation and the 3D bicycle by using the physical bicycle (see Figure 3.16). When he/she pedals the physical bicycle, he/she moves forward in the virtual maze. The participant was also able to control the turns by using the handlebar. When the participant wants to stop the bicycle, he/she only had to press the brake of the physical bicycle. All of these effects were also reproduced in the 3D bicycle.

Figure 3.16: Locomotion interface (physical active condition)

A mechanism of interaction for the locomotion was mounted and it consisted of a mountain bike fixed to a BKOOL[2] roller (see Figure 3.17). The BKOOL was used with an ANT+ Bike Cadence Sensor. The Bkool roller (classical model) was used to obtain the cadence, and to fix the rear wheel of the bicycle. This roller fixed the rear wheel of the bike, while the front wheel sat in a base. The bike and roller lay atop a black, gel-filled rubber mat (1820 × 810 × 6 mm) to protect the floor and ensure the stability of the roller and bike. A fiber plate was placed on the rubber mat to allow easy rotation of

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[2] BKOOL: `http://www.bkool.com`

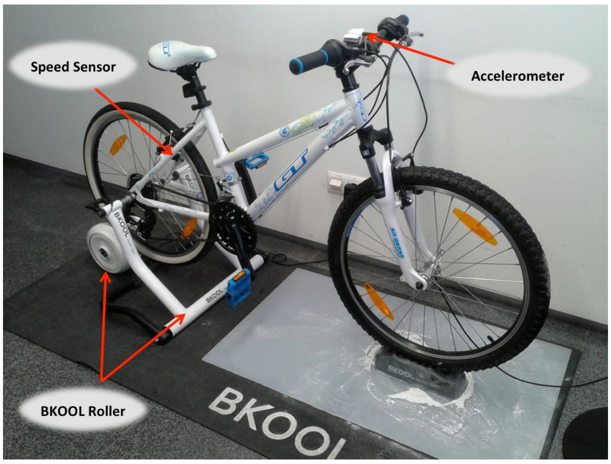

Figure 3.17: Bicycle on the Bkool roller and sensors.

the base under the front wheel. This type of interaction was used only in the first study.

Speed sensor

A MyCiclo Speed Sensor ANT+ was attached via plastic ties to the chain stay. It used ANT+^{TM} wireless technology to transmit speed to a wireless receiver connected to the computer used in this project. The device can be seen in Figure 3.18.

Figure 3.18: Speed sensor.

Accelerometer

In the beginning, the Wii Remote controller was used to obtain the turns of the handlebar of the bicycle. However, since the Oculus Rift-DK2 HMD is used for visualization, there was a conflict between the two devices that made their simultaneous use impossible due to that both use infrared sensors. This must be taken into account in future developments. Then, we decided to test an accelerometer PhidgetSpatial, it worked according to the requirements of the VR system. Therefore, an accelerometer board 1056 PhidgetSpatial (3/3/3) from Phidgets[3] was attached to the handlebar to detect the gyro angle of the front wheel. The device can be seen in Figure 3.19. It was connected to the computer via USB cable. The speed and gyro angle were used to dynamically control the bicycle animation. The dimensions are 36×31×6 mm. The libraries (*Phidget21 Libraries Setup*) supplied by the manufacturer were installed to set this accelerometer.

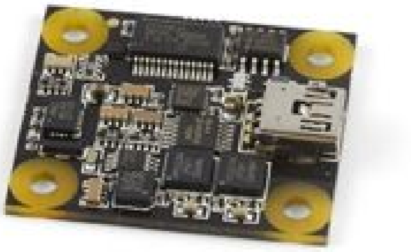

Figure 3.19: Accelerometer board PhidgetSpatial

A program with Visual C++ was developed in order to obtain the angles of rotation of the handlebar. This program also checks that the device is connected, sends error messages, initializes the accelerometer, updates data, and obtains the position data in 3D and the angle in radians.

A script called Interaction was developed in C# to control the movement of the avatar from the data obtained using the two mechanisms of interaction. In the case of interaction using the bicycle, the script uses information from the speed and rotation of the handlebar to calculate the rotation angle of the handlebar “n” degrees relative to the y-axis. It uses the *Quaternion.Euler* method. The *Transform.Rotate* method is used to activate the rotation of the virtual bicycle (avatar). The bicycle speed data is used by the *Controller.Move* method to activate the forward movement and displacement of the virtual bi-

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[3] PHIDGET: `http://www.phidgets.com`

cycle in the environment.

The *Input.GetAxis* method (“axisName”) was used in the Interaction. The *Input.GetAxis* returns values in the range [-1,+1]. The neutral position is 0. When axisName = “Horizontal” returns]0,+1] for the horizontal movement to the right and]0,-1] for the horizontal movement to the left. For the vertical axis, the axisName = “Vertical” and the functionality is similar. A condition that disables the backward movement was added so that the user cannot move in reverse. The values of the horizontal movement of the gamepad lever are used by the *Quaternion.Euler* method to calculate the rotation of the handlebar. The *Transform.Rotate* method is used to activate the rotation of the virtual bike (avatar). The values of the vertical movement of the gamepad lever are used by the *Controller.Move* method to activate the forward movement and the displacement of the virtual bicycle in the environment.

The participant was able to execute four kinds of movements in the virtual environment, which were transmitted to the virtual bicycle through the real one: turning left, turning right, pedalling and braking. The perceptual experience of moving in the virtual environment was created when participants pedalled the stationary bicycle and viewed the resulting 3D visual information through the Oculus Rift-DK2 HMD.

CHAPTER

IV

4

Study 1: Assessment of spatial short-term memory

> *"The true art of memory is the art of attention."*
>
> `Samuel Johnson`

4.1 Introduction

This chapter presents a novel study for assessing spatial short-term memory in adults using a VR system involving physical movement and immersion. The virtual maze task was performed with two types of conditions (physical active and physical inactive) (see section 3.3.4 of Chapter 3). For the immersion and visualization was used the Oculus Rift-DK2 HMD in both conditions of interaction. The capability of the VR system was tested, and the performance and sensations of the participants between both conditions were compared. Also, the performance on the virtual maze task was compared with traditional neuropsychological tests.

4.2 Design of the study

The VR system is described in the section 3.2 of the Chapter 3. This section explains about the sample, the measurements and the procedure carried out during the study.

4.2.1 Participants

University students participated in this study (N=92). A recruitment campaign was conducted to find the participants by advertising within the campus facilities.

All the participants were informed in writing about the aims and procedures of the study, and they signed an informed consent form. They were fully free to leave the study at any time, and the study was conducted according to the principles stated in the Declaration of Helsinki. The Ethics Committee of the Universitat Politècnica de València (Spain) approved the research protocol.

Control and selection of the sample

The participants were randomly assigned to one of the following conditions: physical active condition (N=47) and physical inactive condition (N=45). Three participants did not finish the task as they presented symptoms of cybersickness (in physical active condition were 2 women and physical inactive condition was 1 man). These three participants were excluded from the sample. Therefore, the total of participants considered for our study was 89: physical active condition (N=45) and physical inactive condition (N=44). The 89 participants completed the task and filled out the questionnaires. The mean age in the physical active condition was 26.38 ± 3.87 years old and the mean age in the physical inactive condition was 25.38 ± 4.11 years old. There were 25 women and 20 men in the physical active condition, and 21 women and 23 men in the physical inactive condition. The handedness of the participants was determined (Oldfield 1971).

In the physical active condition, 39 participants were right-handed, 1 participant was left-handed and 5 participants were ambidextrous. In the physical inactive condition, 34 participants were right-handed, 7 participants were left-handed, and 3 participants were ambidextrous.

The participants filled out a questionnaire, which provided information about habits with the aim of controlling variables that could interfere in the interpretation of the results. The participants did not have habits (drugs and medications) that could influence this study. Also, they did not have symptoms of sickness before the task, based on the Simulator Sickness Questionnaire (SSQ) (Kennedy et al. 1993) (see questionnaire in section A.4). The education levels of the participants in the physical active condition in percentages were the following: undergraduate students (42.9%), graduate students (23.8%), Master's students (21.4%), and PhD students (9.5%). In the physical inactive condition, the education levels of the participants were: undergraduate students (27.9%), graduate students (23.2%), Master's students (34.9%), and PhD students (7.0%).

4.2.2 Measurements

The following variables about the performance on the task and the performance on traditional neuropsychological tests were defined.

(a) Performance on the Virtual Maze Task

To measure the performance on the Virtual Maze Task, the following variables were calculated:

- The number of attempts to successfully complete the path in the testing stage (VMAttempts).
- The time for completion of the testing stage in seconds (VMTime).
- The number of participant's head-turns performed at intersections in which he/she chose a correct direction during the testing stage (VMHeading).

