Universitat Politècnica de València

PhD Thesis

Augmented Reality through various sensory channels and its application to orientation and spatial localization processes

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To M.Carmen, my thesis director,
who was there to support me during this academic journey.

Abstract

The development of hardware and software powerful enough for the use of SLAM (Simultaneous Localization and Mapping) in extended reality has been significant in recent years. Augmented reality (AR) has benefited greatly from these advances. AR offers many possibilities in psychology and specifically for the assessment of spatial memory. Spatial memory is used to store and recall spatial stimuli perceived in an environment. This ability is of vital importance in the daily life of humans.

This thesis focuses on exploiting the possibilities of SLAM-based AR for the assessment of spatial memory. The main objective was to develop new indoor localization techniques in the field of AR, taking advantage of technological advances, and to validate them by building frameworks and applications oriented to the assessment of spatial location ability in adults; and studying perceptual augmentation in the visual and tactile channels.

In this thesis, to fulfill this main objective, a framework was developed for the development of author applications to use in the study of spatial memory taking advantage of AR based on SLAM. This framework has been used for the development of all the applications proposed in this thesis. The framework that has been developed enables using different AR engines or SDKs. There are different interfaces incorporated in the framework through which the different AR modules can be connected. This enables a modular and independent use of the AR engine for developers. The general functioning of the applications developed in this thesis consists of three phases. In a first phase, the supervisor selects the number of virtual objects to be memorized and the virtual objects themselves, which she or he places at desired locations in the environment. In the second phase, the user walks through the environment and memorizes the locations of the virtual objects in the real environment. In the third phase, the user must place the virtual objects in the locations they were in the previous phase. Applications store all data for further analysis. In addition, to our knowledge, this is the first work using SLAM-based AR for the assessment of spatial memory, involving physical movement of the user, and considering visual and tactile stimuli.

For the validation, three studies were carried out that focused on studying the feasibility of using the applications in small and large environments, as well as the use of visual and tactile stimuli. The performance of our applications was compared with traditional methods. Subjective variables were also assessed.

The first study considered visual stimulus and small environments. This study involved 55 users (36.53 ± 15.78), 24 females. Participants were divided into two groups: ARGroup (participants memorized the location of virtual objects in the real world in a memorization phase using AR) and the NoARGroup (participants memorized the location of virtual objects by looking at photographs of the augmented environment using the device). The results showed that the performance outcomes regarding object location for the ARGroup was significantly higher than those obtained by the NoARGroup. No statistically significant differences were found for performance and considering gender or age. Both groups of participants rated their experience with the application positively. One contribution of this study was to conclude that walking through the augmented environment helped users better remember the locations of virtual objects added to the

real world in comparison to looking at captured photos of the environment.

The second study considered visual stimulus and large environments. This study involved 46 young adults (24.65 ± 8.54 years), 26 females. The participants had to go through a two-story building and memorize the position of a total of eight virtual objects. Participants' performance was also evaluated in a verbal object recall task, a pencil and paper spatial orientation task and a map-pointing task. The importance of different spatial strategies for orientation and anxiety levels were also evaluated. The results showed that the application worked without any problems in a two-story building. There were no significant differences between men and women, in the performance of the AR task for the location of objects, on the map-pointing task or the recall task. Men required significantly more time to complete the AR learning phase. Positive correlations were obtained between spatial memory for the location of objects in AR and on the map. Trait anxiety was positively correlated to the time spent by the participants during the AR learning phase, while wayfinding anxiety was negatively correlated with the preference for directional cues for orientation.

The third study compared the performance using visual versus tactile stimuli and used small environments. This study involved 53 subjects, 16 females. The participants were divided into two groups: Visual, which used visual stimuli, and Tactile, which used tactile stimuli. The results showed that no statistically significant differences were found in the number of correctly placed shapes for both stimuli. The Tactile group required significantly more time to complete the assessment task and required significantly more attempts. The performance results when using both stimuli were independent of gender.

The following general conclusions were extracted from the development and the three studies carried out:

- SLAM-based AR is suitable for developing spatial memory assessment tasks, working in any environment and without the need to add real objects to the environment for registration.
- The applications developed in this thesis allow task customization and storage of performance variables.
- These applications have allowed an ecological assessment.
- These applications and similar tools could be used to assess and train spatial memory as an alternative to traditional methods.
- Tactile stimuli are valid stimuli that can help the assessment of memory of tactile-spatial associations, but memory of visual-spatial associations is dominant.
- The applications developed in this thesis and similar tools could help in the diagnosis of spatial memory impairments.

Resumen

El desarrollo de hardware y software lo suficientemente potente para el uso de SLAM (localización y mapeo simultáneos) en la realidad extendida ha sido importante en los últimos años. La realidad aumentada (RA) se ha beneficiado en gran medida de estos avances. La RA ofrece muchas posibilidades en psicología y, en concreto, para la evaluación de la memoria espacial. La memoria espacial se utiliza para almacenar y recordar los estímulos espaciales percibidos en un entorno. Esta capacidad es de vital importancia en la vida cotidiana de los seres humanos.

Esta tesis se centra en explotar las posibilidades de la RA basada en SLAM para la evaluación de la memoria espacial. El objetivo principal fue desarrollar nuevas técnicas de localización en interiores en el ámbito de la RA, aprovechando los avances tecnológicos, y validarlas mediante la construcción de frameworks y aplicaciones orientadas a la evaluación de la capacidad de localización espacial en adultos; y estudiar el aumento perceptivo en los canales visual y táctil.

En esta tesis, para cumplir con este objetivo principal, se desarrolló un framework para el desarrollo de aplicaciones de autor para utilizar en el estudio de la memoria espacial aprovechando la RA basada en SLAM. Este framework ha sido utilizado para el desarrollo de todas las aplicaciones propuestas en esta tesis. El framework desarrollado permite utilizar diferentes motores/SDKs de RA. Existen diferentes interfaces incorporadas en el framework a través de las cuales se puede acceder a los diferentes módulos de RA. Esto permite un uso modular e independiente del motor de RA para los desarrolladores. El funcionamiento general de las aplicaciones desarrolladas en esta tesis consta de tres fases. En una primera fase, el supervisor selecciona el número de objetos virtuales a memorizar y los propios objetos virtuales, que coloca en los lugares deseados del entorno. En la segunda fase, el usuario recorre el entorno y memoriza las ubicaciones de los objetos virtuales en el entorno real. En la tercera fase, el usuario debe colocar los objetos virtuales en las ubicaciones que tenían en la fase anterior. Las aplicaciones almacenan todos los datos para su posterior análisis. Además, hasta donde sabemos, este es el primer trabajo que utiliza la RA basada en SLAM para la evaluación de la memoria espacial, implicando el movimiento físico del usuario, y considerando estímulos visuales y táctiles.

Para la validación, se realizaron tres estudios centrados en investigar la viabilidad del uso de las aplicaciones en entornos de pequeñas y grandes dimensiones, así como el uso de estímulos visuales y táctiles. El rendimiento de nuestras aplicaciones se comparó con los métodos tradicionales. También se evaluaron las variables subjetivas.

En el primer estudio se consideraron los estímulos visuales y los entornos de pequeñas dimensiones. En este estudio participaron 55 usuarios (36,53 $\pm$ 15,78), 24 mujeres. Los participantes se dividieron en dos grupos: ARGroup (los participantes memorizaron la ubicación de los objetos virtuales en el entorno real en una fase de memorización mediante RA) y el NoARGroup (los participantes memorizaron la ubicación de los objetos mirando fotografías del entorno aumentado mediante el dispositivo). Los resultados mostraron que los datos obtenidos sobre el rendimiento respecto a la localización de objetos para los participantes del ARGroup fueron significativamente mayores que los obtenidos por los participantes del NoARGroup. No se encontraron diferencias estadísticamente

significativas en cuanto al rendimiento y teniendo en cuenta el género o la edad. Ambos grupos de participantes valoraron positivamente su experiencia con la aplicación. Una de las aportaciones de este estudio fue concluir que caminar por el entorno aumentado ayudó a los participantes a recordar mejor las ubicaciones de los objetos virtuales añadidos a la escena real en comparación con la observación de fotografías del entorno.

El segundo estudio consideró los estímulos visuales y los entornos de grandes dimensiones. En este estudio participaron 46 adultos jóvenes (24,65 $\pm$ 8,54 años), 26 mujeres. Los participantes tenían que memorizar la posición de ocho objetos virtuales mientras caminaban por un edificio de dos plantas. Se evaluó el rendimiento de los participantes en una tarea verbal de recuerdo de objetos, una tarea de colocación en mapas y una tarea de orientación espacial con lápiz y papel. También se evaluó la importancia de las distintas estrategias espaciales de orientación y los niveles de ansiedad. Los resultados mostraron que la aplicación funcionaba sin problemas en un edificio de dos plantas. No hubo diferencias significativas entre hombres y mujeres, en el rendimiento de la tarea de RA para la localización de objetos, en la tarea colocación en mapas o en la tarea de recuerdo. Los hombres emplearon significativamente más tiempo en completar la fase de aprendizaje de la tarea de RA. La memoria espacial para la localización de objetos en RA y en el mapa se correlacionó positivamente. El rasgo de ansiedad se correlacionó positivamente con el tiempo empleado por los participantes durante la fase de aprendizaje de la tarea de RA, mientras que la ansiedad de orientación se correlacionó negativamente con la preferencia por las señales direccionales para orientarse.

En el tercer estudio se comparó el rendimiento con estímulos visuales y táctiles y se utilizaron entornos de pequeñas dimensiones. En este estudio participaron 53 sujetos, 16 mujeres. Los participantes se dividieron en dos grupos: Visual, que utilizó estímulos visuales, y Táctil, que utilizó estímulos táctiles. Los resultados mostraron que no se encontraron diferencias estadísticamente significativas en el número de formas colocadas correctamente para ambos estímulos. El grupo que utilizó el estímulo táctil necesitó mucho más tiempo para completar la tarea de evaluación y requirió muchos más intentos. Los resultados de rendimiento al utilizar ambos estímulos fueron independientes del género.

Del desarrollo y de los tres estudios realizados se extrajeron las siguientes conclusiones generales:

- La RA basada en SLAM es adecuada para desarrollar tareas de evaluación de la memoria espacial, pudiéndose utilizar en cualquier entorno y sin necesidad de añadir elementos reales al entorno para su registro.
- Las aplicaciones desarrolladas en esta tesis permiten la personalización de la tarea y el almacenamiento de las variables de rendimiento.
- Estas aplicaciones han permitido una evaluación ecológica.
- Estas aplicaciones y otras herramientas similares podrían utilizarse para evaluar y entrenar la memoria espacial como alternativa a los métodos tradicionales.

- Los estímulos táctiles son estímulos válidos que pueden beneficiar la evaluación de la memoria de las asociaciones táctiles-espaciales, pero la memoria de las asociaciones visuales-espaciales es dominante.

- Las aplicaciones desarrolladas en esta tesis y otras herramientas similares podrían ayudar en el diagnóstico de las alteraciones de la memoria espacial.

Resum

El desenvolupament de hardware i software prou potent per a l'ús d'SLAM (localització i mapeig simultanis) en la realitat estesa ha sigut important en els últims anys. La realitat augmentada (RA) s'ha beneficiat molt d'aquests avanços. La RA ofereix moltes possibilitats en psicologia i, en concret, per a l'avaluació de la memòria espacial. La memòria espacial s'utilitza per a emmagatzemar i recordar els estímuls espacials percebuts en un entorn. Aquesta capacitat és de vital importància en la vida quotidiana dels éssers humans.

Aquesta tesi se centra en explotar les possibilitats de la RA basada en SLAM per a l'avaluació de la memòria espacial. L'objectiu principal va ser desenvolupar noves tècniques de localització en interiors en l'àmbit de la RA, aprofitant els avanços tecnològics, i validar-les mitjançant la construcció de frameworks i aplicacions orientades a l'avaluació de la capacitat de localització espacial en adults; i estudiar l'augment perceptiu en els canals visual i tàctil.

En aquesta tesi, per a complir amb aquest objectiu principal, es va desenvolupar un framework per al desenvolupament d'aplicacions d'autor per a utilitzar en l'estudi de la memòria espacial aprofitant la RA basada en SLAM. Aquest framework ha sigut utilitzat per al desenvolupament de totes les aplicacions proposades en aquesta tesi. El framework desenvolupat permet utilitzar diferents motors/SDKs de RA. Hi ha diferents interfícies incorporades en el framework a través de les quals es poden connectar els diferents mòduls de RA. Això permet un ús modular i independent del motor de RA per als desenvolupadors. El funcionament general de les aplicacions desenvolupades en aquesta tesi consta de tres fases. En una primera fase, el supervisor selecciona el nombre d'objectes virtuals a memoritzar i els propis objectes virtuals, que col·loca en els llocs desitjats de l'entorn. En la segona fase, l'usuari recorre l'entorn i memoritza les ubicacions dels objectes virtuals en l'entorn real. En la tercera fase, l'usuari ha de col·locar els objectes virtuals en les ubicacions que tenien en la fase anterior. Les aplicacions emmagatzemen totes les dades per a la seua posterior anàlisi. A més, fins on sabem, aquest és el primer treball que utilitza la RA basada en SLAM per a l'avaluació de la memòria espacial, implicant el moviment físic de l'usuari, i considerant estímuls visuals i tàctils.

Per a la validació, es van realitzar tres estudis centrats en estudiar la viabilitat de l'ús de les aplicacions en entorns de xicotetes i grans dimensions, així com l'ús d'estímuls visuals i tàctils. El rendiment de les nostres aplicacions es va comparar amb els mètodes tradicionals. També es van avaluar les variables subjectives.

En el primer estudi es van considerar els estímuls visuals i els entorns de xicotetes dimensions. En aquest estudi van participar 55 usuaris (36,53 $\pm$ 15,78), 24 dones. Els participants es van dividir en dos grups: ARGroup (els participants van memoritzar la ubicació dels objectes virtuals en l'entorn real en una fase de memorització mitjançant RA) i el NoARGroup (els participants van memoritzar la ubicació dels objectes mirant fotografies de l'entorn augmentat mitjançant el dispositiu). Els resultats van mostrar que les dades obtingudes sobre el rendiment respecte a la localització d'objectes per als participants del ARGroup van ser significativament més alts que els obtinguts pels participants del NoARGroup. No es van trobar diferències estadísticament significatives

quant al rendiment i tenint en compte el gènere o l'edat. Tots dos grups de participants van valorar positivament la seua experiència amb l'aplicació. Una de les aportacions d'aquest estudi va ser concloure que caminar per l'entorn augmentat va ajudar els participants a recordar millor les ubicacions dels objectes virtuals afegits a l'escena real en comparació amb l'observació de fotografies de l'entorn.

El segon estudi va tindre en compte els estímuls visuals i els entorns de grans dimensions. En aquest estudi van participar 46 adults joves (24,65 $\pm$ 8,54 anys), 26 dones. Els participants havien de memoritzar la posició de huit objectes virtuals mentre caminaven per un edifici de dues plantes. També es va avaluar el rendiment dels participants en una tasca verbal de record d'objectes, una tasca de col·locació en mapes i una tasca d'orientació espacial amb llapis i paper. També es va avaluar la importància de les diferents estratègies espacials d'orientació i els nivells d'ansietat. Els resultats van mostrar que l'aplicació funcionava sense problemes en un edifici de dues plantes. No va haver-hi diferències significatives entre homes i dones, en el rendiment de la tasca de RA per a la localització d'objectes, en la tasca de col·locació en mapes o en la tasca de record. Els homes van emprar significativament més temps a completar la fase d'aprenentatge de la tasca de RA. La memòria espacial per a la localització d'objectes en RA i en el mapa es va correlacionar positivament. El tret d'ansietat es va correlacionar positivament amb el temps utilitzat pels participants durant la fase d'aprenentatge de la tasca de RA, mentre que l'ansietat d'orientació es va correlacionar negativament amb la preferència pels senyals direccionals per orientar-se.

En el tercer estudi es va comparar el rendiment amb estímuls visuals i tàctils i es van utilitzar entorns de xicotetes dimensions. En aquest estudi van participar 53 subjectes, 16 dones. Els participants es van dividir en dos grups: Visual, que va utilitzar estímuls visuals, i Tàctil, que va utilitzar estímuls tàctils. Els resultats van mostrar que no es van trobar diferències estadísticament significatives en el nombre de formes col·locades correctament per a tots dos estímuls. El grup que va utilitzar l'estímul tàctil va necessitar molt més temps per a completar la tasca d'avaluació i va requerir molts més intents. Els resultats de rendiment en utilitzar tots dos estímuls van ser independents del gènere.

Del desenvolupament i dels tres estudis realitzats es van extraure les següents conclusions generals:

- La RA basada en SLAM és adequada per a desenvolupar tasques d'avaluació de la memòria espacial, podent-se utilitzar en qualsevol entorn i sense necessitat d'afegir elements reals a l'entorn per al seu registre.

- Les aplicacions desenvolupades en aquesta tesi permeten la personalització de la tasca i l'emmagatzematge de les variables de rendiment.

- Aquestes aplicacions han permés una avaluació ecològica.

- Aquestes aplicacions i altres ferramentes similars podrien utilitzar-se per a avaluar i entrenar la memòria espacial com a alternativa als mètodes tradicionals.

- Els estímuls tàctils són estímuls vàlids que poden beneficiar l'avaluació de la memòria de les associacions tàctils-espacials, però la memòria de les associacions visuals-espacials és dominant.
- Les aplicacions desenvolupades en aquesta tesi i altres ferramentes similars podrien ajudar en el diagnòstic de les alteracions de la memòria espacial.

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Chapter 1

Introduction

1.1 Motivation

The development of hardware (such as the Microsoft HoloLens 1 and 2, LiDAR-enabled mobile devices (such as the iPad Pro or iPhone 12, 13 and 14 Pro)), and software (such as the Tango SDK, ARCore, ARKit) with the necessary power to build SLAM-based Augmented Reality (AR) applications and for mobile platforms has significantly increased in recent years. Researchers and developers had access to SLAM-based AR on mobile devices since the end of 2016 with the appearance of the Tango SDK. The appearance of that SDK and compatible mobile devices marked a turning point in AR possibilities. ARCore and ARKit followed. To date, ARCore's functionality is not comparable to that of Tango SDK, mainly because of the features of the compatible devices. With the addition of LiDAR sensor in iOS devices (e.g., iPad Pro, iPhone 12 Pro, iPhone 13 Pro or iPhone 14 Pro), ARKit has similar power to that offered by Tango SDK. SLAM is a tracking method that tracks the world without requiring the addition of any physical elements (e.g., image targets or markers). In SLAM, the mapping process gathers spatial information (such as 3D point clouds) from the environment to create a world reference map while tracking the subject's position (Bailey & Durrant-Whyte, 2006). SLAM-based AR offers a lot of possibilities, and localization indoors is certainly one of them. Generally these environments can be controlled so that they do not undergo major structural or organizational changes to their constituent elements. The application can store and process a point cloud of what the environment looks like at the time of configuration and continue to use it as long as necessary. In addition, this technology can also be used in conjunction with GPS location sensors to locate outdoors, as in the case of use with drones (López et al., 2017) or unsupervised vehicles (Chiang et al., 2020).

Specifically, the technology used in this thesis (Tango SDK) offers the following features. Motion Tracking, which allows the device to track its movement while it moves. Learning Area, that gives the device the ability to identify and remember "the key visual features" of a physical space. Depth Perception, with which the application can understand the distance to real-world objects. The combination of these features makes Tango a very powerful technology and ideal for the developments carried out in this thesis.

Spatial memory is used to store and recall spatial stimuli perceived in an environment.

With the help of this spatial ability, we can solve spatial problems like estimating (or calculating) distances and directions, mentally transforming objects in relation to their position in the real world, locating elements in an environment, remembering the path to a previously visited location, or remembering where we left our belongings (like glasses or keys, for example) (Burgess et al., 2001). For brief periods of time, people may memorize and recall representations of spatial stimuli. This skill is referred to as short-term spatial memory (Baddeley, 1992). The information that needs to be memorized is vital for stable storage for upcoming needs. Given the implications for daily and professional life, it is crucial to understand how a person orients spatially and what influences this ability. The information that humans consciously retain in spatial memory comes mostly from visual and auditory stimuli, according to neurobiological and cognitive theories (Bizley & King, 2008; Pearson & Kosslyn, 2015; Setti et al., 2018; Yamamoto & Shelton, 2009). Nevertheless, the brain of humans has the capacity to store information from all stimuli (Schmidt & Blankenburg, 2018). Even if it is not the most researched sense, the sense of touch is one of these sensory modalities and has been one of the senses explored in this thesis.