- The score (VMScore) was obtained by adding the number of correct directions chosen in each of the five attempts established to complete the path in the testing stage. We defined ten points per attempt and a maximum VMScore of fifty points.
- The average time of the task for each interaction.

(b) Performance on traditional neuropsychological tests

To measure the performance on traditional neuropsychological tests, the following tests were applied:

- Spatial ability was also assessed with classical neuropsychological tests. The Corsi Blocks Task (CBT forward (CBTF) and backward (CBTB) versions) were administered to assess visuospatial short-term working memory (Kessels et al. 2000).
- Verbal short-term working memory was assessed. For this purpose, two verbal span subtests of the TOMAL battery were used: Digits Forward (DF) and Digits Backward (DB) (Reynolds and Bigler 1994). The DF is a task that measures low-level rote recall of a sequence of numbers. The DB task (a variation of the DF task) consists of a recall of a sequence of numbers, but in reverse order.
- For the assessment of left-right orientation ability, a paper pencil adaptation of the computerized Random Walker Test (RWT) was used (Uchiyama, Mitsuishi, and Ohno 2009). The verbal version of the RWT provides verbal instructions, and the participants must judge the spatially correct direction. The score and the time for completion were used as measures of performance on the RWT, and the acronyms RWTS and RWTT were used respectively. Also, the direct scores for the CBTF, CBTB, the DF and the DB subtests were considered.

4.2.3 Procedure

The participants were tested individually in two sessions, which took place on the same day. The participants were randomly assigned to one of the two experimental sessions. The virtual task lasted around six minutes, and the traditional tests lasted around thirty minutes. The steps of the experimental procedure are shown in Figure 4.1.

- In Session I, the participants were assessed with the Virtual Maze Task, and they then were evaluated with neuropsychological tests.
- In Session II, the participants were evaluated with neuropsychological tests, and they then were assessed with the Virtual Maze Task.

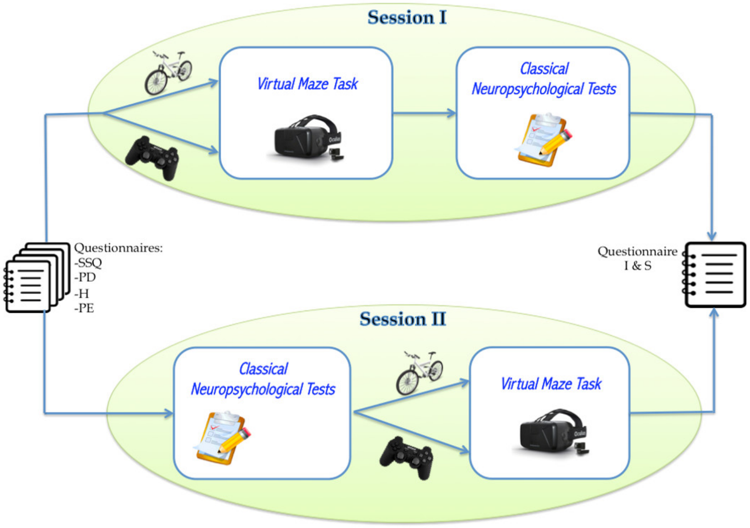


Figure 4.1: Protocol of the experimental study for the assessment of spatial short-term memory.

Before starting the testing sessions, each participant was verbally informed about the exposure session, the virtual environment, the Oculus Rift-DK2 HMD as the visualization device, and the type of interaction used. Also, each participant completed the handedness questionnaire, the questionnaire about personal data, and the Simulator Sickness Questionnaire (SSQ) (see questionnaire in the appendix A.4) (Kennedy et al. 1993). The previous experience of the participants with 3D technology and other technological devices were also assessed (see appendix A.1.1). When he/she finished the virtual task, he/she answered another questionnaire on the interaction and satisfaction (see appendix A.2).

Furthermore, one group of participants explored the virtual maze under the active physical condition. They wore an immersive HMD that allowed tracking the head turns and to explore the virtual environment from a stationary bicycle (pedaling a bike) (see Figure 4.2). The average time for this condition was 6.52 minutes.

The other group engaged in the same virtual maze under the inactive physical condition. This type of interaction used a gamepad and the participant was seated on a chair (physical inactive condition) (see Figure 4.3). The average time under this condition was 5.27 minutes.

Figure 4.2: A participant carrying out the task with the bicycle.

Figure 4.3: A participant carrying out the task with the gamepad.

4.3 Results

This section presents the analysis of the data collected from this study. The statistical program SPSS, version 20 (SPSS Inc., USA, 2011) was used to conduct all statistical analysis. In order to explore means and standard deviation, an initial descriptive analysis was carried out. First, data normality was checked. The data fit the normal distribution. Therefore, the tests used were parametric. A one-way analysis of variance (ANOVA) was performed to analyze questionnaire responses regarding interaction and satisfaction outcomes.

A two-way ANOVA was conducted which examined the effect of gender and interaction on the Virtual Maze Task results.

Pearson's correlations were carried out to explore the relationship between Virtual Maze Task measures and neuropsychological tests. For all of the tests, a $p < .05$ determined significance.

4.3.1 Interaction and satisfaction outcomes

The responses to each question about interaction (QI) were averaged to yield a composite score for interaction (7 items, $\alpha = .693$). We did the same for the questions about satisfaction (QS) (5 questions, $\alpha = .789$) and the questions about previous experiences with 3D technology and other technological devices (QPE) (3 items, $\alpha = .530$). As Table 4.1 shows, no statistically significant differences were found for any of the interaction and satisfaction questions. Similarly, there were no differences between the two groups considering previous experiences. The interaction with the bike was 6.52 minutes, and the average time for the interaction with the gamepad was 5.27 minutes. However, the time could increase based on the number of attempts.

Table 4.1: Mean ± Standard Deviation for the composite score about interaction (QI), satisfaction (QS), and previous experiences (QPE). One-way ANOVA between the physical active condition (Bike) and the physical inactive condition (Gamepad) and r effect size.

Questions	**Bike**	**Gamepad**	***F***	***p-value***	***r***
QI1-QI7	3.87 ± 0.49	4.08 ± 0.52	3.85	.053	0.042
QS1-QS5	4.05 ± 0.61	4.12 ± 0.69	0.28	.595	0.003
QPE1-QPE3	1.74 ± 0.67	1.98 ± 0.72	2.75	.101	0.031

4.3.2 Virtual Maze Task outcomes and correlations with neuropsychological tests

A two-way ANOVA (Gender × Interaction) was used to analyze the measures obtained in the Virtual Maze Task. The results are shown in (Table 4.2). Men performed a higher number of attempts to complete the testing stage than women. Also, the participants who used the bike made more attempts than those who used the gamepad. There were no differences between men and women or between conditions assigned for the time spent to complete the testing stage. The men who used the physical active condition made more head turns. Finally, the participants who used the physical inactive condition scored better than those who performed in the physical active condition.

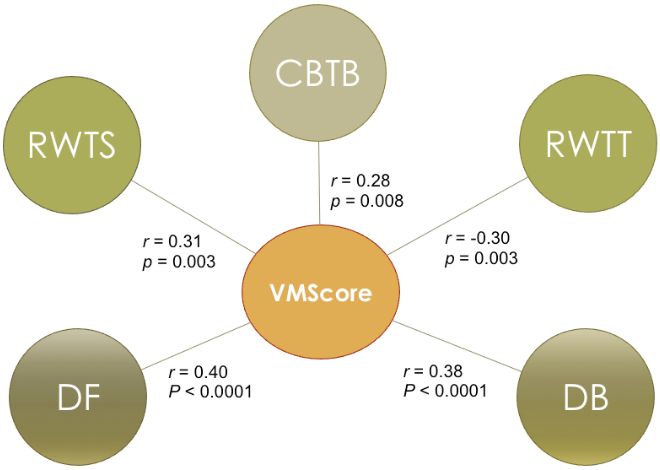


Figure 4.4: Correlations between the Virtual Maze Task and the neuropsychological tests. VMScore (Score of the virtual task); CBTB (Corsi Block Task Forward); DF(Digits Forward); DB (Digits Backward); RWTS (Random Walker Test Score); RWTT (Random Walker Test Time).

The results of the correlations found between the Virtual Maze Task measures and the performance scores on classical neuropsychological tests are shown in (Figure 4.4 and Table 4.3). There are significant correlations between our task and classical tests.

Table 4.2: Mean ± Standard Deviation for measures obtained in the Virtual Maze Task by men and women in the physical active condition (Bike) and physical inactive condition (Gamepad). Two-way ANOVA (Gender × Condition). The asterisks (**) indicates significant differences.