Impairments in spatial memory have serious consequences in everyday life. Spatial memory can be assessed and trained using several tools. These tools can be used to identify issues that might limit a person's independence (Cimadevilla et al., 2014; Neguţ et al., 2016). Through the use of these training tools, helpful tactics can be used to improve spatial orientation (Caffò et al., 2013).

Spatial orientation difficulties usually occur due to diseases of neurological etiology, such as stroke (Barrett & Muzaffar, 2014), Alzheimer's disease (Doniger et al., 2018), acquired brain damage (Kuil et al., 2018), epilepsy (Cimadevilla et al., 2014) or healthy brain aging (van der Ham & Claessen, 2020). Improving spatial abilities not only benefits orientation skills, but also has a positive impact on recovery in other areas, such as motor skills or social relationships (Barrett & Muzaffar, 2014).

Motion and visual cues, such as proprioceptive and vestibular signals, are both important for human spatial orientation in the real world (Cullen & Taube, 2017). Extended Reality (XR) can be of great help in the development of tools for the assessment and training of spatial memory. This thesis explores how useful virtual reality (VR), augmented reality (AR), and mixed reality (MR) can be when a subject needs to perform physical activity in the real world. In such cases, the user has to physically move around the real world to perform different tasks. This movement is similar to what he or she experiences in real life. In addition, it has been shown that the physical displacement of the user during navigation is crucial for the development of their spatial abilities (Ruddle & Lessels, 2009).

Spatial memory has traditionally been assessed using the visual modality and with pencil-and-paper tests (Langlois et al., 2015; Mitolo et al., 2015). The development of XR applications offers some advantages over traditional testing. XR applications allow obtaining and storing objective indicators of an individual's spatial performance (e.g., successes and errors, times, speed, distance traveled, etc.) for further analysis. Stimulus presentation (number and location) can be varied and controlled (Juan et al., 2014;

Picucci et al., 2011; Walkowiak et al., 2015). In addition, XR applications have the advantage of lower economic and temporal costs. To date, different works have used VR to assess spatial memory in humans (Bohil et al., 2011; Fabroyir & Teng, 2018; León et al., 2016; Münzer & Zadeh, 2016). In early VR applications for spatial memory assessment, users were seated in front of a computer screen, without physical movement. Subjects explored a VR environment during the task (Cimadevilla et al., 2014; Picucci et al., 2011; Walkowiak et al., 2015). However, an important aspect to consider in spatial ability is physical displacement (Ruddle & Lessels, 2009). Some works have developed virtual reality environments in which the movement of the avatars has been based on the physical movement of the user. The research group in which this thesis is framed has contributed significantly in this aspect (Cárdenas-Delgado et al., 2017; Rodríguez-Andrés et al., 2016; Rodriguez-Andres et al., 2018; Mendez-Lopez et al., 2016). Rodríguez-Andrés et al. (2016) studied the influence of two different modalities of interaction in a VR environment (an active versus an inactive physical condition). In their study, the authors found no statistically significant differences in task performance for the two interaction types. Their conclusion was that the modality of interaction did not affect the performance of the participants in the VR task. Although participants moved physically with the Wii balance board, they did not have the sensation of walking in the real world. Cárdenas-Delgado et al. (2017) created a VR maze task that required users to walk physically. As in the previous work, they took into account two different modalities of interaction (an active versus an inactive physical condition). The inactive physical condition offered better performance outcomes. The physical movement was performed on a real bicycle. The user was wearing an HMD and had to pedal on a stationary bike. Even so, the participants did not have the sensation of riding a bike in the real world. Very few works have been published for the assessment of spatial memory using AR. The research group in which this thesis is framed has developed most of these works, being a pioneer in the development and validation of AR applications for spatial memory assessment (Juan et al., 2014; Mendez-Lopez et al., 2016). In the first work (Juan et al., 2014; Mendez-Lopez et al., 2016), an AR application was developed using image targets that were physically placed in the real world. The basic principle of the application was to show objects in a location in the room and the users, in this case children have to remember where they were. The number of objects to be remembered was increased according to the participant's performance in the previous trials. The objects were displayed when the device's camera focused on the image targets used, which were placed inside cardboard boxes and the boxes were strategically placed in the testing area. The task consisted of seven different levels. The difference between the levels was the number of boxes and the objects used in each trial. A maximum of seven trials were allowed for each level. Each trial was divided into two parts. Participants had to locate the objects in the first phase and recall the box (location) where they were. In the second stage, an object was displayed on the app, and the user had to recall which box it was in (successes and errors were stored). The quantity of successes and/or errors determined the possibility of completing a level. The level was successfully completed if there were three consecutively successful trials for a number of trials less than or equal to seven. If a participant completed the prior level successfully, she/he advanced to the following one. There were two boxes and one object to be discovered on each trial in the first level. There were four boxes and two objects to find in each trial on the second level. The same sequence was followed for the remaining levels. From their study, a significant improvement in performance was found in the older group of children. The correlations found between task performance and traditional tests showed that skills in solving the AR task were related to short-term spatial memory skills in real life. No statistically significant differences were found between boys and girls. Another work is presented by Keil et al. (Keil et al., 2020) in which they developed an AR system for memorizing object location and distance estimation. Using the HoloLens, the application projected holographic grids onto the ground. They carried out a study to determine how grids on the floor affected people's ability to remember object locations and estimate distances in indoor environments. Their study's findings revealed that when a grid was displayed, distance estimates were more accurate. Object location memory performance was worse when displaying a grid.

Auditory stimuli have also been studied for spatial memory assessment (Juan et al., 2022b; Loachamin Valencia et al., 2019). Loachamin Valencia et al. (2019) developed a system that had 5 Karotz (basic robot) and 2 Kinect. The Karotz were distributed around the room. The interaction was natural using gestures and the participants only had to raise their arms for the selection of the Karotz. A study (N=148) was conducted comparing performance using the system with traditional neuropsychological tests. Performance with the system correlated with traditional neuropsychological tests. Both adults and children found the system easy to use. In the work of Juan et al. (2022b), a SLAM-based AR system was developed and validated using ARCore and visual and auditory stimuli were compared (Juan et al., 2022b). Work that is part of the AR3Senses project and detailed later in this section.

This thesis contributed to the AR3Senses project (TIN2017-87044-R) and was supported by the Generalitat Valenciana (ACIF/2019/031). In AR3Senses, new indoor localization techniques were developed in the AR domain. A framework and an authoring tool were designed and developed for spatial memory assessment using visual and tactile stimuli, and for use in small and large environments. All developed applications were compared with traditional methods or with other developed applications. Two types of applications were developed. One for spatial memory assessment and one for indoor guidance.

AR applications for spatial memory assessment allow users to walk through a real environment in which they have to search for virtual objects and remember their location. To do this, the supervisor must first (and only once) to set up the environment for the users' work in which he or she must identify the quantity of objects to be recalled and their positions. Depending on the device used, he or she must also scan the environment, as is the case for the applications in this thesis. For its part, the user must carry out two phases, a first one of memorization, in which she or he must go through the environment, search for virtual objects and memorize their location. A second one of assessment, in which the user must place the stimuli memorized in the previous phase (visual, auditory or tactile) in the place where they were located. The user has three attempts to do so.

On the third attempt, the user is not told whether he/she has succeeded or failed in placing the stimulus, but the application stores successes, errors and times. Also, the application stores the path followed by the user. Using the framework and the author's tool, three studies were carried out, which are part of this thesis, which are detailed in this document and therefore only mentioned in this paragraph. A first study, in which visual augmentation was used in an environment of small dimensions (Munoz-Montoya et al., 2019b). A second study, in which visual augmentation was used in an environment of large dimensions, two floors of a building at the University of Zaragoza, Teruel Campus (Munoz-Montoya et al., 2019a). In a third study, visual and tactile stimuli were compared (Munoz-Montoya et al., 2021).

Another AR3Senses application used ARCore and had both visual and auditory stimuli (Juan et al., 2022b). A study with 48 participants was carried out. GVisual and GAuditive were the two groups into which the participants were divided. In the GVisual group, users utilized the application initially with visual stimuli and then, after a few days, with audio stimuli; in the GAuditive group, it was the other way around. According to the study, there were about the same amounts of correctly placed objects for the two stimuli. However, the GAuditive spent much more time to complete the task and required a lot more tries. Age and gender did not influence performance outcomes, including correct recall and time needed. All application variables and variables from two other tasks (recalling objects verbally and placing them on a map) correlated for the audio stimuli. Additionally, the perceived level of competence and the amount of mental work required decreased as the number of correctly placed auditory stimuli increased. The study concluded that although audio stimuli are valid stimuli that can help in the evaluation of the memorizing of spatial-auditory associations, the memorization of spatial-visual associations is dominant.

In addition, a VR application with and without 360º photography was developed in AR3Senses (Juan et al., 2022a). In this application, 360º photography is used as the environment and objects are incorporated on this environment. In addition, it allows interaction with the added objects. The performance outcomes and subjective experiences of participants using two applications (VR with and without 360º photography) were compared in a study (N=50). The findings demonstrated the efficiency of both applications in evaluating short-term spatial memory. The results using 360º photography to highlight are as follows: 1) Performance results (correct recall, attempts, and times) were age and gender independent; 2) Perceived level of presence was directly correlated with perceived cybersickness when using the application; and 3) The greater the familiarity with VR applications, the lower the perceived cybersickness.

The AR application for indoor guidance included visual and auditory stimuli for indoor guidance, which can be used simultaneously or separately (Calle-Bustos et al., 2021). The application requires a setup step, in which the environment must be scanned to create the required area description file and define the possible virtual routes in the real environment. The application was evaluated in a study involving 20 users. From the analysis, it was concluded that the participants achieved the objective using both types of stimuli (visual and auditory). Participants using the visual stimuli required less time and traveled less total distance compared to the use of auditory stimuli. However, the auditory stimuli forced people pay closer attention, which improved their ability to remember the route. Gender and age did not influence the results of the performance variables (time and distance traveled). This result indicates that auditory stimuli allow route retention and could be exploited when spatial memory retention is crucial or in situations where vision cannot be used as the main sensory channel.

To our knowledge, the main contribution derived from this thesis and AR3Senses is to pioneer the use of SLAM-based AR for spatial memory assessment, providing greater ecological validity, since the tasks to be performed in the augmented environments simulate real situations. That is, the tasks are similar to tasks that can be performed in daily life, for example, looking for where certain belongings have been left in the user's own home, with physical displacement. The applications do not require adding additional objects to the scene (e.g., image targets) because the real environment is used in which both horizontal and vertical surfaces are detected. In addition to using visual stimuli, this is the first time that tactile stimuli have been used. Therefore, this thesis has identified the possibilities of SLAM-based AR for spatial memory assessment and has also explored a sense other than the visual one, such as touch. These possibilities are applicable not only in psychology, but also in many other fields or specialties of psychology such as perception or ergonomics.

1.2 Scientific goals and research hypotheses

The main objective of this thesis was to develop new indoor localization techniques in the field of AR, taking advantage of technological advances, and to validate them by building frameworks and applications oriented to the evaluation of spatial location ability in adults; and studying perceptual augmentation in the visual and tactile channels. The specific objectives were the following:

- Determine the effects of SLAM-based AR with visual and tactile augmentation on indoor spatial localization processes.
- To design and develop a framework and authoring tool to enable the creation of applications with the aforementioned features.
- Validate the framework and authoring tool with the creation of two use cases for orientation and spatial localization in small and large environments.
- Determine the effects of the applications with the aforementioned features on young adults, and considering gender.
- Determine if there are significant differences in the effects produced on users between the different applications developed.
- To carry out as many validations as possible to exploit the developments to the maximum.

- To carry out an exhaustive analysis that considers all the variables involved in the validations.

The general hypotheses are the following:

GH-1 An indoor spatial localization system with SLAM-based AR using the sense of sight and touch will be effective and offer significant improvements over current methods.

GH-2 Users will positively value a system with the above features with respect to: motivation, enjoyment, ease of use, and satisfaction.

GH-3 A system with the above features will measure the user's orientation ability and the recorded performance will be related to other determining factors of spatial behavior.

To achieve the objectives, a framework and an authoring tool were designed and developed, and two spatial-location applications were created, using the sense of sight and touch, respectively. The applications can be used in both small and large environments. These two applications were validated in three studies.

Study 1 – Visual stimulus and environments of small dimensions.

The study involved 55 users (36.53 ± 15.78), 24 females.

Participants were divided into two groups: NoARGroup (participants memorized the location of objects by looking at photographs of the augmented environment using the device) and the ARGroup (participants memorized the location of virtual objects in the real world in a memorization phase using AR). The real environment, as well as its photographic version, consisted of a large living room.

The aim of this study was to determine the influence of touring the augmented environment on the memorization of the location of virtual objects. The performance of the participants in the two groups (NoARGroup versus ARGroup) was evaluated and compared. The results obtained were also compared in terms of subjective variables, and considering age and gender.

The first hypothesis (H1) was that there would be statistically significant differences for participants' performance in favor of the ARGroup. The second hypothesis (H2) was that there would be no statistically significant differences in terms of gender or age.

Study 2 – Visual stimulus and large environments.

Forty-six young adults (24.65 ± 8.54 years), 26 females, participated in the study.

Only one group was considered in which participants had to memorize the position of eight virtual objects while walking through a two-story building of a University. Participants' performance was also evaluated in a verbal object recall task, a pencil and paper spatial orientation task and a map-pointing task. The importance of different spatial strategies for orientation and anxiety levels were also evaluated.

The first objective of this study was to determine whether the application worked properly in a two-story building. The second objective of this study was to determine whether emotional factors affect spatial orientation in a larger environment than the one used in Study 1.

The third hypothesis (H3) was that the application would function correctly in a two-story building. The fourth hypothesis (H4) was that emotional factors would affect spatial orientation.

Study 3 – Visual versus tactile stimuli and small environments.

Fifty-three subjects, 16 females, participated in the study. After applying the exclusion criterion, the sample used was 47 subjects, 33 males (30.18 ± 9.25 years) and 14 females (32.86 ± 11.22 years).

The participants were divided into two groups: Visual, which used visual stimuli, and Tactile, which used tactile stimuli.

The objective of this study was to determine the influence of the type of stimulus on the participants' performance. The performance of the participants in the two groups (Visual versus Tactile) was evaluated and compared. The results obtained were also compared in terms of subjective variables, and considering age and gender.

The fifth hypothesis (H5) was that the sense of touch would be a valid sense in the assessment of spatial memory. The sixth hypothesis (H6) was that there would be statistically significant differences for participants' performance in favor of the visual sense. The seventh hypothesis (H7) was that there would be no statistically significant differences for gender.

1.3 Structure of the thesis

The thesis document is structured as follows:

Part I. This part introduces the thesis, including the motivation, the scientific goals, the research hypotheses, the studies carried out, the organization of the document.

Part II. This part presents a selection of the most representative publications supporting this thesis which were published in journals. Specifically, it includes three publications.

Paper 1. Munoz-Montoya, F., Juan, M.-C., Mendez-Lopez, M., & Fidalgo, C. (2019b). Augmented reality based on SLAM to assess spatial short-term memory. IEEE Access, 7, 2453– 2466. https://doi.org/10.1109/access.2018.2886627

It describes the first development and study of the thesis for spatial memory.

Paper 2. Munoz-Montoya, F., Fidalgo, C., Juan, M.-C., & Mendez-Lopez, M. (2019a). Memory for object location in augmented reality: The role of gender and the relationship among spatial and anxiety outcomes. Frontiers in Human

Neuroscience, 13, 113. https://doi.org/10.3389/fnhum.2019.00113

The performance in a large environment was compared with the performance in paper-and pencil tasks.

Paper 3. Munoz-Montoya, F., Juan, M.-C., Mendez-Lopez, M., Molla, R., Abad, F., & Fidalgo, C. (2021). Slam-based augmented reality for the assessment of short-term spatial memory. a comparative study of visual versus tactile stimuli. PLOS ONE, 16(2), 1–30. https://doi.org/10.1371/journal.pone.0245976

The performance in the task with different sense stimulus were compared.

Part III. This part discusses the results of the thesis, summarizes the work with the general conclusions and future works, and enumerates the publications derived from this thesis.

Chapter 2

Augmented Reality Based on SLAM to Assess Spatial Short-Term Memory

Visual stimulus and environments of small dimensions

Munoz-Montoya, F., Juan, M. C., Mendez-Lopez, M., Fidalgo, C. (2019) Augmented Reality Based on SLAM to Assess Spatial Short-Term Memory. IEEE Access, vol. 7, pp. 2453 - 2466, 10.1109/ACCESS.2018.2886627

2.1 Abstract

Spatial short-term memory is defined as the limited ability of people to retain and remember the location of elements for short periods of time. In this paper, we present the first AR app based on SLAM (Simultaneous Localization and Mapping) to assess spatial short-term memory. A total of 55 participants were involved in a study for remembering the real place where four virtual objects were located in the real environment. The participants were divided into two groups: the ARGroup (the participants learned the location of the virtual objects in the real environment in an adaptation phase using AR) and the NoARGroup (the participants learned the location of the objects by looking at photographs). The results indicated that the performance outcomes in remembering objects and their location for the participants in the ARGroup were statistically significantly greater than those obtained by the participants in the NoARGroup. From this result and our observations, we can conclude that touring the augmented environment helped the participants to better remember the location of virtual objects added to the real scene compared to looking at photographs of the environment. Furthermore, statistically significant differences were not found in relation to gender or age. Finally, our app has several advantages: 1) Our app works in any environment and does not require adding real elements to the environment; 2) The evaluators can select any real environment and

place the virtual elements where they want and even change them between sessions; and 3) Our app could work in a way similar to the way that spatial memory does in everyday life.

2.2 Introduction

In the last two years, hardware (e.g., Microsoft HoloLens and Magic Leap One) and software (e.g., Tango SDK, ARCore, and ARKit) have been developed with enough power to create Augmented Reality (AR) apps based on SLAM (Simultaneous Localization and Mapping) for mobile platforms. SLAM is a markerless tracking technology that tracks the environment without the need for adding any physical objects to the environment (e.g., markers or image targets). The SLAM mapping process obtains spatial data (e.g., 3D point clouds) of the environment to build a global reference map while simultaneously tracking the position of the subject (Bailey & Durrant-Whyte, 2006). AR based on SLAM offers many possibilities, and indoor location is undoubtedly one of them.

AR has not been exploited for processes of spatial orientation and location. The spatial ability of a person refers to the ability to solve spatial problems, such as perceiving distances and directional relationships, mentally transforming objects with respect to their position in space, locating elements in space, etc. It is important to know how the person is spatially oriented and what the factors are that influence this ability for the implications in daily and working life.

AR apps can be used for both assessment and training of spatial memory. As assessment tools, they enable the identification of alterations in spatial memory in both children and adults, e.g., determining if a person has difficulties that may affect his/her independence (Neguţ et al., 2016). As training tools, they can improve human performance in situations involving spatial orientation, e.g., practicing aid strategies (Caffò et al., 2013). Improving spatial capabilities not only benefits orientation behavior, but it also has a positive impact on the recovery of other areas, such as motor and social relationships (Barrett & Muzaffar, 2014). From a psychological point of view, knowing which variables are related to the performance obtained in AR apps will allow us to develop improved future designs oriented to spatial assessment and training with AR apps.

In this paper, we present a SLAM-based AR app to assess spatial memory. The objective of our work was to develop and validate our AR app for the assessment of spatial short-term memory by comparing the participants' outcomes in two different conditions: the ARGroup (learning the location of objects by using AR) vs. the NoARGroup (learning the location of objects by observing photographs of the environment). To our knowledge, there is only a single task that has been tested in two studies that has used AR (based on image targets, not SLAM) on mobile devices (Juan et al., 2014; Mendez-Lopez et al., 2016). Juan et al. (2014) and Mendez-Lopez et al. (2016) demonstrated that AR allows the development of applications that evaluate spatial ability while the person is moving. Using AR in any real environment (not limited to an area controlled by elements added to the scene) has great potential in the study of spatial orientation. This would allow the tasks to be more similar to those of everyday life. An important difference with these works (Juan et al., 2014; Mendez-Lopez et al., 2016) is that our app can be used in any indoor environment and it does not require the inclusion of additional elements to the real scene. Moreover, the evaluator can personalize the environment by placing the virtual objects in the desired place. The primary hypothesis of our work was that the performance outcomes for remembering the objects in their location would be significantly greater for the ARGroup.

The paper is organized as follows. Section II focuses on the state of indoor positioning and the assessment of spatial memory assisted by computer. Section III presents the design and development of our app. It also briefly explains the hardware and software used to develop and run the app. Section IV details the characteristics of the participants involved in the study, the measures and the configuration of the environment used, and the protocol followed. Section V presents the results. Section VI discusses our work and results. Section VII presents our conclusions and identifies areas for future research.

2.3 Background

2.3.1 Indoor Positioning

The technologies that are currently available for indoor positioning (Indoor Positioning System (IPS)) are the following (https://www.infsoft.com/solutions/basics/whitepaper): WiFi, Bluetooth, VLC (Visible Light Communication), and UWB (Ultra Wide Band). In exceptional cases, the use of GPS is possible, but this technology does not work when there is no visual contact with several GPS satellites. GPS accuracy can vary between 5 and 20 meters. In many cases, since there are already WiFi access points in many buildings, WiFi positioning systems (WPS) can be installed. The method known as fingerprinting is used for positioning. The accuracy of this method varies between 5 and 15 meters. Another possibility is the use of Bluetooth beacons (BLE Beacons). With this method, the accuracy varies between 1 and 3 meters. The use of WiFi and Bluetooth are two technologies that have proven to be useful for indoor location. One technology still to be exploited is VLC. In this case, special LEDs and infrared lamps emit imperceptible flickering light, which is detected by the camera of a mobile phone or other sensor. In this case, the accuracy can be less than 50 cm. Recently, the company Decawave (https://www.decawave.com) introduced a technology based on ultra wide band radio (UWB) signals that can reach an accuracy of 10 cm., both indoors and outdoors. By placing a series of beacons, the position of a node can be located with high precision. This technology is based on the ability to measure the propagation time of the radio signal (and, therefore, the distance) between the elements of the system. According to the manufacturer's specifications, the range can be up to 40 meters through walls, and 300 meters in direct vision. However, our experience is that the presence of metal objects, water, and even people affects accuracy.

If the location is required to augment the scene (AR), none of the above-mentioned technologies offer the accuracy required to achieve an acceptable static error in the registration of augmented objects (placing the virtual object in the real scene with accuracy). The alternative is to use the SLAM technique for indoor positioning. The use of SLAM with mobile devices offers many possibilities. One of the most important ones is that it is wireless. The users have freedom of movement since movement is not limited by cables. Moreover, it is not necessary to add other elements to the environment such as beacons.

Recently, much attention has been paid to the possibilities of SLAM for indoor positioning. For example, Rehman & Cao (2017) used the Metaio SDK (a framework for marker and SLAM tracking) for indoor tracking. Using the Metaio SDK, they scanned the environment that consisted of visual features (3D point clouds) that were stored as trackables. Those trackables were associated with their corresponding locations and navigation-related information. The camera and inertial sensors of the device were used to track the 3D point clouds and device orientation. They conducted a study for indoor navigation to compare the performance of the participants using a HMD (Google Glasses), a Smartphone (Samsung Galaxy S4), and a paper map. They found that both digital navigation tools were better than the paper map in terms of shorter time and lower workload, but the digital aids resulted in worse route retention. Polvi et al. (2016) presented SlidAR, which is a 3D positioning method for SLAM-based handheld AR. SlidAR utilizes 3D ray-casting and epipolar geometry for virtual object positioning. They conducted a study that involved 23 participants. They compared the efficiency of the SlidAR method against a device-centric positioning method. Their results showed that SlidAR was significantly faster, required significantly less device movement, and got significantly better subjective evaluations from the participants. SlidAR offered somewhat higher positioning accuracy. Piao & Kim (2017) presented an adaptive monocular visual-inertial SLAM method for real-time AR applications in mobile devices. Their results demonstrated the effectiveness of performance improvement using their proposed method (up to 18.8%). Egodagamage & Tuceryan (2018) presented a collaborative AR framework based on distributed monocular visual SLAM.

Besides the possibilities for indoor positioning, SLAM-based AR can be used in many other applications. For example, Chen et al. (2018) presented an efficient and effective 3D surface reconstruction framework for an intra-operative monocular laparoscopic scene. They checked the accuracy of the camera tracking by comparing the results of the video camera tracking with the recorded ground-truth camera trajectories. Root mean square errors of 1.24 mm and 2.54 mm. were obtained for the camera trajectories and the surface reconstruction, respectively. Their results show the potential of AR based on SLAM to be used in minimally invasive surgery.

2.3.2 Assessment of Spatial Memory Assisted by Computer

Spatial short-term memory can be defined as the limited ability of people to retain and remember the location of elements for short periods of time (Baddeley, 1992). Virtual Reality (VR) or AR applications allow objective indicators of a person's spatial learning to be obtained through a presentation of stimuli (varied and diverse) and the storage of responses (reaction times, successes-failures, distance traveled, speed, etc.) (e.g., Picucci et al. (2011); Juan et al. (2014); Walkowiak et al. (2015)). Applications of this type suppose an advantage with respect to the evaluation and training of the person in a natural environment (temporal and economic costs, etc.). Therefore, the use of VR in the study of human spatial ability is becoming more frequent. Traditionally, VR applications were used in procedures that were developed in simple natural environments (rooms, laboratories, etc.). In these scenarios, the person interacts in a more or less complex virtual environment without physical displacement such as rooms where the person is sitting in front of a computer screen and performs a task exploring a VR environment (e.g., Picucci et al. (2011); Cimadevilla et al. (2014); Walkowiak et al. (2015)). However, the physical displacement component is important in spatial ability [16]. Following this idea, the latest VR works have incorporated physical displacement (Rodríguez-Andrés et al., 2016; Rodriguez-Andres et al., 2018; Cárdenas-Delgado et al., 2017)).

Rodríguez-Andrés et al. (2016) presented a VR task for the assessment of spatial short-term memory. In this work, they examined the influence of the type of interaction used on the ability to recall the place of the objects and the perceived usability and satisfaction of the children with the task. They used a large screen (120") for the visualization. Two interaction modes (the physical active condition vs. the physical inactive condition) were examined. For the physical active condition, they used a Wii mote and a Wii balance board. For the physical inactive condition, they used a gamepad. A total of 160 children participated in their study. There were no statistically significant differences in the results of the task using the two types of interaction. They found correlations between the scores obtained using their VR task and a traditional procedure for assessing spatial short-term memory. Their results revealed that the type of interaction used did not affect the performance of children in the VR task.

Cárdenas-Delgado et al. (2017) presented a VR task based on a maze that assesses spatial short-term memory in adults involving physical movement and immersion. As in previous works (Rodríguez-Andrés et al., 2016; Rodriguez-Andres et al., 2018), they used two different interaction types (the physical active condition vs. the physical inactive condition). For the physical active condition, they used a real bicycle. For the physical inactive condition, they used a gamepad. For immersion, they used a VR HMD (Oculus Rift). A total of 89 adults participated in their study. Their results showed that the performance on their task was better in the participants who used the physical inactive condition. Usability and satisfaction did not differ between conditions. The performance on the task correlated with the performance on other classical neuropsychological tests for the assessment of short-term memory and spatial memory.

With regard to physical displacement, AR offers new possibilities. To our knowledge, only a single task tested in two studies has used AR for the assessment of spatial orientation (Juan et al., 2014; Mendez-Lopez et al., 2016). Their task assessed the ability of the participants to remember the location in the real world of an increasing number of virtual objects that appeared augmented in the real world. The AR app used image targets. The testing area was a square of about five meters on each side. The testing area was surrounded by light brown paper to a height of 1.5 meters. The boxes were distributed in a circle with a radius of 1.85 meters. The image targets were placed inside real boxes, which served as locations. These boxes were strategically located in the testing area.

The task consisted of seven different levels. The number of boxes ranged from 2 to 14, depending on the level. Their study involved 76 children divided into two groups: preschool (5-6 years old) and primary school (7-8 years old). They obtained significant performance outcomes in the AR task in favor of the older group. They found significant correlations between traditional tests and scores for the AR task. Their study revealed that the younger children were more satisfied with the AR task. As mentioned above, our work goes one step further in demonstrating the potential of SLAM-based AR to assess spatial memory.

2.4 Design and Development

In this section, we describe the phases of the app. We also detail the hardware and software used.

2.4.1 The App

The central part of the app is a task that allows the participants to tour a real environment in which they must look for virtual objects and remember their location. For this purpose, the person in charge of the evaluation must first (and only once) configure the scene for the task in two phases: 1) environment scanning; and 2) object configuration. The phases for configuring the scene for the task are the following:

1) Configuration Phase. The Environment Scanning Phase
This is a configuration phase in which the supervisor scans the real environment where the validation of the task will be performed (Figure 2.1). This scan is necessary in order to store the morphology of the environment in the device.

2) Configuration Phase. The Object Configuration Phase
Using the information stored in the previous phase, the supervisor locates the different 3D objects in the real scanned environment. A total of four objects are available for positioning. These four objects are: a sculpture, a telephone, a fountain pen, and a toy car. The supervisor can place these four objects in the desired locations using the strategy she/he chooses. The objects should be placed on plane surfaces (horizontal or vertical). The orientation of an object is obtained by the normal vector of the identified surface and the direction from the camera to the object. The forward face of the object is facing the position of the supervisor, who handles the device at each moment. The up vector of the object has the same direction as the normal vector of the detected surface. The supervisor has the freedom to choose the spot on a surface where the object will be placed (with two degrees of freedom (x and y)). For example, if the detected plane is on a horizontal table, the supervisor has the possibility of moving the object forward and backward (Y axis) as well as to the right and to the left (X axis) on the table. The supervisor will not be allowed to move the object up and down (Z axis). The bottom side of the object is attached to the detected surface. The supervisor will not be allowed to rotate the object. The objects are always facing the supervisor's position, and their up

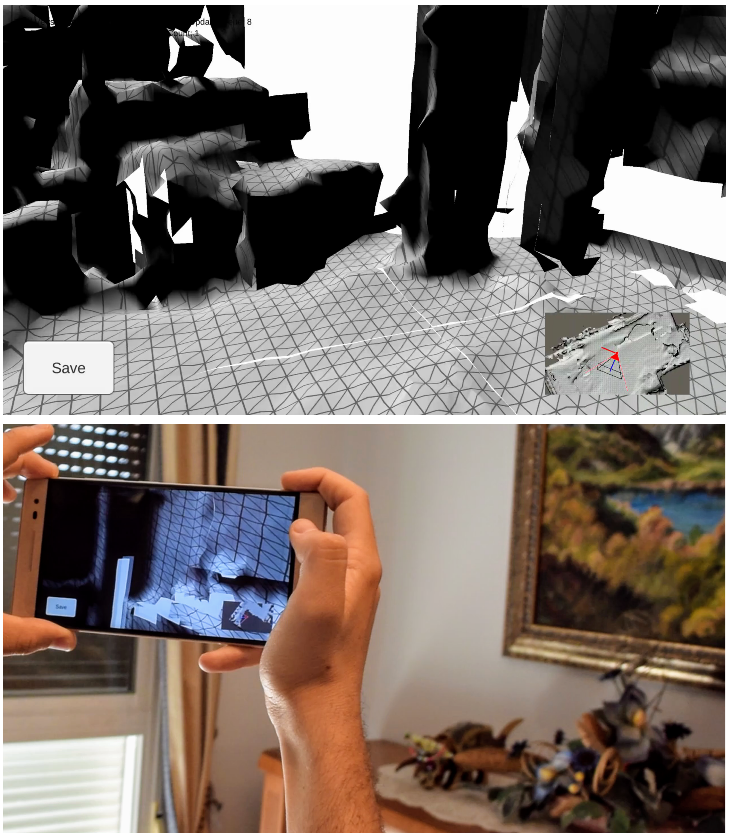

Figure 2.1: Scanning phase. View of the environment used in the study.

vectors are perpendicular to the plane of the table. During this phase, the supervisor takes photographs of the environment where the virtual objects are located. These photographs will be used in the memorization phase.

The phases of the task for the assessment of spatial memory that should be performed by the user are the following (see the Video File for a video demonstrating the functionality of our app):

1) User's Phase. The Adaptation Phase

This phase has two objectives. The first objective is to provide an initial experience with the mobile device and the task so that the user becomes familiar with them. The user learns how to hold the device, how to move inside the virtual environment, and how it works. Two conditions are used:

A. The AR Condition in which the virtual elements appear overlapped in the real environment (AR). The users can approach the virtual objects as close as they like and view them from different angles while familiarizing themselves with the environment, the device, and the task.

B. The NoAR Condition in which the users only see the real environment through the device screen, but without virtual elements.

These two conditions were defined in order to corroborate that the performance outcomes for remembering the virtual objects in their location would be significantly greater for the AR Condition (the primary hypothesis). In other words, our hypothesis is that seeing the virtual objects integrated in the real environment helps to memorize them. This memorization would be statistically greater when compared to not seeing the virtual objects in the real environment and memorizing their location using only photographs. During this phase, the users are asked to inspect the environment looking for virtual objects that are not visible in the real environment. These objects are the objects that were added in the object configuration phase. These virtual objects appear in the ARCondition (Figure 2.2), but they do not appear in the NoAR Condition (Figure 2.3). As can be observed in Figures 2.2-2.3, a virtual red car appears on the table in the AR Condition (Figure 2.2), but it does not appear in this location in the NoAR Condition (Figure 2.3). The users have a total of two minutes to complete this phase. They do not receive any help regarding where the objects are, the objects that they have seen, or those that they must see.

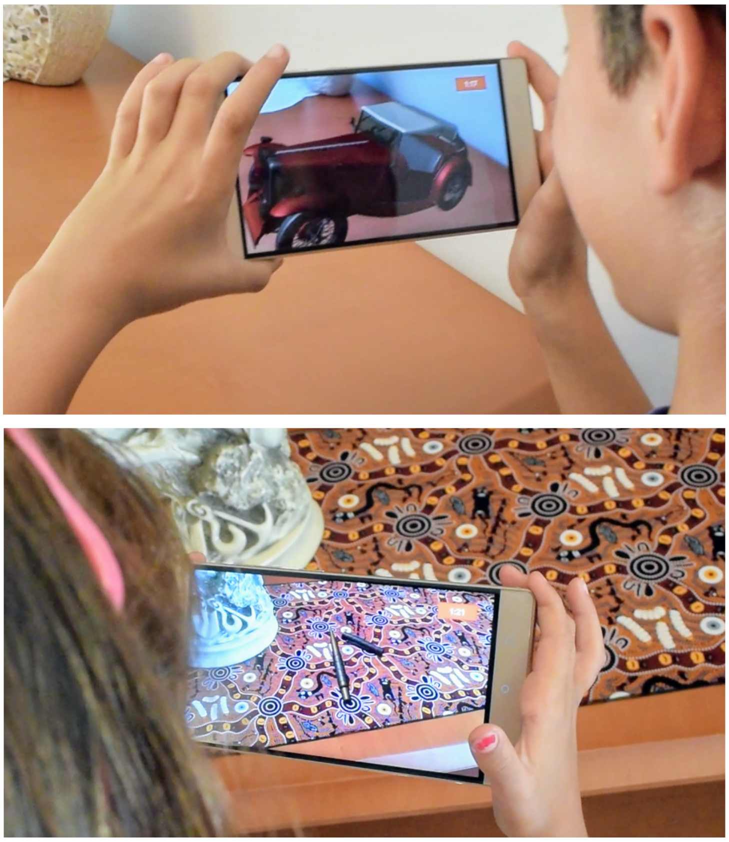

Figure 2.2: Two examples of children performing the adaptation phase in the AR Condition.

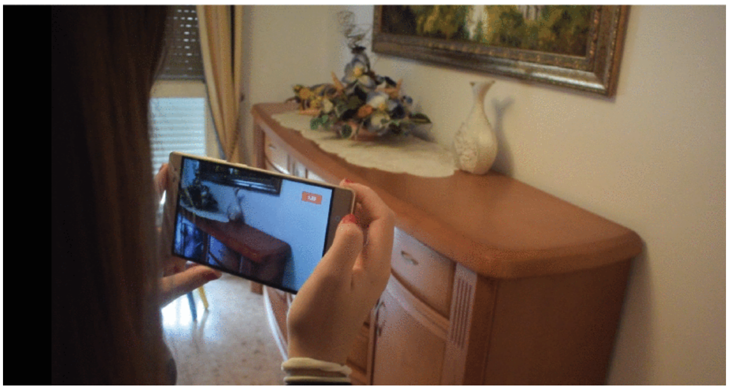

Figure 2.3: An example of a participant performing the adaptation phase in the NoAR Condition.

2) User's Phase. The Memorization Phase

During this phase, the photographs taken in the configuration phase are shown (Figs. 4-5). These photographs show the virtual objects in the real environment. During this phase, the users must memorize the location of the different objects in the real space. This phase is the same for the two groups (AR and NoAR). However, depending on the condition used in the adaptation phase, the users may have already memorized these locations (the AR Condition) or it may be the first time that they see the objects through 2D photographs (the NoAR Condition). In other words, the participants in the AR Condition may have already seen the objects mixed with the real world in the adaptation phase. This memorization phase could serve to reaffirm the information perceived in the adaptation phase. However, the participants in the NoAR Condition had not seen these objects because they did not appear in the real world when they were touring with the mobile device in the adaptation phase. Since this is the first time that these participants see the virtual objects, they must memorize these virtual objects and relate them to their real-world locations. The users can zoom in or zoom out of the photographs as many times as they wish. The participants have a total of one and a half minutes to complete this phase. The participants in the AR Condition did not pay as much attention as the participants in the NoAR Condition. However, in this study the time for the memorization phase was fixed and the participants could not leave before the fixed time.

3) User's Phase. The Evaluation Phase

This phase assesses the users' ability to remember the location of the virtual objects in the real environment learned in the previous phases. The users are asked to locate the virtual objects in their correct locations. The users can select the object to be located among the four virtual objects that appear in a selection bar with buttons on the right side of the screen (Figure 2.6). When the button of a given object is selected, it is automatically positioned in the center of the device screen. The object adapts to horizontal and vertical surfaces. In other words, the app identifies the horizontal and vertical surfaces and allows objects to be placed on them. The functionality for the placement of the objects by

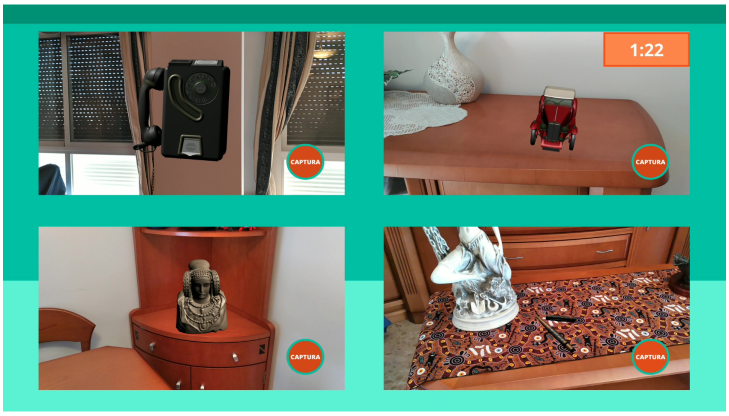

Figure 2.4: Memorization phase. The photographs taken in the configuration phase are shown on the screen device.

Figure 2.5: Memorization phase. A user performing the memorization phase.

the participants is the same as that described in the object configuration phase. When the object is on the desired surface, the user presses the "Set" button and the object is anchored in its current position (Figure 2.7). The objects do not have to be placed in exactly the same location. There is a margin of error of a sphere of half a radius meter from the point where the object should be placed. The users are informed whether or not they have positioned the object correctly. The users have three attempts to position each object correctly. On the last attempt, the object remains fixed in the position where it was placed, informing the user whether it was a success or failure, and then disappears from the selection bar. The users do not get any help regarding where to place the objects.

Figure 2.6: Evaluation phase. The selection bar with 4 buttons showing the images of the objects to be placed in the real environment on the right side of the screen.

Figure 2.7: Evaluation phase. The car is placed on the correct table.