Measures	**Condition**				**Effect**		
	Bike		**Gamepad**		**Gender**	**Condition**	**Interaction**
	Men	**Women**	**Men**	**Women**	***(F)*** ***p-value***	***(F)*** ***p-value***	***(F)*** ***p-value***
VMAttempts	2.25 ± 1.74	0.80 ± 1.22	0.78 ± 1.24	0.95 ± 0.74	(5.55) .02**	(5.85) .02**	(8.88) .004*
VMTime	382 ± 136	328 ± 179	290 ± 167	379 ± 130	(0.26) .61**	(0.39) .53	(4.66) .034*
VMHeading	2.45 ± 1.93	1.08 ± 0.91	0.87 ± 0.92	1.38 ± 1.11	(2.57) .11	(5.72) .02**	(12.37) .001*
VMScore	44.75 ± 5.68	46.64 ± 4.34	48.26 ± 2.86	47.00 ± 3.25	(0.13) .72	(4.82) .03**	(3.19) .080

Table 4.3: The correlation matrix of the Virtual Maze Task and classical neuropsychological test performance scores. The correlation coefficients (*r*) that reached significance (*p: p-value*) are displayed in bold type.

		VMTime	**VMHeading**	**VMScore**	**CBTF**	**CBTB**	**DF**	**DB**	**RWTS**	**RWTT**
VMAttempts	*r*	**.59**	**.62**	**-.48**	**-.21**	**-.25**	-.17	**-.24**	**-.29**	.17
	p	**<.0001**	**<.0001**	**<.0001**	**.04**	**.02**	.11	**.02**	**.005**	.11
VMTime	*r*		**.59**	**-.33**	-.19	-.16	**-.26**	**-.21**	-.17	.19
	p		**<.0001**	**.002**	.07	.13	**.01**	**.04**	.11	.07
VMHeading	*r*			**-.51**	.01	-.02	-.16	-.19	-.12	-.01
	p			**<.0001**	.92	.87	.14	.09	.28	.92
VMScore	*r*				.18	**.28**	**.40**	**.38**	**.31**	**-.30**
	p				.08	**.008**	**<.0001**	**<.0001**	**.003**	**.003**
CBTF	*r*					**.73**	**.36**	**.23**	.10	**-.53**
	p					**<.0001**	**<.0001**	**.03**	.36	**<.0001**
CBTB	*r*						**.35**	**.31**	**.26**	**-.60**
	p						**.001**	**.003**	**.02**	**<.0001**
DF	*r*							**.61**	.09	**-.41**
	p							**<.0001**	.39	**<.0001**
DB	*r*								.16	**-.33**
	p								.12	**.001**
RWTS	*r*									-.17
	p									.11

4.4 Discussion

In this study, the capability of the VR system to assess spatial short-term memory in adults was tested. Some applications for assessing spatial memory in humans have been previously developed (Koening et al. 2011; Cánovas, García, and Cimadevilla 2011). These applications used basic methods of human computer interaction. A review of the literature indicates that a task that incorporates stereoscopy (VR HMD) and physical movement (ride a bike) for the assessment of spatial short-term memory has not yet been developed.

The significant correlations found between the performance on the virtual task and classical neuropsychological tests suggest that the task involved sustained attentional demands and higher working memory capacity. These results also corroborate the primary hypothesis (H1). Based on the correlation with the RWT, egocentric orientation also played a significant role in the performance of this VR task (Uchiyama, Mitsuishi, and Ohno 2009). The positive relation with the DF and DB could suggest that verbal strategies contributed to solving the task, helping to verbally memorize the body turns associated with choice points and the landmarks (Spiers and Maguire 2008). The negative correlation found between the head turns made at intersections and the score on the task was interesting. This result reinforces the possibility of the verbal strategy being a better strategy than other types, such as memorizing the body turns. In line with this, it should be pointed out that the Oculus Rift-DK2 HMD was a good tool for the assessment of the position of the participant's head in the 3D space, providing us with valuable information that has not been considered in other studies with virtual mazes (Werkhoven, Erp, and Philippi 2014; Zancada-Menendez et al. 2015). This information helps us to understand the factors that contribute to learning in complex spatial environments.

Differences in the Virtual Maze Task score were not statistically significant for gender. This result corroborates our second hypothesis (H2). However, the Virtual Maze Task score showed statistically significant differences between the two types of conditions, in favour of the physical inactive condition. This result does not corroborate the third hypothesis (H3). It was expected that there would be no differences and that if they had been, they were in favor of the physical active condition. As mentioned in the introduction section, the physical movement is directly related to the vestibular system and it was hypothesized that it would have a positive influence on spatial memory. However, this influence has not been reflected in the results. Although unexpected, this result in favour of the physical inactive condition is in line with the study of Cutmore et al. (2000), which found that spatial learning in virtual environments with an active exposure was not more advantageous than a passive exposure. Also, the differences for type of interaction show the importance of methodological factors in the study of spatial memory in humans (Andreano and Cahill 2009). Moreover, in this study, the physical inactive condition can also be performed by people with reduced mobility (Hill-Briggs et al. 2007).

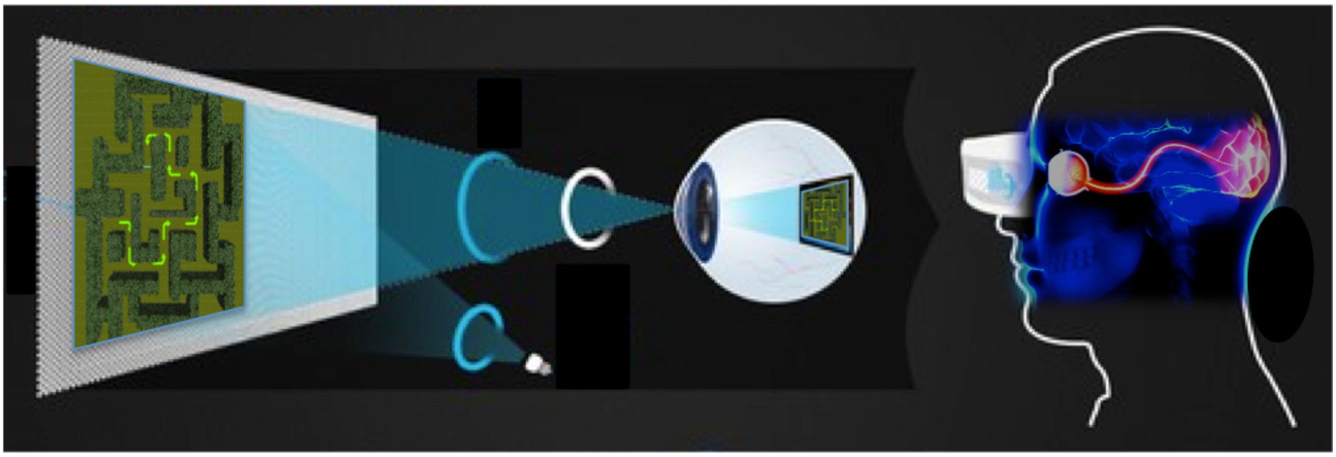
The participants did not differ in their opinions about interaction and satisfaction with the experience in the Virtual Maze Task. These results corroborate the fourth hypothesis (H4).

The results of this study suggest that the current HMDs (e.g., Oculus Rift) and other HMDs have great potential for psychology, especially for the assessment of spatial short-term memory. The Oculus Rift has already been used in psychology. For example, Gutiérrez-Maldonado et al. (2015) used it for training diagnostic skills in eating disorders.

Even though the Oculus Rift has several benefits, it also has some drawbacks. One of the drawbacks to our proposal is that the Oculus Rift-DK2 HMD needs a computer connection by wire. The use of a wireless VR HMD with the same or greater immersion features would make the system more free, and would allow the user freedom of movement without fear of stumbling upon or becoming tangled in cables. According to some predictions (The Farm 51 2015), half a billion VR headsets will be sold per year by 2025, and more than 400 hundred million will be wireless VR HMD. In these predictions, the number of wireless VR HMD sold in 2016 is more or less the same as the wired VR HMD. However, this trend is not predicted to continue. It has been predicted that a hundred million of VR HMDs will be sold by 2020. Of these, less than 20% will be wired VR HMDs. This opinion is shared, the wireless VR HMD would be decisive in the future for many applications. Another drawback of the Oculus Rift (in general of the HMDs) is the cybersickness that the HMDs may induce. As Davis et al. (2015) indicated, the more realistic the environment with higher levels of visual flow, the greater the chance of inducing cybersickness. It would be very interesting to determine whether the Oculus Rift induces more cybersickness than other HMDs. Cybersickness is a limitation in this task. In fact, 3 out of 92 participants in the study did not finish the task. Therefore, people prone to cybersickness could not use this type of task. Another limitation of the physical active condition is for people with mobility problems.