2.4.2 Developement

2.4.2.1 Hardware & Software

The device used for the development of the app and the study was a Tango smartphone, Lenovo Phab 2 Pro. The main characteristics of the mobile phone are: Dimensions (179.8×88.6×10.7 mm); Weight (259 grams); Size (6.4 inches); and Resolution (1440×2560 pixels). This is one of the two devices available on the market that can run apps developed with Tango SDK. The main feature that provides this device with such special functionality is that it has three built-in cameras (a color camera with 16 MP, a wide-angle camera, and a depth camera). These three cameras and the Tango SDK provide the device with SLAM technology. The three main functionalities are: motion tracking, learning area, and depth perception.

The app was developed using the Unity3D game engine (https://unity3d.com). For our app, Unity3D offers two advantages: the abstraction of the life cycle of a graphic application, and the integration of the Tango SDK.

2.4.2.2 User Interface

An intuitive interface was designed with a minimal number of buttons and elements in order not to distract the user from the task. The interface changes during the process of the task, while still maintaining a common thread. During the adaptation and evaluation phases, the users hold the mobile device in front of their body while the image captured by the camera is displayed on the screen. In the adaptation phase with the AR Condition, the virtual elements overlap this image. Additional buttons are incorporated in the evaluation phase. As already mentioned, a selection bar with different buttons appears on the right side of the screen with the images of the objects to be placed in the real environment (Figure 2.6). The process of positioning the object in the real environment begins once one of these buttons is selected.

Different options were considered to facilitate a stable positioning by the user. One proven option was to drag objects across the screen and drop them into place using touch. However, this method becomes difficult when the user has to hold the device with one hand and drag the objects with the other. Since precise positioning was very difficult to achieve with this method, we chose to place the object in the middle of the screen and adapt its position to the surface at the corresponding point. The object adapts its position to the surfaces in the center of the screen as the user moves around with the device. A "Set" button was incorporated. This button is pressed by the user when the object is in the desired position and the object is anchored in its place.

In the memorization phase, the interface consists of a frame showing the four different photographs of the objects positioned in the real environment. The user is able to zoom in and out by pressing on them.

2.4.2.3 AR Service

For the development of the app, we used three features offered by the Tango SDK:

- **Area Learning.** This feature allows the environment to be scanned. It performs an initial scan of the environment in which the scene morphology is stored in the device. The SLAM technique is used to find and store visual features that enable a future location of the device in the environment. With the scanned and saved environment, it is possible to indicate certain points where the virtual elements will be located. These points in the space are stored along with the characteristics of the environment.

- **Motion Tracking.** The device knows its relative position with respect to the real environment at any moment. This feature allows the mobile device to show the virtual objects in their proper place and even trace the path that users follow. This feature is used in the adaptation and evaluation phases.

- **Depth Perception.** The depth camera is used to detect flat surfaces in the space on which to place virtual objects. To obtain these flat surfaces, the app generates a

	CHILDHOOD (<=15)	YOUTH (16-25	ADULTHOOD (26-50)	MIDDLE AGE (>50)
Men	10	4	13	4
Women	0	3	17	4

Table 2.1: Gender and age distribution of the participants.

cloud of points of the environment that appears on the screen. This cloud of points is analyzed to find flat surfaces. The flat surfaces that we use can be horizontal and vertical.

2.4.2.4 Storage of Data

During the adaptation and evaluation phases, the app stores different data. We used some of this data in our analysis. This data includes: the user ID, the condition of the adaptation phase (AR or NoAR), the time spent on each phase, the successes achieved in the evaluation phase, and the relative position of the user with respect to the environment. The data is collected without altering the execution of the task.

2.5 Description of the Study

This section presents the characteristics of the participants involved in the study, the measurements used, the configuration of the environment, and the steps followed.

2.5.1 Participants

A total of 55 subjects, ranging in age from 8 to 72 years old, were involved in the study. The mean age was 36.53 ± 15.78 years old. There were 31 men (56.36%) and 24 women (43.63%). Table 2.1 shows the participants' distribution for gender and age. The participants or their parents were informed about our study and their objectives. They signed a written consent form. The principles expressed in the Declaration of Helsinki were followed for all of the clinical research. The study and the written consent form were approved by the Ethics Committee of the Universitat Politècnica de València, Spain.

2.5.2 Measurements

The app stored the following variables: the type of augmentation (AR or NoAR in the habituation phase), the errors committed in the evaluation phase, and the duration of the phases.

Presence in virtual environments can be defined as an individual and context-dependent user's response that is related to the experience of "being there" (Bowman & McMahan, 2007). Witmer et al. (2005) define presence as a psychological state of "being there" mediated by an environment that engages our senses, captures our attention, and fosters our active involvement. However, according to Regenbrecht & Schubert (2021), this definition cannot be applied exactly to AR. However, in AR, presence can also be achieved by measuring the presence of virtual elements in the real environment (Regenbrecht & Schubert, 2021). To measure the sense of presence, we added ten questions that are adapted from the Witmer and Singer questionnaire (Witmer et al., 2005). We also added two questions from the questionnaire proposed by Slater et al. (1994). These two questionnaires have commonly been used to measure presence in VR environments. For AR environments, we adapted five questions from the Regenbrech and Schubert questionnaire (Regenbrecht & Schubert, 2021). We included ten questions from the Witmer questionnaire (vs. 3.0, 4-factor model) (Witmer et al., 2005) to measure presence. These 10 questions considered the four factors identified for their presence questionnaire. The numbers in parentheses are the number of the questions in the Witmer questionnaire version 3.0. These factors are: Involvement (2, 6, 18); Visual fidelity (15, 16); Adaptation/Immersion (20, 21, 24), and Interface Quality (19, 23). In total, we have seventeen questions to measure presence.

For perceived usability, we included six questions adapted from the SUS questionnaire proposed by Brooke et al. (1996).

To assess interest/enjoyment, perceived competence, and pressure felt, we included eleven question from the Intrinsic Motivation Inventory (IMI) (Whepley, 2012). Specifically, we included five questions for interest/enjoyment, five questions for perceived competence, and one question to measure the pressure felt. We also included two questions to measure the perceived mental effort and the physical effort in arms and hands.

For perceived satisfaction, we included four questions based on our previous experiences (e.g., Calle-Bustos et al. (2017)).

The questionnaire (39 questions) was filled out online in a web-based format. All of the questions were formulated in a positive manner. All of the questions used a 7-point Likert scale ranging from 1 "Totally disagree" to 7 "Totally agree".

2.5.3 Configuration of the Environment

The study was carried out in a room of 42 square meters. The room had the furniture commonly found in a dining room. The virtual objects could be mimicked in that environment. The four virtual objects were positioned in the room. Figure 2.8 shows the shape of the room and the location of the four virtual objects.

2.5.4 Procedure

The participants were counterbalanced and randomly assigned to one of two conditions:

- The ARGroup: Participants who learn the location of the virtual elements that are overlapped in the real environment in the adaptation phase using AR.
- The NoARGroup: Participants who see the real environment through the device screen, but without virtual elements. These participants learned the location of the objects by looking at photographs in the memorization phase.

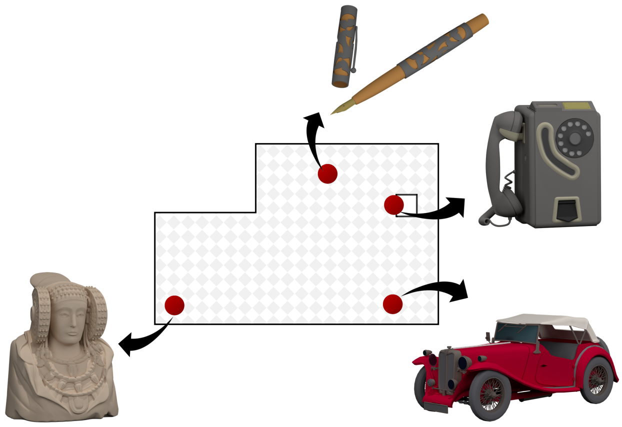

Figure 2.8: Study environment: shape of the room and location of the four virtual objects.

The protocol was the following:

1. The participants performed the task (ARGroup or NoARGroup).

2. The participants filled out a questionnaire.

2.6 Results

This section details the analysis carried out with the data collected during our study. An initial descriptive analysis was carried out to explore means, standard deviations, and other measurements. Data normality was checked, and the appropriate statistical tests were applied. To check data normality, we applied the following tests: Shapiro-Wilk ($W = 0.591$, $p < 0.001$**), Kolmogorov-Smirnov ($D = 0.428$, $p = 0.001$**), and Anderson-Darling ($A = 11.305$, $p < 0.001$**). The three tests indicated that our sample did not fit the normal distribution. Therefore, non-parametric tests were used (the Mann-Whitney U test and the Spearman correlation for correlation tests). All of the tests are presented in the format (statistic U/W, normal approximation Z, p-value, r effect size). The symbol ** indicates the statistical significance at level $\alpha = 0.05$. The statistical open source toolkit R (http://www.r-project.org) was used to analyze the data.

2.6.1 Performance Outcomes

In order to know how the use of AR for learning the location of different objects affects the performance outcomes of the participants, we compared the performance outcomes between the two groups (the ARGroup vs. the NoARGroup). The score variable was created by counting the number of objects placed correctly for the four objects.

To determine whether or not there were differences in remembering and placing objects in their correct location between the participants of the two groups (AR (3.926 ± 0.267) vs NoAR (3.25 ± 0.799)), a Mann-Whitney U test was applied ($U = 187$, $Z = 0.428$, $p <$

0.001**, r = 1.143). This result showed that there was a statistically significant difference between the two groups in favor of the ARGroup (the group that learned using AR). From this result, we can deduce that AR helped users to better learn the position of objects in the environment.

2.6.2 Subjective Perception and Satisfaction Outcomes

The online questionnaire described in Section IV.B (Measurements) was used to measure the subjective perception of the participants with the task and their performance. The questions in that questionnaire were grouped in variables to measure different factors. The means of these variables are shown in Figure 2.9. This figure shows that all of the mean scores were quite high. The lowest value was 6.23 in presence for the NoARGroup. Our explanation for this result is that the participants did not visualize the virtual objects in the adaptation phase.

Figure 2.9: Graph showing the mean scores for the different variables measured in the questionnaire.

A Mann-Whitney U test was applied to the defined variables and the two groups (AR vs. NoAR). There was a statistically significant difference in the satisfaction experienced by the users between the two groups in favor of the ARGroup (U = 255, Z = 0.356, p = 0.0148**, r = 0.57). There was a statistically significant difference in presence experienced by the users between the two groups in favor of the ARGroup (U = 247, Z = 0.189, p = 0.0271**, r = 0.599). There were no statistically significant differences for the other variables. We would like to add that the means for all of the variables and for the two groups were above 6 on a scale from 1 to 7. The means for all of the variables except one (Mental Effort) in the ARGroup were higher than in the NoARGroup (e.g., the mean for Satisfaction in the ARGroup was 6.907). These means and the analysis performed demonstrate the positive perception of our task by the participants.

Since statistically significant differences were observed in the satisfaction and presence variables with respect to both groups, correlations between variables were applied separately. A Spearman correlation was applied to determine if there is a significant correlation between some of the measured variables in each of the two groups (the ARGroup vs. the NoARGroup). Figure 2.10 shows the correlation plot. There are six significant positive correlations in the ARGroup and there are ten significant positive correlations in the NoARGroup.

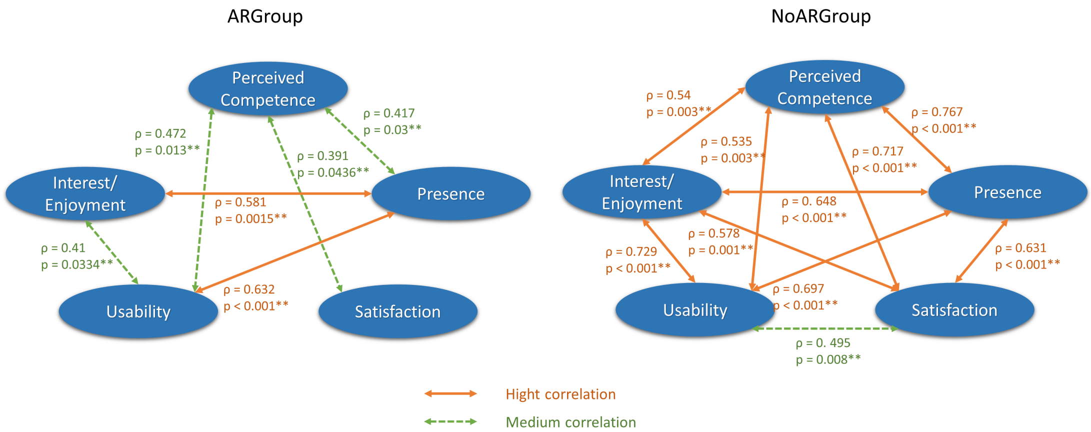

Figure 2.10: The correlation plot among the analyzed variables for the two groups (the ARGroup and the NoARGroup).

In order to measure presence, questions based on the questionnaires of Slater, Regenbrench, and Witmer were used. A Spearman correlation test was applied to the variables related to these three questionnaires for the two groups (Figure 2.11). Figure 2.11 shows that there are significant positive correlations among the variables related to the three questionnaires in the two groups. This is a good result because it indicates that the selected and adapted questions of these three questionnaires were appropriate for measuring the level of presence in our task.

The different factors identified in the Witmer questionnaire were also analyzed. Figure 2.12 shows the correlation plots for the two groups. In the work of Witmer et al. [24], four significant positive correlations were obtained (Involment $\Longleftrightarrow$ Adaptation/Immersion; Adaptation/Immersion $\Longleftrightarrow$ Sensor Fidelity; Sensor Fidelity $\Longleftrightarrow$ Involvement; Adaptation/Immersion $\Longleftrightarrow$ Interface Quality). In our study, we found five significant correlations in the ARGroup and the NoARGroup. Three of them were the same as in the Witmer study (Involment $\Longleftrightarrow$ Adaptation/Immersion; Visual Fidelity $\Longleftrightarrow$ Involvement; Adaptation/Immersion $\Longleftrightarrow$ Interface Quality). The other two significant correlations were: Involment $\Longleftrightarrow$ Interface Quality and Visual Fidelity $\Longleftrightarrow$ Interface Quality.

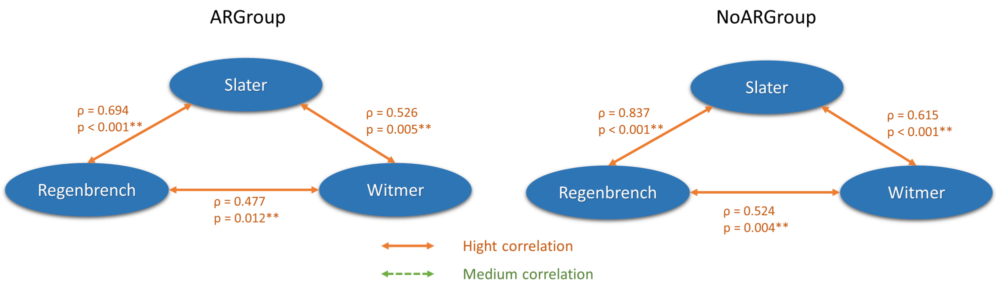

Figure 2.11: The correlation plot for the variables related to the presence questionnaires of Slater, Regenbrench, and Witmer for the two groups (the ARGroup and the NoARGroup).

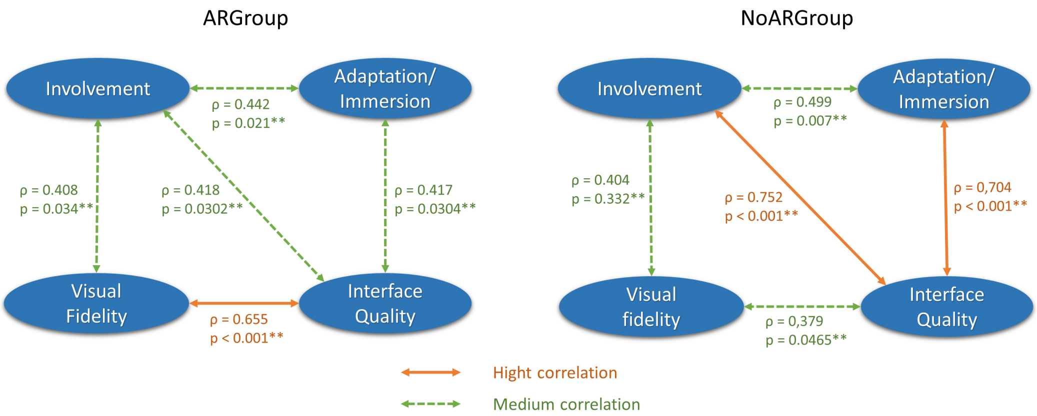

Figure 2.12: The correlation plot for the factors identified by Witmer for the two groups (the ARGroup and the NoARGroup).

2.6.3 Gender and Age Comparisons

A Mann Whitney U test was applied to check if gender affected the score. The results indicated that there was no statistically significant difference in gender (U = 385.5, Z = 0.278, p = 0.792, r = 0.037). To determine if the score obtained by the participants was affected by age, we applied a Kruskal Wallis test. The results showed no statistically significant differences for the age factor ($\chi^2(3) = 0.986$, p = 0.805, r = 0.107). For the variables of the questionnaire (Perceived Competence, Interest, Presence, Pressure, and Usability), Mann Whitney U tests were applied and no statistically significant differences were obtained regarding gender.

With regard to the participants' experience and their age, we checked if there were differences in the experience that the users had during their performance due to their age. A Kruskal Wallis test was applied to each variable. The results showed that there were two variables that offered statistically significant differences depending on the age of the participants. These variables were: Interest ($\chi^2(3) = 9.003$, p = 0.029**, r =

0.303) and Usability ($\chi^2(3) = 19.298$, $p < 0.001$**, $r = 0.532$). For Interest, there was a statistically significant difference between children and the rest of the groups and no significant difference between groups who were over 15 years old. Mann-Whitney U tests were applied and the results were: Childhood vs. Youth ($U = 13$, $Z = 2.275$, $p = 0.0186$**, $r = 0.552$); Childhood vs. Adulthood ($U = 66$, $Z = 2.746$, $p = 0.005$**, $r = 0.434$); Childhood vs. Middle Age ($U = 16.5$, $Z = 2.152$, $p = 0.031$**, $r = 0.507$). For the Usability variable, the results after applying the Mann-Whitney U tests were similar to the results obtained for the Interest variable. In other words, there were statistically significant differences between the group of children and the rest of the groups. Childhood vs. Youth ($U = 0$, $Z = 3.467$, $p < 0.001$**, $r = 0.841$); Childhood vs. Adulthood ($U = 35.5$, $Z = 3.656$, $p < 0.001$**, $r = 0.578$); Childhood vs. Middle Age ($U = 11.5$, $Z = 2.548$, $p = 0.00873$**, $r = 0.601$). There were no statistically significant differences between the groups who were over 15 years old. Figure 2.13 shows a box plot where the values for the Usability variable and different age groups are shown graphically. The box plot for the Interest variable shows a similar trend.

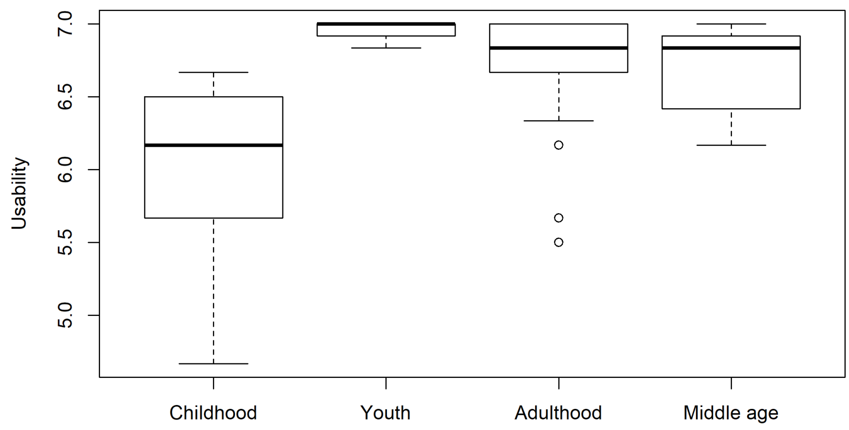

Figure 2.13: Box plot for the Usability variable and different ages.