CHAPTER

V



5

Study 2: Assessment of 3D experience using VR devices for people with stereo-deficiencies

"There are things known and there are things unknown,
and in between are the doors of perception."

`Aldous Huxley`

5.1 Introduction

In this chapter is described the assessment of depth perception between participants who had not and who had stereopsis. The participants were exposed to a virtual maze task described in Chapter 3. For visualization, two display systems were used, the Oculus Rift-DK2 and a Large Stereo Screen using polarized glasses. For interaction, the participants used a gamepad.

5.2 Design of the study

The VR system and the two display systems described in Chapter 3 were also employed in this study. The study compared the participant's perceptions using a 3D environment in two conditions: Oculus Rift-DK2 (HMD) and Large Stereo Screen (LSS). This section describes the participants, the measurements considered, and the protocol followed during the study.

5.2.1 Participants

Students of the Universitat Politècnica de València (Spain) participated in this study (N = 59; mean age 25.83 ± 3.97; 35 men and 24 women). A recruitment campaign was conducted to find the participants by advertising within the campus facilities. The participants were randomly assigned to each condition. Since the task was the same, each participant used only one of the two conditions. The participants were assigned randomly to two groups (30 participants for the HMD condition, and 29 for the LSS condition).

5.2.2 Measurements

For the analysis of data were defined the following measures: control variables, performance on the task, also two questionnaires and the Lang Stereotest I were applied.

(a) Control Variables

To carry out the study, two control variables were defined. The main goal was to establish homogeneous groups in terms of previous experiences with 3D activities and to determine which participants had stereopsis and which ones did not.

(a.1) Previous Experience Questionnaire (PEQ)

The PEQ was used to determine whether the participants of both groups had previous experience with 3D activities and video games. The PrevExperience variable combines the answers to questions related to previous experience (see appendix A.1.2). The questionnaire used a Likert scale [from 1 to 5 (1 being "none" or extremely low and 5 being "very high")].

(a.2) Lang Stereotest I

The Lang Stereotest I was applied to determine which participants had stereopsis and which ones did not. The objective was to have the sample of participants without stereopsis as large as possible to compare them with the population with stereopsis. Brown et al. (2001) administered the Lang Stereotest I to 292 participants and concluded that this test correctly identified people with vision defects associated with reduced stereopsis and that it was appropriate for vision screening of both adults and children. The Lang Stereotest I has three objects. We followed the protocol suggested by Brown et al. (2001). A participant passed the test when he/she had 3/3 positive responses, 3/3 partial positive responses, or 2/3 positive and/or partial positive responses where the negative response was at the 550" level. A participant failed the test when he/she had 3/3 negative responses and 2/3 negative responses where the single positive or partial positive response was at the 1200" level. In the sample, 22 participants were successful in the Lang Stereotest I for the HMD condition (73.33%), and 22 participants were successful for the LSS condition (75.86%). Therefore, 8 participants failed the Lang Stereotest I in the HMD condition (26.67%), and 7 participants failed in the LSS condition (24.14%). These results ensure an equivalent number of participants in the two conditions. In a study by Brown et al. (2001), 6.5% of the participants failed the test. Other studies have indicated that this percentage can be between 5% and 10% (Castanes 2003), or as high as 34% in older subjects (Zaroff, Knutelska, and Frumkes 2003). In this case, this percentage is considerably higher than in normal population. This is because we especially invited people who we knew did not have stereopsis to participate in the study.

(b) Performance on the task

To determine the performance on the task, the following variables were calculated:

- The time for completion of the task in seconds (Time).
- The number of head turns by the participant performed at intersections (Headings).
- The number of attempts made to successfully complete the path (Attempts).
- The score (Score). The Score was obtained by adding the number of correct directions chosen in each of the five attempts established to complete the path. We defined ten points per attempt and a maximum Score of fifty points. Specifically, the Score was obtained as follows. Each participant had five attempts to reach the end of the maze. If in the first attempt, the participant reached the end of the maze, the task ended. If a participant chose a wrong direction at an intersection, the participant automatically returned to the starting point and went to the next attempt. If the participant went through all the five attempts, the task ended. The participants received a point for each correct choice of an intersection in each attempt. There are 10 intersections in total. The participants received 10 points for each attempt that they did not have to complete. Thus, if the participants reached the end of the maze on the first attempt, they received 50 points.

(c) Questionnaire on the Interaction, 3D sensations, and Satisfaction

This questionnaire was applied to know the perceptions of the participants about interaction, 3D sensations, and satisfaction with the VR system. The questionnaire can be seen in the appendix A.3. Most of the questions related to presence were adapted from the Presence Questionnaire proposed by Witmer and Singer (1998).

5.2.3 Procedure

A general scheme of the protocol of the experimental study can be seen in Figure 5.1. All of the participants were duly informed about the purpose of the study before each session. They signed the Informed Consent for participation, and the study was conducted according to the principles stated in the Declaration of Helsinki. The Ethics Committee of the Universitat Politècnica de València (Spain) approved the research protocol.

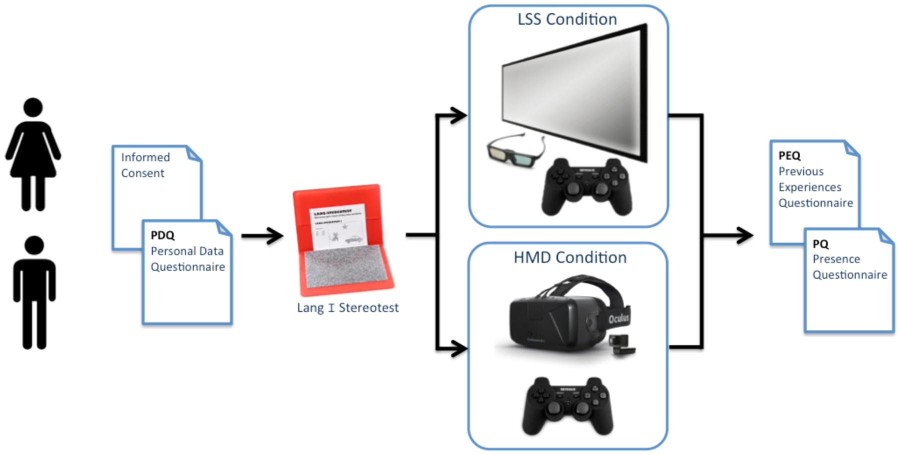


Figure 5.1: Protocol of the experimental study for assessment of 3D experiences.

Before each session, all of the participants filled out the Personal Data Questionnaire (PDQ). Afterwards, they were checked for stereopsis using the Lang Stereotest card I (Lang 1983a; Brown et al. 2001). The participants were divided into two groups. Each group participated in only one session and was exposed to only one of the two different conditions. One group used the HMD and the other group used the large stereo screen (intersubject analysis). Finally, when they had finished, they completed the questionnaire about previous experiences (PEQ), and another questionnaire to know their perceptions about interaction, 3D sensations, and satisfaction (see appendix A.3).

In the HMD condition, the participants were seated in a chair and wore an Oculus Rift-DK2 HMD with head tracking enabled. Figure 5.2 shows a participant carry out the task in the HMD condition. The lenses of the HMD were positioned properly for each user's eyes. This adjustment was achieved by turning the lateral adjuster to fix the separation between the participant's eyes (interpupillary distance). The HMD was kept firmly in place by strapping it tightly to the participant's face.

Figure 5.2: A participant carrying out the task wore the Oculus Rift and using the gamepad.

Figure 5.3: A participant in front of the large stereo screen handling the gamepad and carrying out the task.

In the LSS condition, the participants were standing in front of the large, high-resolution display. Figure 5.3 shows a participant carrying out the task in the LSS condition. Displacement and rotation depend on the decision points shown in the virtual environment. Each participant was instructed about how to use the gamepad, the HMD, and the polarized glasses. The participant was also urged to pay attention at each stage of the exposure. Each participant was instructed to remember the route in order to find a way out of the maze. After ending the session, the participants answered a questionnaire on the interaction with the system, 3D sensations, and satisfaction. The questions of the questionnaire are shown in the appendix A.3.

5.3 Results

This section presents the analysis of the data collected from this study. Data normality was checked and the pertinent statistical tests were carried out based on those results. The Shapiro-Wilk and Anderson-Darling are inferential tests that were used to check data normality. Since the tests reported that the data did not fit the normal distribution, non-parametric statistical tests (the Mann-Whitney U test) were applied for the Likert questions to determine whether or not there were statistically significant differences for the questionnaire on the interaction, 3D sensations, and satisfaction (see appendix A.3). There were two groups: one group used the HMD and the other group used the large stereo screen. These two groups were also divided into two different populations, those participants who had stereopsis and those participants who did not have stereopsis. The data from the study were analyzed using the statistical open source toolkit R[1] with the R-Studio IDE[2]. The results of the questionnaire were grouped by Interaction, 3D Sensations, and Satisfaction. The results are shown in Table 5.1 to Table 5.6.

5.3.1 Control variables outcomes

For the group of participants who did not have stereopsis, the mean for the HMD condition was: 3.09 ± 0.61; and the mean for the LSS condition was: 2.78 ± 0.58. These means indicate that those participants had moderate experience with 3D. For the group of participants who had stereopsis, the mean for the HMD condition was: 3.10 ± 0.59; and the mean for the LSS condition was: 2.96 ± 0.61. These means indicate that those participants had moderate experience with 3D. There were no statistically significant differences in previous 3D experiences between the HMD condition and the LSS condition

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[1] R-Project: `http://www.r-project.org`

[2] R-Studio: `http://www.rstudio.com`

($U = 34, Z = 0.714, p = 0.483, r = 0.184$). This result demonstrates the homogeneity of the sample regarding this aspect.

5.3.2 Interaction outcomes

As Table 5.1 and Table 5.2 show, no statistically significant differences were found in the QI2-QI4 questions between the HMD condition and the LSS condition. The participants thought that the interaction with the 3D environment seemed natural (QI2). The users were concentrated on the assigned task rather than on the mechanisms used to perform it (QI3). The participants did not perceive significant differences for ease of use (QI4). However, there was a statistically significant difference in QI1 in favor of the HMD. In Q1, the participants perceived the mechanism, which controlled movement through the environment, to be more natural. These results were obtained for the two groups of participants (stereopsis vs. no stereopsis). For the HMD condition and the two population groups (stereopsis vs. no stereopsis), no statistically significant differences were found in the QI1-QI4 questions. The same result was obtained for the LSS condition and the two population groups.

Table 5.1: Means and Standard deviations, Mann-Whitney U test analysis, and r effect size between the HMD condition and the LSS condition of those who did not have stereopsis for the questions about interaction. The asterisks (**) indicates statistically significant differences.

# Q	HMD	LSS	*U*	*Z*	*p-value*	*r*
QI1	4.38 ± 0.52	1.14 ± 0.38	56.0	3.426	< 0.001**	0.885
QI2	4.88 ± 0.35	4.43 ± 1.13	33.0	0.829	0.446	0.214
QI3	4.00 ± 0.93	3.86 ± 0.69	30.5	0.308	0.962	0.079
QI4	4.13 ± 0.64	3.14 ± 1.22	41.5	1.662	0.101	0.429

Table 5.2: Means and Standard deviations, Mann-Whitney U test analysis, and r effect size between the HMD condition and the LSS condition of those who had stereopsis for the questions about interaction. The asterisks (**) indicates statistically significant differences.

# Q	**HMD**	**LSS**	U	Z	***p-value***	r
QI1	4.00 ± 0.93	1.14 ± 0.35	481.0	5.906	< 0.001**	0.890
QI2	4.64 ± 0.73	4.36 ± 0.66	307.0	1.757	0.101	0.265
QI3	4.09 ± 0.68	3.59 ± 0.91	319.0	1.952	0.055	0.294
QI4	4.00 ± 0.93	3.77 ± 1.31	255.5	0.332	0.747	0.050

5.3.3 3D sensation outcomes

To determine the outcomes for 3D sensations, the participants answered questions QE1-QE6 after their exposure to the virtual environment in two conditions (HMD vs. LSS). Statistically significant differences were found in all six questions in favor of the HMD. These statistically significant differences can be observed for the group of participants who did not have stereopsis (Table 5.3 and Figure 5.4) and those who had (Table 5.4 and Figure 5.4). Overall, the HMD allowed the participants to feel a more enhanced experience than the large stereo screen for the two groups (stereopsis vs. no stereopsis). For the HMD condition and the two groups of population (stereopsis vs. no stereopsis), no statistically significant differences were found in the QE1-QE6 questions. For the LSS condition, no statistically significant differences were found for any of the questions, except for QE3 in favor of the participants who had stereopsis ($U = 32, Z = -2.687, p = 0.011, r = 0.499$). Although the means of the two groups for QE3 are low, the participants who had stereopsis were able to closely examine objects to a significantly greater extent than the participants who did not have stereopsis. Moreover, the participants who had stereopsis in the LSS scored higher in all the questions (except QE1) than those who did not have stereopsis.

In QS1, there were no statistically significant differences between the two conditions for the participants who did not have stereopsis regarding general discomfort during or at the end of the session (see Table 5.5). However, in QS1, there was a statistically significant difference between the two conditions and for the participants who had stereopsis (see Table 5.6). The values of the means for the two groups show that the participants who had stereopsis felt greater general discomfort with the HMD.

Table 5.3: Means and Standard deviations, Mann-Whitney U test analysis, and r effect size between the HMD condition and the LSS condition of those who did not have stereopsis for the questions about 3D sensations. The asterisks (**) indicates statistically significant differences.

# Q	**HMD**	**LSS**	***U***	***Z***	***p-value***	***r***
QE1	4.63 ± 0.52	3.57 ± 0.54	50.0	2.750	0.009**	0.710
QE2	3.62 ± 0.74	1.14 ± 0.38	56.0	3.392	< 0.001**	0.876
QE3	3.88 ± 0.84	1.14 ± 0.38	56.0	3.376	< 0.001**	0.872
QE4	4.38 ± 0.74	3.43 ± 0.54	46.5	2.277	0.034**	0.588
QE5	4.00 ± 0.54	2.29 ± 0.76	54.5	3.210	< 0.001**	0.829
QE6	3.75 ± 0.89	1.71 ± 1.11	50.5	2.726	0.008**	0.704

In QS2 and QS3, the results show that there were statistically significant differences between the two conditions in favor of the HMD (see Table 5.5 and Table 5.6). This means that, in general, the participants had a more satisfying experience using the HMD.

For the HMD condition and the two population groups (stereopsis vs. no stereopsis), no statistically significant differences were found in the QS1-QS3 questions. For the LSS condition, no statistically significant differences were found for any of the questions, except for QS2 in favor of the participants who had stereopsis. This result for QS2 implies that the participants who had stereopsis rated the experience of movement and interaction with the virtual environment significantly higher than the participants who did not have stereopsis. Comparing the HMD column of Table 5.5 and Table 5.6 (HMD condition, no stereopsis vs. stereopsis), and the LSS column of Table 5.5 and Table 5.6 (LSS condition, no stereopsis vs. stereopsis), in all cases, the participants who had stereopsis scored higher in all the questions than the participants who did not have stereopsis. The results for the comparison of the LSS column were similar.

Table 5.4: Means and Standard deviations, Mann-Whitney U test analysis, and r effect size between the HMD condition and the LSS condition of those who had stereopsis for the questions about 3D sensations. The asterisks (**) indicates statistically significant differences.

# Q	HMD	LSS	*U*	*Z*	*p-value*	*r*
QE1	4.18 ± 0.96	3.50 ± 1.01	338.0	2.365	0.018**	0.357
QE2	3.68 ± 1.13	1.18 ± 0.40	465.0	5.510	< 0.001**	0.831
QE3	3.96 ± 0.84	1.73 ± 0.46	476.0	5.712	< 0.001**	0.861
QE4	4.46 ± 0.51	3.50 ± 0.91	385.5	3.590	< 0.001**	0.541
QE5	4.14 ± 0.77	2.64 ± 1.18	405.0	3.964	< 0.001**	0.598
QE6	3.96 ± 1.09	1.86 ± 1.21	423.5	4.398	< 0.001**	0.663

Table 5.5: Means and Standard deviations, Mann-Whitney U test analysis, and r effect size between the HMD condition and the LSS condition of those who did not have stereopsis for the questions about satisfaction. The asterisks (**) indicates statistically significant differences.

# Q	HMD	LSS	*U*	*Z*	*p-value*	*r*
QS1	1.50 ± 0.53	1.14 ± 0.37	38.0	1.414	0.282**	0.365
QS2	3.75 ± 0.46	1.43 ± 0.53	56.0	3.395	< 0.001**	0.877
QS3	4.38 ± 0.52	3.57 ± 0.53	46.0	2.372	0.039**	0.612

5.3.4 Task outcomes

The results of the performance on the task of participants with and without stereopsis using the HMD condition are shown in Table 5.7. Table 5.8 shows the results considering gender. The results for the participants with and without stereopsis using the LSS condition are shown in Table 5.10. Also, Table 5.9 shows the results taking gender into account. For the two conditions considered independently, the results show that there were no statistically significant differences in the performance on the task between the participants with stereopsis and the participants without stereopsis. The performance on the task was also independent of gender.