2.7 Discussion

In this paper, we have presented a SLAM-based AR app to support the assessment of spatial memory. The central part of the app is a task that allows participants to tour a real environment, in which they must to search for virtual objects and remember their location. To our knowledge, only one task has been tested in two studies that used AR for the assessment of spatial memory (Juan et al., 2014; Mendez-Lopez et al., 2016). However, those studies did not use SLAM-based AR. Those studies used AR based on fiducial markers (image targets) added to the real environment. Our work goes one step further in demonstrating the possibilities of SLAM-based AR for assessing spatial memory. In this paper, we carried out a study comparing the effects of using and not using AR for learning where the different objects were placed in the real environment. We also tried to determine whether using AR creates a significant difference in the user's experience. Our study involved 55 participants counterbalanced in AR vs. NoAR conditions (gender and age).

The main difference between the two groups (the ARGroup and the NoARGroup) was that the participants of the ARGroup learned the location of the virtual objects placed in the real environment in the adaptation phase using AR. This phase allowed them to pay attention to details of the environment and thus facilitate more specific learning. These participants also observed the photographs of the environment with the virtual objects in the memorization phase. This phase was useful for participants to reinforce information about virtual objects and their location. Some of these participants were interested in this reinforcement, but other participants perceived it as being redundant and did not pay much attention. In contrast, the participants of the NoARGroup toured the real environment and could pay attention to details, but without seeing the virtual objects in the environment. These participants had to pay attention to the photographs of the environment with the virtual objects shown in the memorization phase. In this phase, these participants paid attention to the photographs and looked at the real environment in order to be sure of the position in which they should place the virtual objects.

The results of this study show that, for the participants in the ARGroup, there was a statistically significant difference in remembering objects and their location. This corroborates our main hypothesis. The difference was basically due to two objects, the fountain pen and the telephone. The fountain pen was placed on a table with a tablecloth that was the same as the one on another table in the environment. The participants of the NoARGroup confused the two tablecloths and some of them placed the fountain pen on the wrong tablecloth. This tablecloth is shown in Figure 2.2. The telephone was placed on a pillar of the room that the users of the NoARGroup confused with the wall behind it. Figure 2.14 shows a participant of the NoARGroup placing the telephone on the wall and not on the pillar. From these results and our observation, we can conclude that touring the augmented environment helped participants better remember the location of virtual objects that were added to the real scene. Moreover, if we take into account the successes when placing objects using the AR condition (3.926 ± 0.267), we can conclude that SLAM-based AR can be used for the development of apps to assess spatial orientation.

This result complements the results that we obtained in previous works (Juan et al., 2014; Mendez-Lopez et al., 2016), which demonstrated that AR based on fiducials could also be used for the development of apps for the assessment of spatial memory.

When Juan et al. (2014) and Mendez-Lopez et al. (2016) are compared with our work, our proposal has several advantages: 1) The app presented works in any environment and does not require adding real elements to the environment; 2) The evaluators can select any real environment and place the virtual elements where they want and even change them between sessions; 3) Our app could work in a way similar to the way spatial

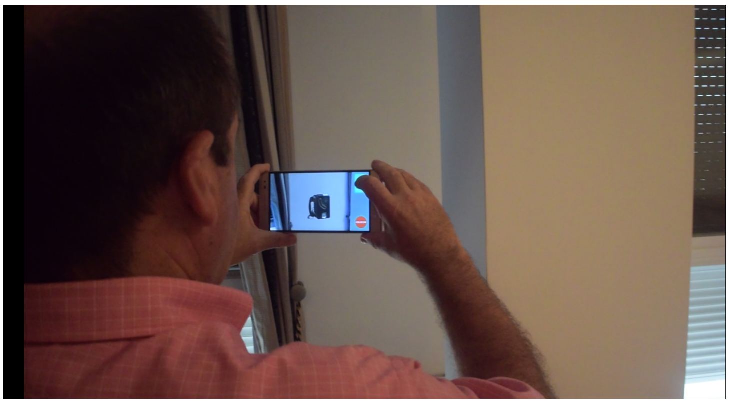

Figure 2.14: Participant of the NoARGroup placing the telephone on the wall and not on the pillar.

memory does in everyday life.

The app also has some advantages when compared to other methods of evaluating short-term memory: 1) The mental representation of the environment differs on the kind of space that is coded. Our app offers the possibility to investigate short-term spatial orientation by walking through the environment (i.e., the navigational space). The navigational space is the type of space in which many human behaviors take place. This is a great advantage compared to classical neuropsychological tests (e.g., Corsi Block Tapping Test (Kessels et al., 2000)), which evaluate spatial memory in the physical environment within the reaching distance (i.e., near space). 2) VR systems have already been used to assess short-term spatial memory (e.g., Cánovas et al. (2008); Spieker et al. (2012)). VR through Head-Mounted Displays tends to induce cybersickness (Rosa et al., 2016). None of the side effects attributed to cybersickness was experienced by any of the participants in our study.

The results also show that the performance outcomes were independent of the gender and age of the participants. This suggests that, regardless of gender or age, our task has proven to be suitable for assessing spatial memory. With regard to gender, our result is in line with the work in Juan et al. (2014). With regard to age, our result is different from the work in Juan et al. (2014). In Juan et al. (2014), the study involved two groups of children, preschool (5-6 years old) and primary school (7-8 years old). Significant improvement outcomes were obtained with the task in the older group. The task had seven levels, with three trials in each level and with an incremental number of objects to remember in each level (from 1 to 7). In this regard, it is well-known that visuospatial short-term memory skills increase as the brain develops (Gathercole et al., 2004; Best & Miller, 2010). Our argument for this result is that the level of complexity of the work in Juan et al. (2014) is different from the work presented here. If the task were more complex, similar results could be obtained. Greater complexity could be incorporated and studied in future developments.

With regard to the experience with the app and the answers of the participants to the on-line questionnaire, the means rated for all of the variables except one (Mental Effort) in the ARGroup were greater than for the NoARGroup (Figure 2.2). The participants in the ARGroup also experienced a statistically significant higher level of satisfaction and sense of presence. With regard to Mental Effort, our explanation for this result is that the participants in the NoARGroup did not have virtual objects to look for. Therefore, their mental effort was lower. The participants in the ARGroup had to tour the environment in order to search for virtual objects.

However, the differences in the users' experience regarding age but not gender were significant. No statistically significant differences were obtained for gender. Only two variables, Interest and Usability, showed statistically significant differences when children under 16 years old were compared with the rest of the groups. The scores for Interest and Usability were lower in the childhood group. These results are in contrast to previous works such as the work of Bacca et al. (2014), which indicates that AR offers advantages such as "motivation", "student engagement", and "improved perceived enjoyment". Our explanation for the low score in Interest of the childhood group is that the children expected the task to be more entertaining and fun. They expected to play with a game similar to the ones that they are used to (e.g., soccer). If our task is to be used with this group, it should be customized so that the objects are more suitable for them and offer more playful activities. For Usability, all of the users handled the mobile device without any physical support. Sometimes, the users had to hold the mobile device with one hand and touch the screen with the other without covering up the cameras on the back of the device. This was more difficult for the children, especially the smaller ones. To facilitate the handling of the device and to provide more stability and safety, an external case could be designed and adapted (Juan et al., 2014; Furió et al., 2013b,a). The external case could be printed on a 3D printer (Juan et al., 2014). This would also protect the device from damage.

For the subjective perception and satisfaction outcomes and their correlation plots (Figure 2.10), there were six significant positive correlations in the ARGroup and there were ten significant positive correlations in the NoARGroup. Our explanation for these results is that the participants of the NoARGroup scored an average of 0.22 lower, and the score for all of the questions was more uniform. This fact facilitates more significant positive correlations between these variables. However, there were statistically significant differences in the level of presence and satisfaction experienced by the users between the two groups in favor of the ARGroup. There were no statistically significant differences for the other variables. The correlation plot for the ARGroup (Figure 2.10) helps in the identification of the variable that is most closely related to the Satisfaction variable, which is the Perceived Competence. Our argument for this relationship is that the more expert a user considers herself/himself to be after completing her/his experience, the greater their overall satisfaction. For the level of presence, the two variables that are most closely related are Usability and Interest/Enjoyment and, to a lesser extent, Perceived Competence. Our arguments for these relationships are that ease in learning and handling has a positive influence on the level of presence. The enjoyment when using the app and how interesting the app seems to users are two factors that also contribute positively to the level of presence.

With regard to the correlations among the three variables related to the three presence questionnaires (Regenbrecht & Schubert, 2021; Slater et al., 1994; Witmer et al., 2005), there were significant positive correlations among these three variables for the two groups (the ARGroup and the NoARGroup), as shown in Figure 2.11. To our knowledge, this is the first study in which questions of the three presence questionnaires are used, and, moreover, correlations are found among them. This result indicates that the selection of the questions is appropriate for measuring the level of presence in our task. This selection could be used in other works to check whether or not the trend is similar.

With regard to Witmer's study (Witmer et al., 2005), we also used four factors. However, the questions that were included in each of our factors were a subset of those used in Witmer's study. In our study (Figure 2.12), there were the same number of significant positive correlations among the four factors in the two groups (the ARGroup and the NoARGroup). We found more significant positive correlations than Witmer (Witmer et al., 2005). Out of the four relationships found by Witmer, we coincide on three. As in Witmer's study, in our work, Involvement is strongly related to Adaptation/Immersion and Visual Fidelity. We also found a relationship between Adaptation/Immersion and Interface Quality, which, in our case, was stronger. Our explanation for the differences in the relationship of Visual Fidelity with the rest of the factors is that Sensory Fidelity was used in Witmer's study and it includes visual, auditory, and haptic items. In our case, the senses of audio and touch have not been considered. This could also explain the close relationship between Visual Fidelity and Interface Quality. The relationship between Involvement and Interface Quality can be explained by the relationship of the questions included in each factor in our study. Our argument for this relationship is that a higher Interface Quality has a positive influence on Involvement. To our knowledge, this is the first study in which the 4-factor model of Witmer has been used as a base for measuring presence using a mobile AR app. Moreover, several questionnaires (Regenbrecht & Schubert, 2021; Slater et al., 1994; Witmer et al., 2005; Brooke et al., 1996; Calle-Bustos et al., 2017; Whepley, 2012) were used as a base to evaluate the users' subjective experience using a mobile AR app.

In this initial study, the app does not control when the user sees the virtual objects in the real environment in the adaptation phase. If these objects are not seen in this phase, the AR and NoAR conditions are the same. Thanks to this study, we solved this problem and we have incorporated this control in the app. Therefore, we are sure that the user has seen all of the virtual elements in the real environment. Now, when the users find a virtual object, they must touch it on the screen and a green sphere with a certain level of transparency envelops the virtual object. This sphere does not disappear during the entire phase.

We used the Tango SDK for the development of the app. There are other SDKs (ARKit, https://developer.apple.com/arkit, and Google ARCore, https://developers.google.com/ar) with similar characteristics. However, when we developed our app, ARCore and ARKit did not offer the same functionality as the Tango SDK. The Tango SDK included the functionality to identify flat horizontal and vertical surfaces.

This functionality has already been incorporated in ARCore as of May 8, 2018.

It would be very interesting to explore the potential of other devices such as head-worn displays that can run SLAM-based apps (e.g., Magic Leap (https://www.magicleap.com) or Microsoft HoloLens (https://www.microsoft.com/en-us/hololens)).

2.8 Conclusions

We have developed the first SLAM-based AR app to assess short-term spatial memory. Our app is an authoring tool that allows the evaluators to perform the assessment in any indoor environment, to add the objects that they require, and to change the objects from one session to the next. We carried out a study involving 55 participants. The participants were divided into two groups: the ARGroup (participants who learned the location of the virtual objects using AR) and the NoARGroup (participants who learned the location of the objects by looking at photographs). The results show that the performance outcomes in remembering objects and their location were statistically significantly greater for the participants in the ARGroup than for the participants in the NoARGroup. That is, our main contribution is that touring the augmented environment helped the participants to better remember the location of virtual objects added to the real scene compared to looking at photographs of the environment. This new contribution can be exploited for the development of tasks to assess or train spatial memory in a way similar to the way that spatial memory performs in everyday life.

This is the first study that we have carried out with this app, but many more studies can be done. In this paper, we compared two conditions of the app. After demonstrating that AR based on SLAM helps in the memory of the location of virtual objects added to the real scene, more studies can be carried out. In our case, we plan to carry out a comparison of our app with traditional neuropsychological tests and involving people without disabilities or mental dysfunctions. This new study would corroborate the hypothesis that the results for our app would reflect the spatial short-term memory ability of participants in the same way as traditional procedures. The corroboration of this hypothesis would also strengthen the contribution of this paper. Another study that we plan to carry out is to test our app with acquired brain damage patients. This type of studies would demonstrate the potential of our proposal for different collectives. Another variable to analyze is the environment used. In our study, we used a small-scale environment, a living room. A study in a more controlled area could also be conducted to rule out context-contingent potential interferences of (unknown or even known) stimuli that could influence test participants. Our app also works in large-scale environments (e.g., several floors of a building such as a university). In another study, the advantages and disadvantages between small-scale and large-scale environments could also be analyzed. Currently, our app stores data about errors committed in the evaluation phase and the duration of the phases. Other data that could be stored are the paths followed in the adaptation and evaluation phases. These paths could be analyzed to identify patterns of behavior between groups. Our task could also be adapted to other types of devices (e.g., Magic Leap).

Chapter 3

Memory for Object Location in Augmented Reality: The Role of Gender and the Relationship Among Spatial and Anxiety Outcomes

Visual stimulus and large environments

Munoz-Montoya, F., Fidalgo, C., Juan, M. C., Mendez-Lopez, M. (2019) Memory for Object Location in Augmented Reality: The Role of Gender and the Relationship Among Spatial and Anxiety Outcomes. Frontiers in Human Neuroscience, vol. 13, Article N. 113, 10.3389/fnhum.2019.00113

3.1 Abstract

The potential of augmented reality (AR) technology for the study of spatial memory and orientation is a new research field. AR defines systems that attempt to enhance the user's experience with the physical world. In our app, we enhance the sense of sight by adding interactive 3D elements to the real environment. Our app can be used in any real environment so that the experimental conditions during the tasks and the way in which an individual navigates are similar to those used in real life. With AR, the experimenter has a high level of control of the task and can store the participant's responses accurately. The classical factors that influence an individual's performance on virtual spatial tasks are gender and cognitive factors. The influence of emotional factors on spatial performance has been studied more recently. Since AR tasks for the study of spatial memory and spatial orientation are new developments, little is known about the factors that are related to performance on tasks of this type. In our study, we tested 46 young adults (26 women) in an AR object-location task that was performed in a building. The participants had to memorize the position of eight virtual objects while they were walking through the

environment. We also assessed the participants' performance on an object-recall task, a map-pointing task, and a paper-and-pencil spatial orientation task. The self-reported importance of different spatial strategies for wayfinding and the levels of trait anxiety and wayfinding anxiety were also evaluated. Our findings indicate that men performed better on the spatial paper-and-pencil test and spent more time completing the learning phase of the AR task. The spatial memory for the location of the objects in AR and on the map correlated positively. Anxiety was related to individual differences in the self-reported use of a spatial orientation strategy, but the association among them was weak. Trait anxiety was positively related to the time employed by the participants during the learning phase of the AR task, whereas wayfinding anxiety correlated negatively with the preference for an orientation strategy. Our results highlight the importance of anxiety in spatial orientation.

3.2 Introduction

The ability to maintain orientation within the spatial environment is one of the most fundamental cognitive functions in humans. In fact, spatial orientation is involved in everyday tasks such as finding the exit in an unknown building or finding one's way in a complex environment. Given that spatial orientation includes multiple and complex cognitive processes (Wolbers & Hegarty, 2010), it is not surprising that individuals differ in their ability to orientate themselves in space, ranging from individuals who get lost easily to those with excellent orientation skills.

Most of the studies that examine factors influencing spatial navigation have focused on cognitive and biological variables (Siegel & White, 1975; Lawton, 1996; Piccardi et al., 2011a; Lawton, 1994). One approach for examining individual differences based on cognitive variables is to investigate which strategy people use in spatial orientation. As individuals may analyze spatial information differently, they may therefore employ different strategies to find a destination (Lawton, 1996). Three spatial strategies or cognitive styles have been described based on the information people seek in order to orientate themselves in an environment: landmark, route, or survey strategies (Siegel & White, 1975). Landmark and route strategies are based on an egocentric reference frame and are less sophisticated than the survey strategy. The landmark strategy is based on perceptually salient or important cues for individuals, whereas the route cognitive style uses paths that are connected to different landmarks (Siegel & White, 1975). In contrast, an extrinsic reference frame is used in the survey strategy in which people use a cognitive map to orientate themselves in an environment (Pazzaglia & Beni, 2001). Similar to the cognitive styles described above, other authors proposed different wayfinding strategies that people use to orientate themselves indoors in the Indoor Wayfinding Strategy Scale (Lawton, 1996). The orientation strategy is similar to the survey strategy, the indoor route strategy is similar to the outdoor route strategy, and the building configuration strategy refers to symmetry in the building and corridor angles. In our experiment, the AR spatial task was performed inside a building; therefore, we investigated the self-reported strategies preferred by participants indoors (orientation, route, and building configuration) using the Indoor Wayfinding Strategy Scale (Lawton, 1996) instead of the outdoor orientation strategies (landmark, route, or survey strategies). However, it should be noted that there is a tendency to use similar wayfinding strategies indoors and outdoors (Lawton, 1996). Thus, a person who prefers a survey strategy outdoors will prefer an orientation strategy indoors.

Another variable that may influence spatial orientation is gender. Gender differences in spatial orientation have been described by several authors (Piccardi et al., 2011b; Coluccia & Louse, 2004; Iachini et al., 2005; León et al., 2016) and could depend on various factors, such as the difficulty of the task, emotional factors, or the spatial strategy used. Accordingly, it has been argued that men and women seem to use different strategies to orient themselves in space. Men are prone to use survey orientation more than women, which is usually more efficient than landmark or route strategies (Lawton, 1994, 1996), whereas women are reported to use route strategies (Lawton, 1996; Lawton & Kallai, 2002). Despite the fact that some studies show that men outperform women in spatial orientation, the results are conflicting and there was also an absence of sexual dimorphism in spatial orientation in other studies (see (Coluccia & Louse, 2004) for review).

One likely reason for the discrepancies between studies is that other variables, such as personality, may influence performance on spatial tasks (Coluccia & Louse, 2004). For example, high scores in psychoticism and neuroticism are associated with a poorer spatial performance (Burles et al., 2014; Walkowiak et al., 2015). Anxiety has also been observed to predict weaker performance on some spatial reasoning tasks (Lawton, 1996; Schmitz, 1997). Mueller et al. (2009) found that children with anxiety disorder exhibit overall impaired performance in a virtual version of the Morris Water Maze when compared to a control group.

The role of wayfinding anxiety in spatial orientation has received more attention. Wayfinding anxiety refers to anxiety about performing spatial tasks (Lawton, 1994) and is also related to the fear of getting lost (Schug, 2015). Wayfinding anxiety has been associated with poorer performance, lower self-efficacy, and less pleasure in exploring in spatial tasks (Lawton, 1994; Coluccia & Louse, 2004; Pazzaglia et al., 2018). Interestingly, even though women have been described as being more anxious than men when wayfinding (Lawton, 1996, 1994; Schmitz, 1997; Schug, 2015) and having less self-confidence to solve spatial tasks (Picucci et al., 2011; Nori & Piccardi, 2015), they perform comparably and achieve similar results as men in spatial tasks such as mental rotation tasks (Neuburger et al., 2012), wayfinding tasks (Lawton, 1996), and spatial environmental tasks (Nori & Piccardi, 2015).

Exploring the possible influence of individual differences in spatial orientation can be assessed using several spatial tests such as self-report questionnaires, paper-and-pencil psychometric tests, bi-dimensional maps, or by means of environmental tasks. In the self-report questionnaires, people assess their own orientation skills and strategies (Lawton, 1996; Claessen et al., 2016). Paper-and-pencil tests assess spatial perception, spatial visualization, and mental rotation (Mitolo et al., 2015). In bi-dimensional maps, all the spatial information is available from a single point of view. In tasks using bi-dimensional maps, the participants do not move around in the environment, but instead make a mental representation of it (Castelli et al., 2008). On another hand, in environmental tasks, an individual's performance can be evaluated in real (Labate et al., 2014) or virtual reality (VR) environments (Walkowiak et al., 2015; Rodríguez-Andrés et al., 2016; Cárdenas-Delgado et al., 2017; León et al., 2016).