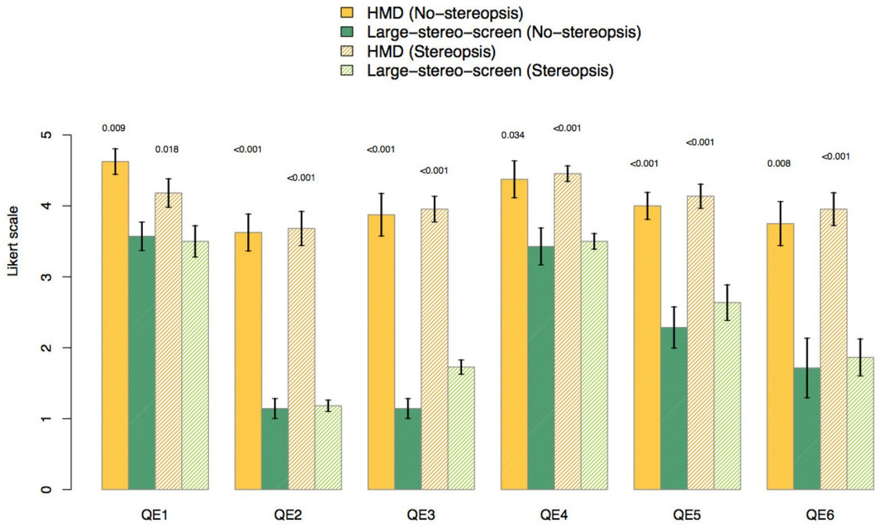

Figure 5.4: Participants who had stereopsis and participants who did not have stereopsis (HMD vs. LSS). Barplot and error bars for QE1-QE6 questions. Confidence interval of 95%. Statistically significant differences are found in all questions.

Table 5.6: Means and Standard deviations, Mann-Whitney U test analysis, and r effect size between the HMD condition and the LSS condition of those who had stereopsis for the questions about satisfaction. The asterisks (**) indicates statistically significant differences.

# Q	HMD	LSS	*U*	*Z*	*p-value*	*r*
QS1	1.55 ± 0.80	1.14 ± 0.35	311.0	2.084	0.055**	0.314
QS2	4.09 ± 0.81	3.32 ± 0.48	369.0	3.241	< 0.001**	0.489
QS3	4.45 ± 0.74	3.59 ± 0.85	371.5	3.209	< 0.001**	0.484

Table 5.7: Means and Standard deviations, Mann-Whitney U test analysis, and r effect size for the HMD condition and between the participants without stereopsis and those with stereopsis.

Variables	No-stereopsis	Stereopsis	*U*	*Z*	*p-value*	*r*
Score	48.0 ± 2.88	47.68 ± 3.23	97.0	0.459	0.667	0.084
Attempts	1.62 ± 0.74	2.05 ± 1.09	70.0	-0.898	0.395	0.164
Time	350.50 ± 191.50	295.89 ± 109.63	106.0	0.844	0.414	0.154

Table 5.8: Means and Standard deviations, Kruskal-Wallis test analysis for the HMD condition and for gender.

Variables	**No-stereopsis**		**Stereopsis**		χ^2	***df***	***p-value***
	Men	**Women**	**Men**	**Women**			
Score	48.00 ± 3.16	48.00 ± 2.83	48.83 ± 2.37	46.30 ± 3.68	0.21	1	0.646
Attempts	1.67 ± 0.82	1.50 ± 0.71	2.00 ± 1.34	2.10 ± 0.74	0.77	1	0.379
Time	364.10 ± 218.40	309.70 ± 116.6	296.30 ± 129.40	295.4 ± 87.0	0.71	1	0.399

Table 5.9: Means and Standard deviations, Kruskal-Wallis test analysis for the LSS condition and for gender.

Variables	**No-stereopsis**		**Stereopsis**		χ^2	***df***	***p-value***
	Men	**Women**	**Men**	**Women**			
Score	41.00 ± 10.82	41.75 ± 9.95	40.14 ± 9.94	43.50 ± 13.44	0.37	1	0.541
Attempts	1.67 ± 0.58	2.50 ± 1.91	2.79 ± 1.72	3.25 ± 1.91	0.31	1	0.579
Time	99.69 ± 15.69	125.59 ± 38.01	130.71 ± 59.73	149.47 ± 60.66	1.23	1	0.268

Table 5.10: Means and Standard deviations, Mann-Whitney U test analysis, and r effect size for the LSS condition for the participants without stereopsis and those with stereopsis.

Variables	**No-stereopsis**	**Stereopsis**	U	Z	***p-value***	r
Score	41.43 ± 9.41	38.09 ± 11.36	91.0	0.729	0.484	0.135
Attempts	2.14 ± 1.46	2.95 ± 1.76	58.5	−0.983	0.373	0.183
Time	114.50 ± 31.56	137.53 ± 59.34	67.0	−0.510	0.636	0.095

For the HMD condition, Table 5.11 shows the results for the Headings variable (head turnings) taking into account gender and group (no stereopsis vs. stereopsis). The results indicate that there were no statistically significant differences between gender and group.

Table 5.11: Multifactorial ANOVA test for the Headings variable, N = 30.

Factors	**F**	***p-value***	**Effect size** (η^2)
Gender	0.09	0.924	< 0.01
Group (no stereopsis/stereopsis)	0.03	0.961	< 0.01
Gender:Group	0.046	0.832	< 0.01

When was analyzed the Score variable for the group who did not have stereopsis, the HMD (48.00 ± 2.88) and LSS (41.43 ± 9.41) conditions, there were no statistically significant differences ($U = 38.5, Z = 1.318, p = 0.210, r = 0.340$). Also, when was analyzed the Score variable for the group who had stereopsis, the HMD (47.68 ± 3.23) and LSS (38.09 ± 11.36) conditions, were found statistically significant differences ($U = 354$, $Z = 2.725, p = 0.006$**, $r = 0.411$) in favor of the HMD condition.

5.4 Discussion

As mentioned, HMDs have already been compared with different visualization systems. In this study, we have compared an HMD (Oculus Rift-DK2) with a partially immersive VR system. Previous works have compared the Oculus Rift with a fully immersive VR system (Young et al. 2014) and with a non-immersive VR system (Tan et al. 2015). The results are in line with these works. Although other works have suggested that a large projection screen may be an effective substitute for an HMD (Patrick et al. 2000), the results indicate that participants had a better 3D experience using an HMD than using a large stereo screen. Juan and Pérez (2009) compared an HMD and a CAVE and observed that the CAVE induced a significantly higher level of presence. The features of their HMD were: 800 × 600 and 40° FOV. The features of the current HMDs are significantly better. We used an HMD with 960 × 1080 and 100° FOV. Another aspect to consider is the inclusion in the system of head tracking. The motion parallax cue plays an important role in stereoscopy. In a fair comparison, the projected stereoscopic display should have head tracking. From the results (QI1 and QS2), non-inclusion of head tracking has negatively affected the results of the LSS condition. In any case, considering this work and previous works, it is possible to conclude that current HMDs offer advantages over basic, partially, or fully immersive VR systems.

The study was motivated by the observation of students who did not have stereopsis and did not have depth perception with other VR devices (e.g., CAVE, a large stereo screen, or autostereoscopic displays). However, those same students did have the sensation of depth using the Oculus Rift-DK2 HMD. This study corroborated with the fifth hypothesis (H5) that current HMDs allow users with stereopsis problems to have the illusion of depth perception. Our explanation for this is that the field of view of current HMDs is much more similar to the human eye than other VR devices or systems. The inclusion of head tracking and a low latency are also very important. Nearly all of the current HMDs include head tracking. As Carmack (2013) indicated that “The latency between the physical movement of a user’s head and updated photons from an HMD reaching their eyes is one of the most critical factors in providing a high quality experience”. Thus, all the new features of current HMDs allow the users to perceive the virtual environment similarly to the way they perceive reality, and, therefore, they feel similar sensations. Stereo-blind individuals rely more heavily on motion based cues for depth. Therefore, the 3D experience could largely be influenced by the head tracking. The argument that the head tracking largely influenced the 3D experience was shared by one of the participants without stereopsis. This participant was a computer graphic Ph.D. student and in an interview, he explained his experience after 3 months of his participation in this study. The participant was not able to identify any of the figures that appear in the Lang Stereotest I. He did not perceive the 3D with an autostereoscopic screen, neither with the large stereo screen used in this study or in the 3D cinemas. However, for the first time in his life, he did experience the feeling of depth with a VR environment using the Oculus Rift. With our virtual maze, he could perceive that the virtual elements were at his side and he could notice the distance they were from. His personal opinion was that the changes in perspective while moving his head enabled him to have that 3D feeling. After this first 3D experience, he tested other stereoscopic devices and he has only been able to appreciate 3D with HMDs that include head tracking. This participant added that when using HMDs that do not include head tracking, instead of perceiving 3D, he suffered from cybersickness. He also experienced cybersickness with the Oculus Rift and with environments that do not allow navigation using head turns. These 3D experiences have not changed the way he perceives the objects in the real world. Other statements expressed by other participants without stereopsis during the experience were as follows: "Oh my God, I can perceive 3D for the first time in my life with this VR device". This reaction was in line with that reported by the participants in the study carried out by Ding and Levi (Ding and Levi 2011), "depth «popped out» in daily life, and I enjoyed 3D movies for the first time".

Previous works have used VR for training adults who were stereo-blind or stereo-deficient (Vedamurthy et al. 2016). After the training, some of those participants recovered or acquired stereopsis. This study tested the same virtual environment with two different visualization systems (HMD vs. a LSS) and with people with and without stereopsis. From the results, the HMD allowed the participants to feel a richer 3D experience than the large stereo screen for both groups (stereopsis vs. no stereopsis). This also indicates that full stereopsis may not be necessary for rich 3D experiences. The performance on the task for the HMD was independent of the participants' condition (stereopsis vs. no stereopsis) and gender. Therefore, this work and previous works are complementary and together opens new possibilities for people with stereo-blindness or stereo-deficiency. The use of HMDs for training people for recovering or acquiring stereopsis could have implications for the recovery of visual function in real life. Several studies have indicated that between 5% and 10% of the population have not the stereoscopic vision (Brown et al. 2001; Castanes 2003). This percentage can be as high as 34% in older subjects (Zaroff, Knutelska, and Frumkes 2003). Therefore, current HMDs could help this population to experience depth perception using VR. As mentioned in the related works section, Bridgeman (2014), with stereo-deficiency, acquired stereopsis when watching a 3D movie. A current HMD has been used for watching 3D movies as an observer or as an actor (Van den Boom et al. 2015). Oculus Story Studios [3] made their first two movies, *Lost* (2015) and *Henry* (2016). The possibility of watching movies in 3D as an observer or as an actor is interesting for people with stereopsis, but it also opens up a new possibility for people with stereopsis problems that could be explored.

In this study, a gamepad has been used for the interaction. However, other devices or types of interaction can also be used. For example, using the touch

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[3] Oculus Story Studios: `https://storystudio.oculus.com/en-us`

motion controllers that can be combined with the Oculus Rift-CV1. Another possibility is to use the VR Manus gloves or to use the Leap Motion for gesture interaction. Leap Motion can be attached to the HMD, allowing an interaction with the user's hands.

Even though current HMDs have several benefits, they also have some drawbacks. One of them is the cybersickness that they may induce. As Davis et al. (2015) indicated, the more realistic the environment with higher levels of visual flow, the greater the chance of inducing cybersickness. Other works have also studied cybersickness. For example, Sharples et al. (2008) studied VR induced symptoms and effects comparing an HMD, a desktop, a projection screen (smaller than ours), and a reality theater. The participants using the HMD and the projection screen experienced a significant increase in symptoms pre-post exposure for oculomotor, disorientation, and total scored. Moreover, the participants using the HMD also reported a significant increase in nausea. We have not carried out a formal study about cybersickness, but the data for the SQ1 question (*To what degree did you feel general discomfort during or at the end of the task?*) indicates that the participants who had stereopsis scored significantly higher on SQ1 using the HMD than using the LSS condition. Taking into account the differences, this observations are in line with the conclusions obtained by Sharples et al. (2008). Recent studies indicate that the Oculus Rift induces motion sickness (Munafo, Diedrick, and Stoffregen 2017). However, further studies are needed to determine whether this or other current HMDs induce more cybersickness than other VR systems, and comparisons between them should also be made. Another drawback is that cables must be connected to the computer. Therefore, wireless HMDs (e.g., Samsung Gear VR, Google Cardboard or Microsoft HoloLens) that offer freedom of movement could also be considered.

CHAPTER

VI

6

Conclusions

> *"When you have reached the mountaintop, then you shall begin to climb."*
>
> `Kahltil Gibran`

In this chapter are summarized the main contributions of this thesis. Also, some lines for future works in the area of virtual reality and development of applications to cognitive processes are described.

6.1 Summary

A new VR system combining immersive, interactive and motion features was designed and implemented. The virtual environment was based on the Cincinnati Water Maze concept. It was designed for assessing short-term spatial memory in humans and depth perception. Several virtual objects were created: 3D animals, a 3D bicycle as an avatar, directional arrows to help in exploring the virtual maze. A cognitive task was defined, which included three stages (habituation, learning, and testing). For the visualization of the virtual maze two display systems were used: an Oculus Rift-DK2 HMD and a large stereo screen. Two types of interaction were used: locomotion-based interaction pedaling a fixed bicycle (active physical condition), and a stationary interaction using a gamepad (inactive physical condition).

The benefit that offers the VR systems that included a Virtual Maze Task and two interaction types (locomotion and stationary) for the assessment of the spatial short-term memory has been shown in the results of this thesis. Also, the impact that can produce the use of stereo devices on people with stereo-deficiencies by comparison between two visualization systems has been assessed.

The conclusions of each study are described as follow:

- **Assessment of the spatial short-term memory.**

  The performance of this new system was compared with the performance on the traditional neuropsychological tests of spatial and memory skills. The interaction and satisfaction of the participants for the new task were measured.

  According to the measurements of overall execution, the performance on the new task was better in the participants who were in the physical inactive condition than in the physical active condition. However, the interaction and satisfaction did not differ between conditions. These results showed that the type of interaction used is a relevant methodological issue in studies of cognition that are based on VR technologies. The Virtual Maze Task could be utilized as an entertaining method to assess or train adults in spatial short-term memory skills. The Cincinnati water maze has commonly been used in studies with rodents. In our system, a version of the Cincinnati water maze has been visualized using the Oculus Rift-DK2 HMD and tested with human adults. This study and other previous works (e.g., Cánovas et al.(2011)) support the potential of VR for adapting tasks developed for animals to humans.

- **Assessment of 3D experience using VR devices for people with stereo-deficiencies.**

  Two different display systems were compared: a partially immersive large stereo screen, and a fully immersive HMD. The study involved participants who had stereopsis and participants who had not stereopsis. To our knowledge, this is the first comparison involving those two different display systems and those two population groups. The HMD has provided a significantly better VR experience than the large stereo screen. Users that have stereopsis problems and cannot perceive 3D when looking at the Lang Stereotest I or use other display systems (CAVE, large stereo screens, or autostereoscopic displays) have the sensation of depth when using the HMD. Therefore, the study suggests that for the people who did not have stereopsis, the head tracking largely influences the 3D experience.

From the studies performed, the following general conclusions are presented:

- These studies carried out allowed exploring possibilities of Virtual Reality to contribute in the assessment of human processes.
- The Virtual Maze Task could be a relevant method in studies of cognition based on VR technologies.
- In this thesis, we adapted the Cincinnati water maze to human adults. This maze has commonly been used in rats for testing spatial orientation. The results suggested that the virtual environments have the potential to adapt the tasks developed for animals to humans.
- The two types of interaction used for navigation within the virtual maze could be helpful to use with different collectives.
- A VR system like the one presented in this thesis could be used to assess or train adults in spatial short-term memory skills.
- The VR system developed showed verisimilitude with the traditional neuropsychological tests applied.
- The Oculus Rift-DK2 HMD has demonstrated significant potential for psychology, in particular, the assessment of spatial short-term memory.
- The use of HMDs with head tracking could allow people with stereo-deficiencies to be able to perceive the depth of the objects in a virtual environment and enjoy a virtual experience.

6.2 Scientific contributions

The publications derived from this thesis are the following:

6.2.1 Papers in conferences indexed in CORE 2017

- Sonia Cárdenas-Delgado, Magdalena Méndez-López, M.-Carmen Juan, Elena Pérez-Hernández, Javier Lluch, Roberto Vivó (2017). Using a Virtual Maze Task to Assess Spatial Short-term Memory in Adults . *In Proceedings of the 12th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2017) - Volume 1: GRAPP,* pp. 46-57. This paper was selected as a candidate to win the GRAPP 2017 best paper award. (CORE B).
- Sonia Cárdenas-Delgado, M.-Carmen Juan, Magdalena Méndez-López, Elena Pérez-Hernández (2017). Could People with Stereo-deficiencies Have a Rich 3D Experience Using HMDs?. *In Proceedings of The 16th IFIP TC.13 International Conference on Human-Computer Interaction (INTERACT 2017) - Part I, Volume: 10513,* pp. 97-116. (CORE A).