VR environments meet the needs of several research domains that are related to spatial cognition and navigation (Bohil et al., 2011; León et al., 2016). VR has been seen to be a valid and feasible tool for investigating spatial memory, with advantages in terms of methodological issues (Rodríguez-Andrés et al., 2016). VR allows participants to be exposed to complex and natural-appearing environments. In contrast to real-world navigation experiments, which are difficult to control and execute, VR facilitates the control of delivered stimuli, the manipulation of variables, and the recording of measurements.

Interestingly, VR has also been used to investigate the effect of emotional variables in the spatial orientation both of adults and children (Burles et al., 2014; Walkowiak et al., 2015; Rodriguez-Andres et al., 2018; Zlomuzica et al., 2016; Pazzaglia et al., 2018). Specifically, it has been shown that the induction of an anxious emotional state decreased spatial context retrieval in healthy participants (Zlomuzica et al., 2016). A poorer spatial performance in VR spatial tasks has been described in healthy participants with higher scores in neuroticism (Burles et al., 2014) and psychoticism (Walkowiak et al., 2015). In children, withdrawal behaviors have been related to an increase in exploratory behavior in a VR spatial orientation task (Rodriguez-Andres et al., 2018). Despite the fact that VR has been used to investigate spatial orientation in several studies, a remaining restriction of this technology is cybersickness. This side effect sometimes leads to nausea, vertigo, and vomiting, limiting the widespread adoption of VR for therapeutic or training applications requiring repeated use over time.

Augmented reality (AR) is a technology that allows the experimenter to superimpose objects upon the real world in order to supplement reality. AR can be used in any real environment so that the experimental conditions during the tasks and the way in which participants navigate are similar to those in real life. Like VR, AR allows the control of the variables of the task and the storage of the participant's responses (Juan et al., 2014) but without the limitation of inducing cybersickness. Despite the fact that AR has great potential to assess cognitive processes, to our knowledge, only two studies (Juan et al., 2014; Mendez-Lopez et al., 2016) have used AR to evaluate spatial ability while a person is moving, showing promising results.

The above-mentioned studies point out the existence of multiple spatial tests to assess how individual differences might influence spatial orientation. However, it should been taken into consideration that the spatial information available in each test and the way in which the task can be solved is different in self-report questionnaires, paper-and-pencil psychometric tests, bi-dimensional maps, or environmental tasks. Accordingly, in bi-dimensional maps, all the spatial information is available from a single point of view, whereas in real or virtual environments, participants move around in the environment. In fact, in real or virtual indoor environments, participants can orientate themselves using orientation, route or building configuration strategies, whereas a survey strategy is needed to solve a bi-dimensional map task. On another hand, basic spatial abilities such as spatial perception or mental rotation are assessed by psychometric tests. Therefore, more studies are needed in order to further investigate the relationship between psychometric tests, bi-dimensional map tasks, and large-scale spatial tasks.

However, discrepant results about the influence of gender in spatial orientation have also been described. Moreover, the relationship of anxiety and spatial skills of individuals and their performance on a spatial orientation task in a complex real-world setting using an app based on AR technology has not yet been investigated.

Accordingly, the research questions are: (1) Does gender has any effect on spatial performance (i.e., the AR task for object location, the bi-dimensional map-pointing task, the spatial orientation test, and self-reported spatial strategy of preference) and on anxiety (i.e., wayfinding anxiety and trait anxiety)? (2) Is there any significant relationship among participants' performance, regardless of gender, on the environmental AR task, the map-pointing task, the paper-and-pencil spatial orientation test, the preferred spatial strategy, and anxiety? (3) Could gender influence any possible significant associations that may be found between participants' spatial performance and anxiety outcomes?

3.3 Materials and Methods

3.3.1 Participants

The participants included 46 adults (78.3% undergraduates and 21.7% graduates). The gender distribution was 43.5% men and 56.5% women. The men's mean age was 24.65 ± 8.54 years. In the case of women, the mean age was 23.73 ± 7.71 years. They were recruited at the University of Zaragoza, Teruel Campus, through campus advertising. In the advertisement, potential participants were encouraged to learn more about their spatial ability. Each participant received a report describing his/her results on the tests of the study as a reward. The final sample was selected after applying the inclusion criteria to a larger sample composed of 105 adults. The participants were right-handed, did not have any motor or sensory impairment, had not suffered a brain injury, were not treated with a medication that could potentially impair their cognitive functioning, and all participants frequented the building where the study took place weekly at least three days a week. Table 3.1 summarizes the main characteristics of the final sample. We determined the town where the participants grew up and their wayfinding experience at ages 3-15 years using the scale reported by (Schug, 2015). The scale asked the participants how far from home in km they were allowed to go without an adult (by themselves or with friends) at the following ages: 3-4 years old, 5-7 years old, 8-10 years old, 11-13 years old, and 13-15 years old. We also determined the participants' experience playing with smartphones or AR apps (Table 3.1). The participants gave written informed consent prior to the study. The Ethics Committee of the Universitat Politècnica de València, Spain, approved the study. The study was conducted in accordance with the declaration of Helsinki.

Measure	Men (n = 20)	Women (n = 26)
Age (years) M (SD)	**24.65 (8.54)**	**23.73 (7.71)**
Student Status		
Undergraduate	80%	76.9%
Graduate	20%	23.1%
Childhood wayfinding experience		
Town (%urban/%rural)	90% / 10%	92.3% / 7.7%
Score M (SD)	15.65 (4.27)	15.85 (3.96)
Experience (%)		
Using mobiles for playing		
Never	25%	23.1%
Once a month	20%	19.2%
Once a week	25%	23.1%
Almost daily	15%	15.4%
Every day	15% (<1h)	19.2% (<1h)
Playing AR apps	65% (hardly ever)	80% (hardly ever)

The town where the participants grew up was coded as urban if population ≥ 2,500 and rural if population < 2,500. The participants who played using smartphones every day were given the following answer options: " < 1 h a day", "2-3 h a day" and " > 4 h a day". They played less than 1 h in all the cases. The question to determine the participants' experience playing AR apps consisted of three answer options: "never", "sometimes" and "often". No participant responded "often". All participants frequented the building in which the study took place, at least, three days a week (item scored on a 1-5 Likert scale; from "1. At least one day a week" to "5. At least five days a week").

Table 3.1: Characteristics of the sample.

3.3.2 The AR Task

The task consists of a short-term memory test for object location, which is performed using an AR app that is played on a smartphone (Lenovo Phab 2 Pro) (Munoz-Montoya et al., 2019b). The app allows the participants to tour a real room/building. The participant must look for virtual objects which are located in the real building and remember their locations in order to place them in their correct real-world locations later.

For this purpose, the examiner first configures the environment for the task in two phases: 1) Environment scanning. The scanning of the environment only has to be done once. In this phase, the examiner scans the real environment where the study will be carried out. 2) Object configuration. The examiner places the different 3D objects in the real scanned environment.

For the participants, there are two phases: the learning phase and the testing phase. In the learning phase, the participants are asked to inspect the scanned environment, looking for virtual objects, and to remember their locations. There are eight objects. In the testing phase, the examiner asks the participants to place the objects in the correct location using the app. For this purpose, a list of objects that the participants have to find is shown on the right side of the screen (Figure 3.1A). The participants have to select these objects one by one to place them in the environment. Once the participants have selected an object, they have to place it in the real environment. In order to achieve this, the device has to be moved to the desired location and focused with the camera on the precise place. The virtual object is shown in the center of the screen and is adapted to the flat surface of the environment (Figure 3.1B). Once the object is displayed on the desired surface, the participant presses the "place" button. If this position is correct, the user is informed about the success, the object is anchored in that place and disappears from the list of available objects. The user can then continue positioning the rest of the objects. In contrast, if it is a failure, the participant is informed about the remaining available attempts. This object still appears on the list of available objects as long as the total number of attempts has not been achieved. More details about the task can be found in (Munoz-Montoya et al., 2019b).

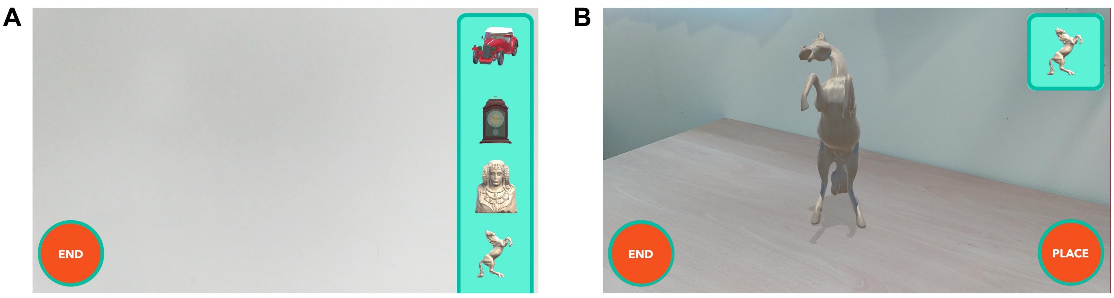

Figure 3.1: Testing phase. (A) Object selection. The sidebar on the right side shows the images of the objects to be placed in the real environment. (B) Object positioning. The sculpture is placed on the correct table.

An examiner accompanied the participant during the task. Before starting to use the app, the examiner told the participant about the goal of the task. The examiner showed the participant how to hold the device, how to move around in the virtual environment and how the app worked.

3.3.3 The Phases

The AR task comprised two phases: the learning phase and the testing phase. In the learning phase, the participants were asked to inspect two floors of a familiar building of the campus, looking for virtual objects, and to remember their locations, without time limitations. Time limit was not established in order to avoid time-pressure, which could be an additional source of stress. There were eight objects. Their distribution in the building was the same for all participants. In section "The Environment," we describe the route for the inspection, the objects, and their location. The participants did not receive any help regarding where the objects were, the objects that they had seen, or those that they were required to see. The examiner accompanied each participant during this phase indicating the route to follow for the inspection. All of the participants did the same tour and, consequently, looked for the objects in the same order.

Once a participant had inspected the last object, the learning phase ended. Then, the experimenter accompanied the participant to the beginning of the route and the testing phase started. The time between phases was 3 minutes because this was the time needed to go from the place where the learning phase finished to the place where the testing phase began.

In the testing phase, the examiner asked the participants to place the objects in the correct location using the app, without time limitations. The participants were told beforehand that they were allowed three attempts to locate each object. The examiner showed the participants how this phase worked. The participants were informed that their success in this phase was determined by the correct location of the objects, regardless of the route followed for this purpose and the order in which they located the objects. The participants were also informed that, at any time, they could select a different object for placing.

In our study, we considered four variables related to performance on the AR task: the time spent on the learning phase (in seconds), the time spent on the testing phase (in seconds); the number of objects that were located correctly during the testing phase (LocObj); and the number of errors committed during the testing phase (ErrObj).

3.3.4 The Instrumentation

The AR app was played using a Tango smartphone, Lenovo Phab 2 Pro (size: 6.4 inches; weight: 259 grams). The participants held the smartphone using an external case to make handling easy. The orientation of the screen was landscape.

3.3.5 The Environment

The task was carried out in the communal areas of the first and second floor of the School of Social and Human Sciences of the University of Zaragoza. The areas to be explored during the task consisted of 282 square meters on the first floor and 331 square meters on the second floor. Figure 3.2 shows the shape of the environment on the second floor and the location of the virtual objects. Figure 3.3 shows the same aspects corresponding to the first floor. There were five objects on the second floor and three objects on the first floor. The objects were decorative items (i.e., bust, horse, toy car, sailing ship, and wall clock) or everyday objects (i.e., telephone, fountain pen, and screwdriver). The location of the objects was decided based on the length and shape of the areas for exploration and their visual cues. The objects were placed on a wall (i.e., wall clock and telephone), the floor (i.e., bust, toy car, sailing ship, fountain pen, and screwdriver) and a bookcase (i.e., horse). Their location was proximal to existing cues (i.e., bookcase, doors, stairs, plants, recycling point, fire hose, fire extinguisher, and board). In addition, the fact that there were physical cues in the real environment guaranteed an optimal recognition of the environment. The app locates the mobile device through the recognition of distinctive visual points. An environment composed of uniform places or identical rooms without distinguishing elements would increase the difficulty in its correct recognition. Thanks to these cues, the app correctly recognizes the environment and facilitates the precise placement of the augmented objects.

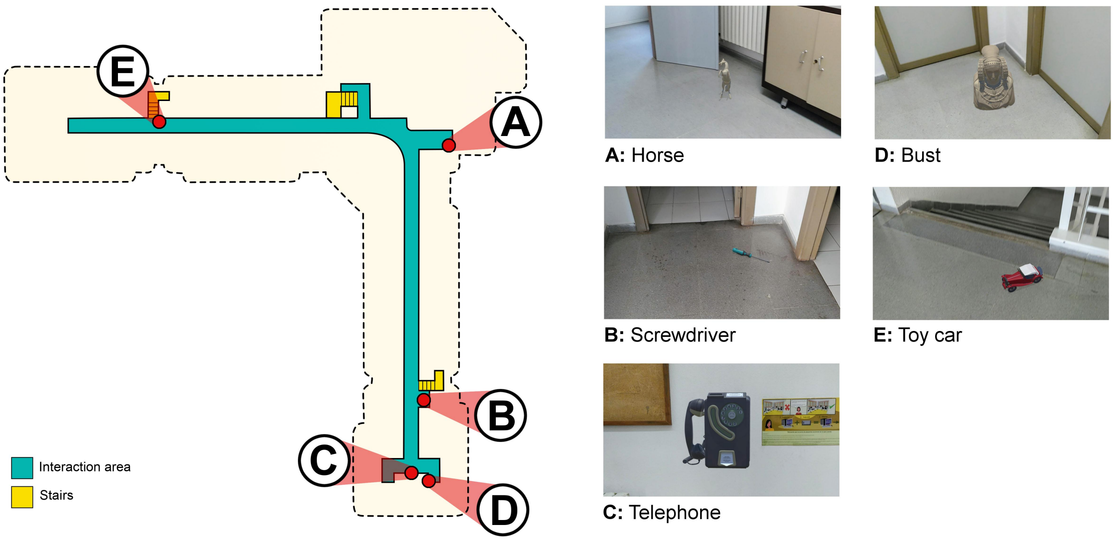

Figure 3.2: A schematic top view of the interaction area and the location of the five virtual objects on the second floor. The dashed black line shows the shape of the building. The objects are designated by letters in order of appearance during the learning phase: (A) horse; (B) screwdriver; (C) telephone; (D) bust; (E) toy car. On the right side of the figure is an image of where the objects were located during the phase.

Together with proximal cues, distal cues were also available: the main entrance of the building, the windows, the natural sunlight, and the Vicerrectorate building. The School of Social and Human Sciences is an L-shaped building, the main entrance is at the angle and faces southwest. From the main entrance, one part of the building (A) is in the north and the other in the east (B) (see Figure 3.4). The entrance is an open area without walls, so it can be observed both from the first and the second floor. The Vicerrectorate building is located in the southwest and can be also observed both from the first and the second floor of the School of Social and Human Sciences, due to the fact that all the windows are located in the southern (part A) and the western face of the building (part B). Therefore, natural light enters the building only through one face of the building. All stairs are placed in the north-eastern face of the building, where there are no windows.

Figure 3.5 shows the route followed by the participants in the learning phase during the tour directed by the examiner. The tour involved exploring hallways and corridors where there were no objects. No objects were placed on the stairs for safety reasons. The

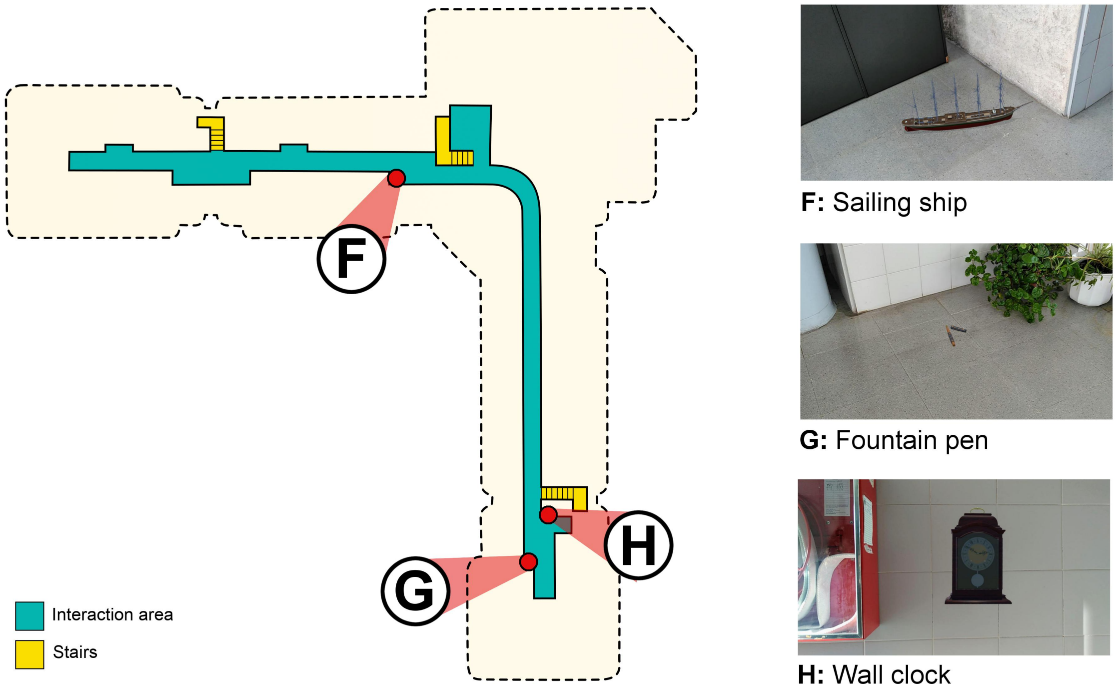

Figure 3.3: A schematic top view of the interaction area and the location of the three virtual objects on the first floor. The objects are designated by letters in order of appearance during the learning phase: (F) sailing ship; (G) fountain pen; (H) wall clock. The dashed black line shows the shape of the building. On the right side of the figure is an image of the objects as they appeared on the phase.

examiner warned each participant to look at the floor when going down the stairs.

3.3.6 The Object-Recall Task

The object-recall task consisted of a free recall of the objects inspected in the AR task. The participants answered verbally, and the examiner wrote down their answers without giving any feedback. The examiner asked each participant "What objects have you inspected with the AR app? Please, list all you remember". There was no time limit for the participant's response, but we established an internal time limit of three minutes to avoid unnecessary response delay. We considered two variables related to performance on the object-recall task: the percentage of errors committed (%ErrRecall), and the percentage of omissions made (%OmitRecall).

3.3.7 The Map-Pointing Task

In this task, the participants viewed two empty maps, which corresponded to the first and the second floors of the building. Each map was a two-dimensional simplified map in which hallways, stairs, corridors, and rooms were illustrated. The floor of each map

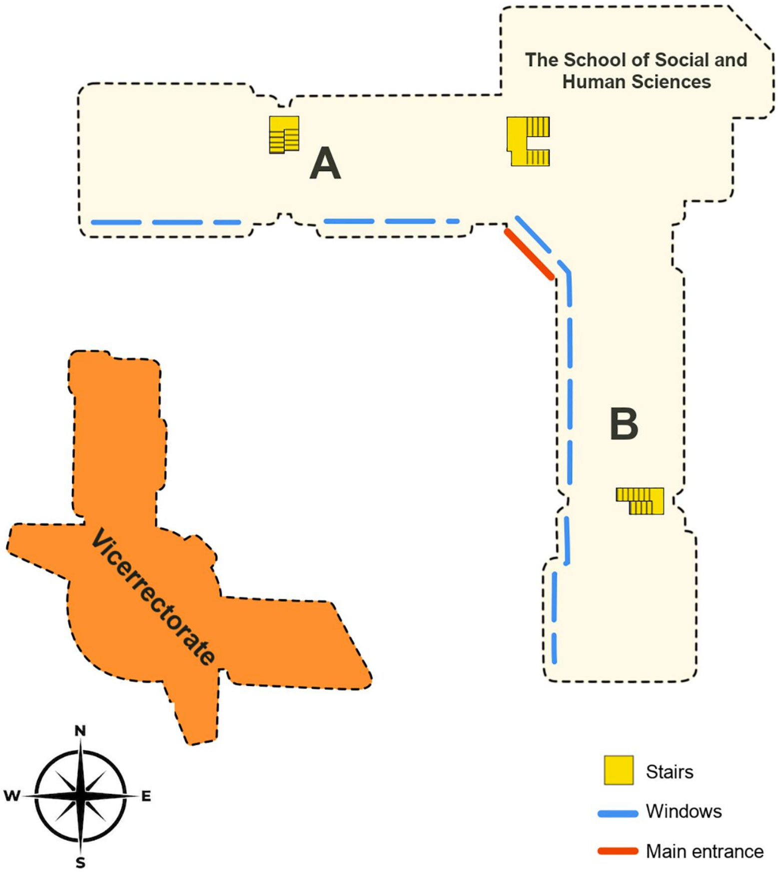

Figure 3.4: A schematic top view of the cardinal orientation of the School of Social and Human Sciences and surrounding buildings. The School consists of an L-shape building. From the main entrance (in the angle), part (A) is in the north of the building and part (B) is in the east of the building. Dotted blue lines represent the position of the windows in the building.

was indicated in print and orally. No other visual cues were shown. The participants also viewed a composite of the eight objects of the AR task labeled with letters. The maps and the composite with the objects were printed on a sheet of DIN A-4 sized paper. Figure 3.6 shows these tools. The examiner asked each participant to point to each object in its correct location according to the AR task, writing its letter on the correct map. There was no time limit to accomplish the task. The performance scores on the map-pointing task were the time spent to complete the task in seconds (ObjPoint) and the percentage of objects correctly located (%ObjPoint). We considered that an object was located correctly on the map when it was pointed to within a 3 mm radius of its precise location. Pointing accuracy is of interest to us because it seems to be related to orientation strategies and spatial anxiety (Bryant, 1982; Lawton, 1996).

3.3.8 The Spatial Orientation Test

The participants completed a paper-and-pencil spatial orientation test. They performed the Perspective Taking/Spatial Orientation Test (PTSOT; the revised version of (Hegarty, 2004) from the test used by (Kozhevnikov & Hegarty, 2001), following the procedures indicated by the authors. This test consists of 12 items that assess the participant's ability to orientate spatially and to image different perspectives. Five minutes were given to perform this test. We considered two variables related to performance on the PTSOT: the total score (PTSOTsc) and the percentage of unattempted items (%uPTSOT).

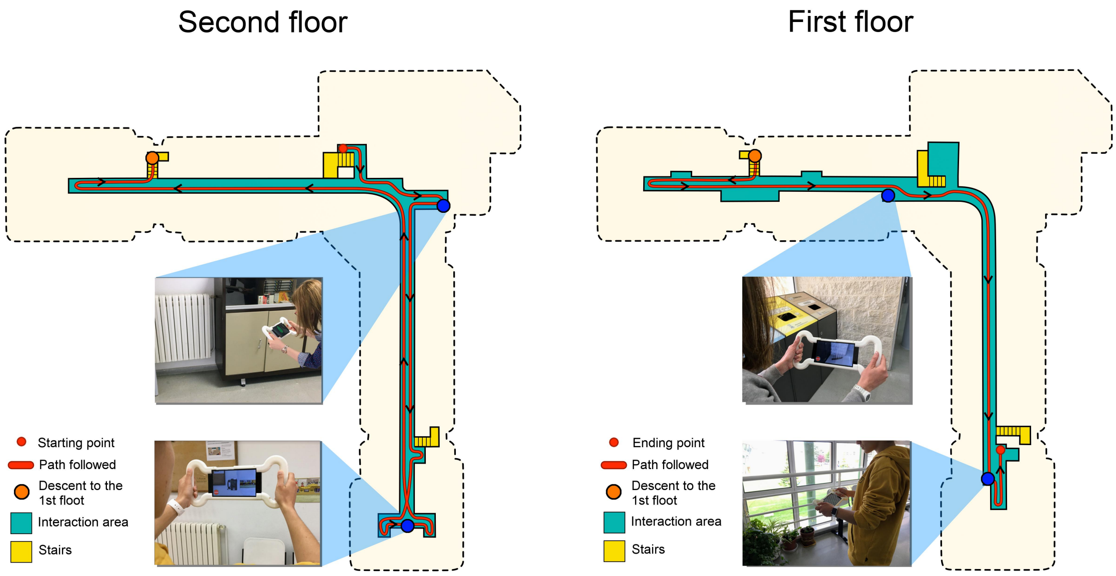

Figure 3.5: The route made by the participants in the learning phase and location of the objects.

Figure 3.6: The tools used in the map-pointing task.

3.3.9 Self-Reported Strategies

The participants completed a self-report questionnaire about their strategies for wayfinding in unfamiliar buildings (the translated version of the Indoor Wayfinding Strategy Scale used by (Lawton, 1996)). This questionnaire is composed of 13 items. The items were statements about certain behaviors that could emerge or certain information that could be used for spatial orientation in a building or a large complex. The participants rated the probability/importance of the statements on a five-point Likert scale. With the questionnaire, we measured the degree of importance of three different strategies during wayfinding: the building configuration strategy (BuilConf), the route strategy, and the orientation strategy. The BuilConf strategy consisted of the importance attached to a uniform layout of the building or complex. The route strategy is based on information about the route to be followed (i.e., visual cues or directions from another person). The orientation strategy is based on directional cues.

3.3.10 Anxiety Scales

The level of trait anxiety was measured using the 20 items of the State-Trait Anxiety Inventory validated in Spain (STAI; Guillén-Riquelme & Buela-Casal, 2011, from the original version of Spielberger et al., 1970). The STAI items were scored on a four-point Likert scale. The raw scores of trait anxiety were used (TraitAnx). The eight items of the Wayfinding Questionnaire (Claessen et al., 2016) were also used. This questionnaire measures self-reported spatial anxiety when navigating in unfamiliar places. The items are scored on a 1-7 Likert scale. We used the raw scores of the wayfinding anxiety factor of the questionnaire (WayAnx).

3.3.11 Procedure

First, the participants filled out a questionnaire on their own on the Internet between 5 and 15 days prior to performing the spatial tests. The questionnaire was created using Google Forms. The link to the questionnaire was distributed through their personal e-mail with a personal code to maintain anonymity. The questionnaire included items related to the participants' general characteristics (i.e., age, educational level, familiarity with the environment, childhood wayfinding experience (Schug, 2015), and experience playing with smartphones or AR apps; see Table 3.1 for more information) and the selected items of the self-report questionnaires in the following order: wayfinding anxiety of the Wayfinding Questionnaire (Claessen et al., 2016), Childhood Wayfinding Experience Scale (Schug, 2015), Indoor Wayfinding Strategy Scale (Lawton, 1996) and trait anxiety of the STAI (Guillén-Riquelme & Buela-Casal, 2011). Afterwards, we invited the participants to complete the spatial tests individually using the following established sequence: AR task (25–30 min.), PTSOT (5 min.), object-recall task (1–2 min.), and map-pointing task (5–7 min.). No time limit was established for any of the tasks except for the PTSOT. We conducted the testing in the School of Social and Human Sciences of the University of Zaragoza. The testing took place from Monday to Friday between 9:00 A.M. and 19:00 P.M.

3.3.12 Data Analysis

The Kolmogorov-Smirnov test was used to check the normal distribution of the dataset variables. Only the Route strategy variable and the ErrObj variable of the AR task followed a normal distribution. Nonparametric tests, which are more suitable for distributions of this type, were used with the entire data-set.

For the research question (1), Mann-Whitney U-tests were applied to investigate gender differences in the variables related to the spatial tasks: the AR task (LocObj, ErrObj, Learn (s.) and Test (s.)); the Object-recall task (%ErrRecall, %OmitRecall); the Map-pointing task (%ObjPoint and ObjPoint(s.)); and the PTSOT (PTSOTsc, %uPTSOT). The same statistical analysis was used to study gender differences in self-reported wayfinding strategies (BuilConf, Route and Orientation) and in anxiety outcomes (trait anxiety (TraitAnx) and wayfinding anxiety (WayAnx)). For the research question (2), partial Spearman correlations, extracting the influence of gender, were calculated.

For the research question (3), in order to study the relationship between wayfinding anxiety and variables related to the spatial navigation performance (i.e., AR task and self reported wayfinding strategies) as mediated by Gender, Spearman's correlations were calculated separately for each gender, considering these variables, and the significant correlation coefficients were compared using Fisher's Z-test (Hidalgo et al., 2014). All of the analyses were conducted using IBMSPSS Statistics, version 19.0. The results were considered to be statistically significant if $p < 0.05$.

3.4 Results

Table 3.1 shows descriptive statistics for the four variables related to the general characteristics of the sample: age, student status, childhood wayfinding experience, and percentage of experience using smartphones or AR apps to play. In the case of childhood experience, we present the descriptive statistics for the percentage of men and women who grew up in an urban or a rural environment. The mean of the total score for each gender is also shown. The mean of this score was the sum of the distance in km reported in each age range on the scale (min.-max. = 5-30). The scores of the males and females revealed that the wayfinding experience was similar between genders (Table 3.1).

Table 3.2 shows the results of the statistical analysis. The Mann-Whitney U-test revealed statistical differences between men and women for the time spent on the learning phase of the AR task ($U = 171$, $Z = -2.0$, $p = 0.049$, $r = -0.29$) and for the PTSOT score ($U = 156$, $Z = -2.3$, $p = 0.021$, $r = -0.34$). The men required more time in the learning phase of the AR task. Also, the men showed better performance on the PTSOT. A lower score on the PTSOT reflects a good performance on the test. The rest of the studied variables did not reveal significant differences.

Table 3.3 shows the correlation among the variables studied. Significant correlations were found between variables of the performance in the AR spatial task. Specifically, the number of objects located correctly in the AR task correlated negatively with the number of errors committed ($r = -0.97$, $p < 0.001$). The time spent to complete the

Measure	Men	Women	U-Test	Sig.
	M (SD)	M (SD)	U,(Z)	P (r, if applicable)
AR task				
LocObj	5.65 (1.31)	5.77 (1.81)	232, (0.6)	0.532
ErrObj	7.85 (4.32)	7.88 (5.49)	248, (-0.2)	0.798
Learn (s.)	590.67 (90.88)	528.70 (128.83)	171, (-2.0)	0.049, r = -0.29
Test (s.)	559.11 (214.87)	565.73 (181.57)	249, (-0.2)	0.807
Object recall task				
%ErrRecall	0.62 (2.79)	0.96 (3.40)	253, -0.4	0.717
%OmitRecall	5.00 (9.42)	2.40 (5.02)	237, -0.7	0.488
Map reading task				
ObjPoint(s.)	143.50 (48.28)	179.62 (90.61)	206, -1.2	0.231
%ObjPoint	63.12 (31.01)	59.13 (25.39)	221, -0.9	0.381
Spatial orientation				
PTSOTsc	31.24 (26.37)	52.65 (39.38)	156, -2.3	0.021, r = -0.34
%uPTSOT	24.17 (25.92)	23.72 (21.30)	256, -0.1	0.928
Self-reported strategies				
BuilConf	7.35 (2.54)	7.88 (2.55)	241, -0.4	0.670
Route	15.55 (2.84)	16.12 (2.30)	225, -0.8	0.441
Orientation	16.70 (4.86)	14.62 (2.71)	188, -1.6	0.111
Anxiety outcomes				
TraitAnx	24.75 (11.33)	26.19 (9.81)	237, -0.5	0.618
WayAnx	25.90 (9.92)	30.50 (10.24)	200, -1.3	0.187

The performance scores on the AR task: LocObj = number of objects located; ErrObj = number of errors made; Learn (s.) = time spent on the learning phase; Test (s) = time spent on the testing phase. The performance scores on the objects-recall task: %ErrRecall = percentage of errors; %OmitRecall = percentage of objects omitted. The performance scores on the map-pointing task: ObjPoint(s.) = time spent indicating the objects; %ObjPoinf = percentage of objects successfully indicated. PTSOTsc = score; %uPTSOT = percentage of unattempted items. BuilConf = building configuration strategy. TraitAnx = trait anxiety. WayAnx = wayfinding anxiety.

Table 3.2: Mean scores (standard deviations) and Mann-Whitney's U tests for the variables used in the study (N = 46).

learning phase correlated positively with the number of objects located correctly in the task (r = 0.33, p = 0.024) and negatively with the number of errors committed (r = -0.33, p = 0.025). We also found that participants who committed more errors took more time to complete the testing phase of the AR task (r = 0.33, p = 0.028).

	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
(1) LocObj	-0.97**	0.33*	-0.29	-0.01	-0.46**	-0.13	0.61**	0.001	0.12	0.22	0.07	0.07	0.06	-0.02
(2) ErrObj		-0.33*	0.33*	0.02	0.48**	0.13	-0.65**	-0.02	-0.12	-0.23	-0.06	-0.10	0.05	0.06
(3) Learn(s.)			0.05	-0.002	-0.09	-0.12	0.25	-0.12	0.05	0.07	0.05	0.19	0.39**	0.05
(4) Test(s.)				0.08	0.03	0.27	-0.27	0.03	0.10	-0.33*	0.07	0.22	0.05	-0.04
(5) %ErrRecall					0.03	0.11	-0.14	0.002	-0.05	0.03	0.03	0.24	-0.02	-0.21
(6) %OmitRecall						0.09	-0.40*	-0.07	-0.13	0.09	0.06	-0.36*	0.14	0.19
(7) ObjPoint(s.)							-0.27	-0.01	0.31*	0.04	-0.15	-0.07	-0.18	-0.03
(8) %ObjPoint								0.07	0.05	0.33*	0.16	0.11	0.01	0.06
(9) PTSOTsc									0.15	-0.17	0.19	0.08	-0.18	-0.12
(10) %uPTSOT										-0.002	0.38*	0.000	-0.12	-0.06
(11) BuilConf											0.12	-0.09	0.09	0.07
(12) Route												0.03	-0.08	0.01
(13) Orientation													-009	-0.32*
(14) TraitAnx														0.33*
(15) WayAnx														1.00

*The performance scores on the AR task: LocObj = number of objects located; ErrObj = number of errors made; Learn (s.) = time spent on the learning phase; Test (s.) = time spent on the testing phase. The performance scores on the objects-recall task: %ErrRecall = percentage of errors; %OmitRecall = percentage of objects omitted. The performance scores on the map-pointing task: ObjPoint(s.) = time spent indicating the objects; %ObjPoint = percentage of objects successfully indicated. PTSOTsc = score; %uPTSOT = percentage of unattempted items. BuildConf = building configuration strategy. TraitAnx = trait anxiety. WayAnx = Wayfinding anxiety. *p < 0.05; **p = 0.001. Size of effect: r = 0.3-0.5 medium; r > 0.5 = large (Cohen, 1988).*

Table 3.3: Partial Spearman correlations (N = 46).

Regarding the correlations between wayfinding anxiety and variables related to the spatial performance as mediated by Gender, there was a significant negative correlation between wayfinding anxiety and the orientation strategy in men (r = -0.45; p = 0.047), but this correlation was not significant in women (r = -0.13; p = 0.54). Significance testing using Fisher's Z-test revealed no significant differences between men and women in this association (z = 1.11, p = 0.28).

On another hand, Spearman's partial correlations controlling for gender differences revealed an association between the AR task and the object-recall task. The percentage of objects omitted in the recall task correlated negatively with the number of objects located correctly in the AR task ($r = -0.46$, $p = 0.001$) and positively with the number of errors committed in the AR task ($r = 0.48$, $p = 0.001$). Interestingly, the more objects correctly located in the AR task, the more the objects correctly pointed to in the map task ($r = 0.61$, $p < 0.001$). As expected, a negative correlation was found between the number of errors in the AR task and the percentage of objects that were pointed to correctly in the map task ($r = -0.65$, $p < 0.001$). It was also observed that the more objects omitted in the recall task, the fewer the objects correctly pointed to in the map task ($r = -0.40$, $p = 0.006$). In addition, a positive correlation was found between the percentage of unattempted items in the spatial orientation paper-and-pencil PTSOT test and the time spent to complete the map-pointing task ($r = 0.31$, $p = 0.041$).

In relation to the self-report indoor wayfinding strategies, the level of importance of the building configuration for wayfinding correlated positively with the percentage of objects pointed to correctly on the map ($r = 0.33$, $p = 0.025$) and negatively with the time spent to complete the testing phase of the AR task ($r = -0.33$, $p = 0.028$). On another hand, a positive correlation was found between the level of importance of the route strategy and the unattempted items on the PTSOT ($r = 0.38$, $p = 0.011$). Interestingly, the more importance attached to the orientation strategy, the fewer the objects omitted during the recall task ($r = -0.36$, $p = 0.016$).

Finally, with regard to the anxiety outcomes, a positive correlation was found between trait anxiety and wayfinding anxiety ($r = 0.33$, $p = 0.028$). Also, the higher the participant's level of trait anxiety, the more the time he/she spent on the learning phase of the AR task ($r = 0.39$, $p = 0.007$). In addition, the greater the preference for directional cues for orientation (i.e., orientation strategy), the lower the participant's level of wayfinding anxiety ($r = -0.32$, $p = 0.033$).

3.5 Discussion

We studied the influence of gender in cognitive (self-reported spatial strategies) and anxiety outcomes as well as in the performance of three spatial tasks (a real-world orientation task using AR, a map-pointing task, and a paper-and-pencil spatial orientation task), which required different spatial orientation strategies/spatial abilities to be solved (route and orientation spatial strategies and perspective-taking spatial ability, respectively). The possible relations between the studied factors were also analyzed.

To our knowledge, this is the first study that investigates the role of gender in the performance of an object-location task using AR in a real-world setting and the relationship between this performance and cognitive factors and anxiety. Our results show no differences between men and women, either in the performance of the AR task for object-location (i.e., objects located and errors made) or in the map-pointing task or the recall task. However, men outperformed women in the paper-and-pencil psychometric test of spatial orientation (i.e., PTSOT).

The AR task was performed in a two-floor building. Although virtual objects were placed in specific areas close to proximal cues to facilitate their correct location in the testing phase, the task was not easy for the participants. In fact, the mean of correctly located objects out of 8 objects was: 5.6 for men and 5.7 for women, and the number of errors was almost 8 (for men and women). Therefore, nobody was able to locate all the 8 objects correctly without making errors. The cues available in the environment and, specially, those proximal to the virtual objects, could promote the use of a spatial strategy in the participants based on route information. The ability to recall and locate the virtual objects was the same in men and women, but there were differences in the speed of exploration of the environment in the learning phase. Men spent more time than women.

One possible interpretation of the similar results between men and women in the ability to locate the virtual objects may be related to the spatial strategy used. This task might require the use of a route strategy. Several studies have shown that women are prone to use a route strategy, and men seem to prefer a survey strategy (Lawton, 1994, 1996; Lawton & Kallai, 2002). In this study, we did not specifically ask the participants about the strategy they had used in the AR task. However, while the participants were performing the AR task, we took notes of the comments that were related to the spatial strategy used. Most of these comments were related to the use of a route-based strategy, probably because distal cues are used more unconsciously and, therefore, they are more difficult to report verbally. However, it should also been taken into consideration that spatial strategies are cumulative and, therefore, survey representation is characterized by the properties of landmark, route, and survey representation together (Lugli et al., 2017). If both men and women used this type of route orientation, it is not surprising that both sexes performed similarly on the task. In fact, no gender difference emerged when only landmark cues were available in the task, so a survey strategy was not possible (Sandstrom et al., 1998; Saucier et al., 2002).

Additionally, it has been described that familiarity with the environment can influence participants' performance in a real environmental spatial learning task, improving skills (Nori & Piccardi, 2011; Nori et al., 2018). In fact, familiarity with the environment allows more successful navigation in people with a poorer navigation style (Piccardi et al., 2011a), and the effect is more evident when, as in our experiment, participants move around freely in a real environment. So, we cannot discard that the lack of gender differences observed in our experiment might be due to the fact that all the participants were familiarized with the building. This variable could have allowed the participants with a more deficient cognitive style (route) to perform the AR spatial task more accurately.

Another possible explanation is the difficulty of the task. It has been suggested that gender differences emerge when the task has an optimum level of difficulty. If the level was very low or the participants were allowed to repeat the task as many times as needed, or to take their time to perform it, both sexes performed similarly (Piccardi et al., 2011b; León et al., 2016). Our task is partially in line with these characteristics because the participants did not have a maximum time to perform the task. However, the difficulty of the task was not low. As stated above, no participant was able to locate all of the objects. We suggest that suppressing the time pressure can significantly contribute to eliminate gender differences.