6.2.2 Other conferences

- David Rodríguez-Andrés, Sonia Cárdenas-Delgado, M.-Carmen Juan, Elena Pérez-Hernández, Magdalena Méndez-López, Javier Lluch (2015). Stereoscopic visualization systems: Comparison between a Large Passive Display and a Head Mounted Display. *XXV Spanish Computer Graphics Conference (CEIG 2015),* pp. 39-42. DOI: 10.2312/ceig.20151198.
- David Rodríguez-Andrés, Sonia Cárdenas-Delgado, Elena Pérez-Hernández, M.-Carmen Juan, Magdalena Méndez-López (2015). Nueva tarea virtual para evaluar la memoria espacial en niños. *VII Congreso de Neuropsicología. Neuropsicología 3.0,* Bilbao, 2015. (Comunicación 9).

6.2.3 Other diffusions

- Sonia Cárdenas-Delgado. Automatic detection with the integration of several devices. *I Encuentro de Estudiantes de Doctorado. Universitat Politècnica de València*, June 12, 2014. Poster 112.
- M.-Carmen Juan, Sonia Cárdenas-Delgado, Mauricio Loachamín-Valencia, David Rodríguez-Andrés, Juan Fernando Martín San José. Aplicaciones

de la realidad aumentada, autoesteroscopía e interfaces naturales en educación y psicología. *I Jornada de Aplicaciones Industriales de la Investigación,* Valencia, 2014.

- M.-Carmen Juan, Sonia Cárdenas-Delgado, Mauricio Loachamín-Valencia. Demostración de aplicaciones de realidad aumentada y autoestereoscopía para aprendizaje. *Jornadas-Recursos educativos digitales: estrategias innovadoras.* Valencia, 2014.
- Sonia Cárdenas-Delgado. Aplicaciones de realidad virtual y sistemas de visualización e inmersión. *United Nations Day 2014*, Valencia, 2014.
- Sonia Cárdenas-Delgado. Visualización de un entorno virtual en un HMD-Oculus Rift. *II Encuentro de estudiantes de doctorado. Universitat Politècnica de València*, June 25, 2015. Poster 109.
- Sonia Cárdenas-Delgado. ¿Los cascos de realidad virtual causan malestar a los usuarios?. Un caso de estudio. *III Encuentro de Estudiantes de Doctorado. Universitat Politècnica de València.* June 30, 2016.
- Sonia Cárdenas-Delgado. Virtual Reality, a case of study: assessing the Spatial Memory in adults. *Open Day 2016: Centre for Human-Computer Interaction Design-City University London,* London, 2016.

6.3 Future Works

A future work will be a study to compare HMDs to other models and brands, taking into account their features such as resolution, field-of-view, and latency. Also a study of the capability of the Virtual Maze Task to detect learning difficulties in samples of people with academic problems or neurological disorders. The same possibilities could be studied for children. Furthermore, other devices could also be used, paying special attention to wireless HMDs, such as Samsung Gear VR. Even in other work, could be tested whether our virtual maze set-up can be adapted to different types of locomotion and other types of HMDs.

Regarding the visual perception of individuals that have not stereopsis, a study could be carried out to determine the different aspects that influence stereoscopy (especially, motion parallax) when using current HMDs. The Oculus Rift, other HMDs, or other 3D-display technologies could be used to design VR environments for training and to facilitate recovery of stereo-vision of people with stereo-deficiencies. With our study and ideas presented here, our aim is to help people who are afflicted with stereo-deficiencies to have rich 3D experiences through VR systems.

Appendix

A

Questionnaires

"What we have to learn to do, we learn by doing."

Aristotle

In this appendix is presented the questionnaires that have been used in this thesis.

A.1 Questionnaires on previous experiences (PEQ)

In this section, the questionnaires on previous experiences that have been used in both studies are shown. The questionnaires used a Likert scale [from 1 to 5 (1 being *'none'* or extremely low and 5 being *'very high'*)].

A.1.1 PEQ-Study 1:

This questionnaire was used to know the previous experiences of the users with video games and activities in 3D.

#QPE	**Previous experiences**
QPE1	I play video games on computer, mobile phone, ...
QPE2	I perform activities in 3D.
QPE3	I play 3D games.

A.1.2 PEQ-Study 2:

This questionnaire was used to determine whether the participants of both groups had previous experience with activities in 3D, video games, and movies 3D.

#QXE	**Previous experiences**
QX1	I perform activities in 3D.
QX2	I play 3D games.
QX3	I see movies in 3D.

A.2 Questionnaire on Interaction and Satisfaction

This questionnaire was used to know the perception that had the users about the interaction (QI) and satisfaction (QS) with the environment of the VR-System and virtual task, as explained in the section 4.2.2 in Chapter 4. This questionnaire used a Likert scale [from 1 to 5 (1 being *'none'* or extremely low and 5 being *'very high'*)].

#QI	**Interaction**
QI1	The environment was easy to use.
QI2	How natural was the mechanism that controlled movement through the environment?
QI3	How responsive was the environment to actions that you initiated (or performed)?
QI4	How natural did your interactions with the 3D environment seem?
QI5	How closely were you able to examine objects?
QI6	How well could you examine objects from multiple viewpoints?
QI7	In general, rate the experience of movement and interaction with the virtual environment.

#QS	**Satisfaction**
QS1	Would you use this environment another time?
QS2	How much fun did you have?
QS3	Would you invite your friends to use the environment?
QS4	Score the game from 1 to 5.
QS5	My 3D experience compared to other previous 3D experiences has been . . .

A.3 Questionnaire on the Interaction, 3D sensations, and Satisfaction

This questionnaire was used to determine whether or not there were statistically significant differences between the two groups, those who used the HMD and who used the large stereo screen (with the population of those participants who had stereopsis and who had not stereopsis); about the perception that were the users on the interaction, 3D sensations, and satisfaction with the virtual environment and the task. As explained in the section 5.3 in Chapter 5, this questionnaire also used a Likert scale [from 1 to 5 (1 being *'none'* or extremely low and 5 being *'very high'*)].

#QI	**Interaction**
QI1	How natural was the mechanism that controlled movement through the environment?
QI2	How natural did your interactions with the 3D environment seem?
QI3	How well could you concentrate on the required tasks rather than on the mechanisms used to perform those tasks?
QI4	The environment was easy to use.

#QE	**Virtual Environment and 3D sensations**
QE1	How involved were you in the 3D virtual environment experience?
QE2	How much did your experiences in the virtual environment seem consistent with your real-world experiences?
QE3	How closely were you able to examine objects?
QE4	How quickly did you adjust to the 3D virtual environment experience?
QE5	At times it seems to me that objects have depth?
QE6	My 3D experience compared to others previous 3D experiences has been . . .

#QS	**Satisfaction**
QS1	To what degree did you feel general discomfort during or at the end of the task?
QS2	In general, rate the experience of movement and interaction with the virtual environment.
QS3	Rate your visualization experience from 1-5 (1- least satisfying).

A.4 Simulator Sickness Questionnaire (SSQ)

This questionnaire was used to assess the cybersickness symptoms that could have the users before their participation in the virtual task. As explained in the section 4.2.1 of the Chapter 4, this questionnaire consisted of a checklist of 16 items with four score levels of severity for each symptom (0 - none, 1 - slight, 2 - moderate, 3 - severe). These symptoms consist of three weighted subscales: Nausea (NA), Ocular Discomfort (OD) and Disorientation (DI). This validated questionnaire allows obtaining a rating of overall simulator sickness for each subscale.

SIMULATOR SICKNESS QUESTIONNAIRE

(Kennedy et al. 1993)

Instructions for users: Circle how much each symptom below is affecting you right now.

#	Item	Options			
1	General discomfort	None	Slight	Moderate	Severe
2	Fatigue	None	Slight	Moderate	Severe
3	Headache	None	Slight	Moderate	Severe
4	Eye strain	None	Slight	Moderate	Severe
6	Difficulty focusing	None	Slight	Moderate	Severe
7	Salivation increasing	None	Slight	Moderate	Severe
8	Sweating	None	Slight	Moderate	Severe
9	Nausea	None	Slight	Moderate	Severe
10	Difficulty concentrating	None	Slight	Moderate	Severe
11	≪Fullness of the Head≫	None	Slight	Moderate	Severe
12	Dizziness with eyes open	None	Slight	Moderate	Severe
13	Dizziness with eyes closed	None	Slight	Moderate	Severe
14	∗Vertigo	None	Slight	Moderate	Severe
15	∗∗ Stomach awareness	None	Slight	Moderate	Severe
16	Burping	None	Slight	Moderate	Severe

∗ Vertigo is experienced as loss of orientation with respect to vertical upright.
∗∗ Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

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