Surprisingly, we observed that men spent more time learning the location of the objects. Although these results may seem to go against the previous literature (Piccardi et al., 2011b; Nori et al., 2018), we hypothesized that the fact that men took more time in the learning phase was not related to spatial orientation, but rather to their interest in the technology we used in this experiment. We observed that men were more enthusiastic about the AR app than women, paying more attention to how the AR app works and taking more time to observe the AR objects in detail, from a closer distance. In fact, differences were observed only in the learning phase, that is, when participants interacted with the AR app for the first time. No gender differences were observed in the testing phase. Our hypothesis might be supported by a recent study using a mobile AR game. In this article, researchers observed that men were more interested than women in a mobile AR game (Delello et al., 2018).

Our results show no significant gender differences in the map-pointing task, either in the percentage of correctly positioned objects or in the time needed to complete the task. In this task, participants had to point to the virtual objects they had previously seen in the AR task on a map. Only a few landmarks were present (i.e., the stairs; see Figure 3.6), so their success was dependent on the creation and use of a cognitive map. More specifically, the participants needed to transform the route representation of the environment (based on spatial cues) into an allocentric representation of the environment (Wolbers & Wiener, 2014). Thus, individuals who can restructure route information into allocentric information might perform this task better. Taking into consideration the results obtained in these two orientation tasks (the AR and map-pointing task), we hypothesize that the men and women who participated in our study did not differ in the spatial strategy used to orientate themselves in these tasks. The participants were volunteers who wanted to test their spatial abilities. Therefore, it is possible that those potential participants who were not self-confident about their spatial orientation did not want to participate in the study. Therefore, our results could be in line with other studies, in which gender differences in spatial orientation were not observed in participants with high spatial abilities and a lot of experience (Verde et al., 2013, 2015). Similarly, Boccia et al. (2017) demonstrated that women and men did not differ in their performance on spatial memory tasks, when they had the same field-dependent/independent cognitive style (referring to the way in which people organize environmental information), as they adopt similar strategies.

Another aspect that supports our hypothesis is the lack of differences between men and women in the self-reported spatial strategies. Despite the fact that most of the studies reported differences between men and women in the spatial strategy preferred (Lawton, 1994, 1996; Lawton & Kallai, 2002), Castelli et al. (2008) also observed that both sexes reported similar importance of the route and survey strategies for orientation. However, the self-reported questionnaires about orientation strategies measure the participants' own spatial perceptions. The self-reported gender differences in spatial orientation tend to parallel people's performance on spatial tasks (Montello & Pick, 1993).

Our data are not in line with previous investigations using self-reported questionnaires in which men and women differed in their strategy of preference Lawton (1994, 1996);

Lawton & Kallai (2002). However, the explanation of why women prefer to use a route strategy instead of a survey strategy was related to their lower wayfinding experience in childhood compared to men (Lawton & Kallai, 2002; Schug, 2015).The fact that women had less freedom to explore the environment during childhood has stunted the development of their spatial skills, leading to higher anxiety during spatial orientation tasks (Lawton & Kallai, 2002; Schug, 2015). However, similarly to the results of Castelli et al. (2008), we did not find gender differences in the degree of importance of the three different wayfinding strategies assessed. In addition, the men and women of our study had the same wayfinding experience during childhood. This could explain their similar level of wayfinding anxiety and their similar levels of preference for spatial strategies.

Whether there is a relation between spatial orientation ability (assessed by large-scale spatial tasks such as the AR task) and the spatial ability assessed by paper-and-pencil psychometric tests (small-scale tasks) is still under debate. Despite the fact that the literature provides considerable evidence that processing spatial information in small-scale spatial tasks (i.e., mental rotation, perspective taking) and in large-scale spatial tasks involves different brain mechanisms and regions (Philbeck et al., 2000; Kosslyn & Thompson, 2003), some studies have argued that perspective-taking ability is related to the performance on large-scale navigation tasks (Kozhevnikov et al., 2006; Pazzaglia & Taylor, 2007). In addition, gender differences have been extensively found in paper-and-pencil tests, such as mental rotation tests (Linn & Petersen, 1985; Voyer et al., 2006; Jansen & Heil, 2009). In our study, gender differences emerged in the performance of the PTSOT, a psychometric test for assessing gender differences in perspective-taking and in the ability to make egocentric spatial transformations (Kozhevnikov & Hegarty, 2001; Hegarty, 2004). Our results support previous studies in which women had a poorer performance on the PTSOT than men (Meneghetti et al., 2012; Zancada-Menendez et al., 2015). As in the case of our work, these studies considered the degrees of error for establishing comparisons between sexes. Other studies that considered the number of correct answers found no gender differences (Hegarty et al., 2006; Iwanowska & Voyer, 2013; Zancada-Menendez et al., 2015).

The relation among the studied variables was also investigated. As expected, the number of objects that were correctly located in the AR task correlated positively with the percentage of correct objects pointed to in the map task. This could indicate that the route representation of the environment (based on spatial cues) needs to be transformed into an allocentric representation of the environment (Wolbers and Wiener, 2014). In fact, these two measures of performance correlated negatively with the percentage of objects omitted during the recall. The more objects located correctly, the fewer the objects omitted in the recall.

On another hand, in our study, we observed a lack of correlations among the PTSOT, the AR, and map-pointing tasks. Our results are in accordance with previous studies in which the performance on spatial large-scale environmental tasks did not correlate with the performance on spatial psychometric tests (Mitolo et al., 2015). In addition, information processing and the brain regions involved were different between small-scale and large-scale spatial tasks (Philbeck et al., 2000; Kosslyn & Thompson, 2003).

The correlation analysis showed a relation between anxiety and spatial orientation. As expected, high levels of trait anxiety were related to high levels of fear of getting lost. Another study found a similar result (Lawton & Kallai, 2002). People who are more anxious in general situations may also experience more anxiety when they have to perform spatial tasks or they may even be more afraid of getting lost.

It is noteworthy that trait anxiety and the time spent by the participants to complete the learning phase of the AR task correlated positively. Trait anxiety influences cognitive domains such as attention and concentration (Bishop, 2008; Vytal et al., 2013)). Anxiety could impair these processes and negatively affect performance. However, in accordance with our data, highly anxious individuals could perform well by increasing their effort, that is, spending more time on the task (Eysenck & Calvo, 1992). Similarly, withdrawal behaviors in children were related to an increase in exploratory behaviors in a virtual spatial memory task, but without effects on spatial learning (Rodriguez-Andres et al., 2018).

Interestingly, we found a significantly negative correlation between wayfinding anxiety and the orientation strategy, regardless of gender. This result supports previous results that showed a low preference for the orientation strategy in individuals with higher levels of wayfinding anxiety (Lawton & Kallai, 2002).Taken together, these results are in line with previous research showing that emotional factors are relevant for the study of individual differences in spatial orientation (Lawton & Kallai, 2002; Walkowiak et al., 2015; Schug, 2015; Pazzaglia et al., 2018).

The present research has some limitations. First, it would have been desirable to increase the sample size. Second, the way in which participants were recruited could have had a deterrent effect on participants with low self-confidence in spatial orientation. However, as discussed above, the lack of gender differences in the AR and the map tasks could be due to familiarity with the building, or to the lack of differences observed between men and women in self-reported strategies, wayfinding anxiety, and wayfinding experience, all of which are related to performance on spatial tasks.

3.6 Conclusion

For the first time, we have used an AR app to test spatial memory for the location of virtual objects that were shown when the person navigated different floors of a building. We have also related this spatial memory performance to spatial factors and anxiety levels. For the first time, we can say that the AR app used in this experiment is a useful technology for assessing spatial orientation in complex, real-world environments. We found that gender did not affect the performance of either the complex real-world spatial task or the map-pointing task in men and women with similar wayfinding experience, preference for spatial strategies, and levels of anxiety. Gender dimorphism appeared in our paper-and-pencil test of spatial orientation, suggesting that the real-world spatial task and the map-pointing task assess spatial competences that are different from those assessed in the paper-and-pencil test. On another hand, anxiety was related to individual differences in the preference for an orientation strategy and the time taken to complete the learning phase of the AR task. Our results highlight the importance of anxiety in spatial tasks. However, more research is needed to further investigate how other emotional factors such as personality or motivational aspects may influence spatial orientation. In particular and considering the possibility that the AR task offers, a new research goal could be to study the variation in levels of state anxiety and related performance outcomes using the AR task. In addition, the effect of age could be considered.

Chapter 4

SLAM-based augmented reality for the assessment of short-term spatial memory. A comparative study of visual versus tactile stimuli

VISUAL VERSUS TACTILE STIMULI, AND ENVIRONMENTS OF SMALL DIMENSIONS

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4.1 Abstract

The assessment of human spatial short-term memory has mainly been performed using visual stimuli and less frequently using auditory stimuli. This paper presents a framework for the development of SLAM-based Augmented Reality applications for the assessment of spatial memory. An AR mobile application was developed for this type of assessment involving visual and tactile stimuli by using our framework. The task to be carried out with the AR application is divided into two phases: 1) a learning phase, in which participants physically walk around a room and have to remember the location of simple geometrical shapes; and 2) an evaluation phase, in which the participants are asked to recall the location of the shapes. A study for comparing the performance outcomes using visual and tactile stimuli was carried out. Fifty-three participants performed the task using the two conditions (Tactile vs Visual), but with more than two months of difference (within-subject design). The number of shapes placed correctly was similar for both conditions. However, the group that used the tactile stimulus spent significantly more

time completing the task and required significantly more attempts. The performance outcomes were independent of gender. Some significant correlations among variables related to the performance outcomes and other tests were found. The following significant correlations among variables related to the performance outcomes using visual stimuli and the participants' subjective variables were also found: 1) the greater the number of correctly placed shapes, the greater the perceived competence; 2) the more attempts required, the less the perceived competence. We also found that perceived enjoyment was higher when a higher sense of presence was induced. Our results suggest that tactile stimuli are valid stimuli to exploit for the assessment of the ability to memorize spatial-tactile associations, but that the ability to memorize spatial-visual associations is dominant. Our results also show that gender does not affect these types of memory tasks.

4.2 Introduction

People have the ability to store and remember representations of spatial stimuli for short periods of time. This ability is known as spatial short-term memory (Baddeley, 1992). From neurobiological and cognitive perspectives, most of the information that humans explicitly store in spatial memory comes from the visual and auditory modalities (Pearson & Kosslyn, 2015; Setti et al., 2018; Bizley & King, 2008; Yamamoto & Shelton, 2009). However, the human brain has the ability to store information from all sensory modalities (Schmidt & Blankenburg, 2018). One of these sensory modalities is the sense of touch, which even though it is not the most studied sense, it is certainly a sense to exploit. Spatial memory is used to store and remember the route to find a previously visited place or to find where we have left our belongings (e.g., keys or glasses) (Burgess et al., 2001). This type of memory is involved in everyday tasks and allows navigation and solving spatial tasks. Thus, impairments in spatial memory have serious consequences in daily life. Different memory-related help tools can be used for assessment as well as training. For assessment, these tools can help in determining the difficulties that may affect people's independence (Neguţ et al., 2016). For training, these tools can contribute to spatial orientation by improving correct way-finding behaviours (Caffò et al., 2013). Orientation difficulties usually occur due to impairments or diseases, such as stroke (Barrett & Muzaffar, 2014), Alzheimer's disease (Doniger et al., 2018), acquired brain injury (Kuil et al., 2018), and healthy aging (van der Ham & Claessen, 2020). Human spatial orientation in real life is based on both self-motion and visual cues (including proprioceptive and vestibular cues) (Cullen & Taube, 2017). Two technologies that can greatly assist in the development of tools for the assessment and training of spatial memory are Virtual Reality (VR) and Augmented Reality (AR). These two technologies can be of great help when the subject has to perform physical movement in the real world. The fact that the subjects have to move around the real world to perform the tasks resembles what they experience in real life. Moreover, physical displacement has been shown to be important in acquiring spatial ability skills (Ruddle & Lessels, 2009).

This work presents a framework for the development of AR based on SLAM (Simultaneous Localization and Mapping). An AR mobile application was developed for this type of assessment involving visual and tactile stimuli by using our framework. Our AR application can be used in any indoor environment (e.g., a hospital ward, the therapist's office, or the patient's home) and requires the subject to physically walk around the real world. The task that the participants must perform is divided into two phases, a learning phase and an evaluation phase. In the learning phase, the participants physically walk around a room, and have to remember the location of virtual geometrical shapes. In the evaluation phase, the participants are asked to recall the locations where the shapes were in the room and place them correctly using AR. Our study compares short-term spatial memory involving visual (visual condition) and tactile (tactile condition) senses. A similar protocol was designed for the sense of touch, but using real objects. In the learning phase, the subjects touch real objects that are placed inside boxes in a real room, and they must remember their location. In the evaluation phase, the participants touch real objects that are hidden inside boxes and they have to place a virtual box that represents the touched object in the correct location. To our knowledge, this is the first work that uses AR to compare visual and tactile stimuli for the assessment of short-term spatial memory.

4.3 Assessment of spatial memory using virtual and augmented reality

Spatial memory is typically assessed in the visual modality, using paper and pencil tests (Langlois et al., 2015; Mitolo et al., 2015). The development of computerized tools that use VR or AR provides some advantages over traditional tests. VR and AR applications allow objective indicators of the spatial learning of an individual (e.g., successes-failures, reaction times, speed, distance travelled, etc.) to be obtained and stored for later study. The presentation of stimuli can be varied and controlled (Walkowiak et al., 2015; Picucci et al., 2011; Juan et al., 2014). Since VR and AR applications provide advantages regarding the evaluation and training of people in a real environment (i.e., lower economic and time costs, etc.), the use of these technologies in the study of human ability has increased.

Different works have used VR to assess spatial memory in humans (Bohil et al., 2011; Fabroyir & Teng, 2018; León et al., 2016; Münzer & Zadeh, 2016). In the first VR applications for the assessment of spatial memory, the users were sitting in front of a computer screen without performing physical displacement. The users explored a VR environment during the task (Walkowiak et al., 2015; Picucci et al., 2011; Cimadevilla et al., 2014). However, physical displacement is an important aspect to consider for spatial ability (Ruddle & Lessels, 2009). Some works have included physical displacement in VR environments (Rodríguez-Andrés et al., 2016; Rodriguez-Andres et al., 2018; Cárdenas-Delgado et al., 2017). Rodríguez-Andrés et al. (2016) studied the influence of two different types of interaction on a VR task (an active physical condition versus an inactive physical condition). From their results, no statistically significant difference in task outcomes was found for the two types of interaction. They concluded that the type of interaction did not affect the children's performance in the VR task. Even though the physical movement was performed on the Wii balance board, the users did not have the feeling of walking in the real world. Cárdenas-Delgado et al. (2017) developed a maze-based VR task in which the participants had to perform physical movement. As in the previous work, they considered two different types of interaction (an active physical condition versus an inactive physical condition). The performance outcomes on their task were better for the inactive physical condition. As in the previous work, the physical movement was performed on a bicycle and the participants did not have the feeling of riding a bike in the real world, even when the user had to pedal on a stationary bike and had the HMD on.

Very few works have been presented for the study of the performance of spatial memory using AR. Our research group has presented most of these works. Our group has pioneered the development and validation of AR applications for the assessment of spatial memory (Juan et al., 2014; Mendez-Lopez et al., 2016; Munoz-Montoya et al., 2019b,a). In the first work (Juan et al., 2014; Mendez-Lopez et al., 2016), we developed an AR application that used image targets that were distributed in the real world. In the second work (Munoz-Montoya et al., 2019b,a), we presented an AR application based on SLAM for visual stimuli. The main difference with the previous work was that no additional elements were added to the real environment. The application used in this second work was created using the framework that is presented in this paper, but it only focuses on visual stimuli. Our group has also studied auditory stimuli for the assessment of spatial memory (Valencia et al., 2019). Meanwhile, Keil et al. (2020) have recently presented a development and a study that are closely related to our work. They developed an AR system for location memory and distance estimation. The system shows holographic grids on the floor. They carried out a study to determine the effects of grids on the floor on location memory and distance estimation in an indoor environment. The results of their study showed that distance estimations were more accurate when a grid was displayed. The performance of location memory was worse when a grid was displayed.

Other works, which are not as closely related to ours, have focused on the use of AR to help in navigation. Chu et al. (2017) presented a mobile AR tool to help in navigation. The scene captured by the camera was augmented with virtual 2D icons to guide users to their destination. Their study compared an AR tool and two map navigation modes. Their conclusion was that the AR tool was better than the two map navigation modes. Rehman & Cao (2017) presented an AR application to help people navigate indoors. They compared the navigation using Google Glass, a smartphone, and a paper map. Their results showed that the participants perceived Google Glass to be the most accurate tool. No statistical differences were found between Google Glass and the smartphone in terms of workload. Google Glass and the smartphone were better than the paper map in terms of lower workload and less time of execution. However, the route retention was better with the paper map. Peleg-Adler et al. (2018) presented a tool for route planning in public transportation. The performance using a mobile AR application and a non-AR application was compared. The augmented scene showed the expected times that buses go through each station on the map. They carried out a study in which they compared the performance of older participants and younger participants. The participants who used the AR application completed the task in less time, but with higher error rates. These results were independent of the age of the participants. The younger participants showed significantly faster performance compared to the older participants while using the AR application. However, there were no significant differences regarding error rates.

4.4 Design and development

In this section, we describe the SLAM-based AR application used for the assessment of spatial short-term memory and how it has been used to configure the environment and in the visual condition. We describe the steps followed in the tactile condition and how the use of the AR application and touching real objects have been combined. We also present the three applications that were developed to automate tasks that have traditionally been evaluated using pen and paper. We finally present the hardware and software used for the development of our applications and the architecture of the framework presented in this paper.

4.4.1 Configuration of the environment

The AR application based on SLAM is designed to assess spatial short-term memory for shape location. The AR application runs on a smartphone. The participants have to perform a task that consists of walking around a real room. The dimensions of the room are 5 x 7.5 (around 38 m^2). The participants must look for virtual geometrical shapes and remember their locations. These geometrical shapes can only be seen through the mobile screen. For this purpose, the scene must be configured in two phases: room scanning and shape configuration.

The room scanning phase. In this configuration phase, the supervisor scans the real room. This scan stores the geometry of the room in the smartphone (Figures 4.1a and 4.1b). This scan includes the walls as well as tables, chairs, computers, etc.

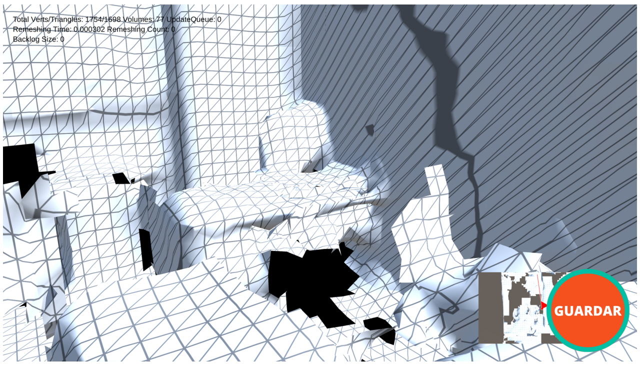
The shape configuration phase. The supervisor places the different geometrical shapes in the real scanned room (Figure 4.1c) using the geometry stored in the smartphone. The application has about fifty 3D models of different types. In our study, we used eight geometrical shapes. These eight shapes are: cube, rectangular prism, wide cylinder, narrow cylinder, sphere, semi-sphere, cone, and pyramid. The application allows objects to be placed on planar surfaces (horizontal or vertical). In our case, they were all placed on tables. The bottom side of the geometric shape is attached to the detected surface. The shapes cannot be rotated. The shapes are always facing the camera position of the smartphone, and their up vectors are perpendicular to the plane of the surface.

4.4.2 The visual condition

For the visual condition, to use the AR application, the user must complete the following two phases. Figure 4.2 graphically shows the steps followed by the users in the visual condition.

The study with the visual condition is performed in two phases: learning and evaluation. During the learning phase, the subject has to follow a predefined path, searching for the eight virtual shapes placed on the desks in the room. When a shape is found, the subject

(a)



(b)

(c)

Figure 4.1: Configuration phase. (a) and (b) room scanning phase. (c) Shape configuration phase (an example of the supervisor placing a pyramid in the real scanned room).

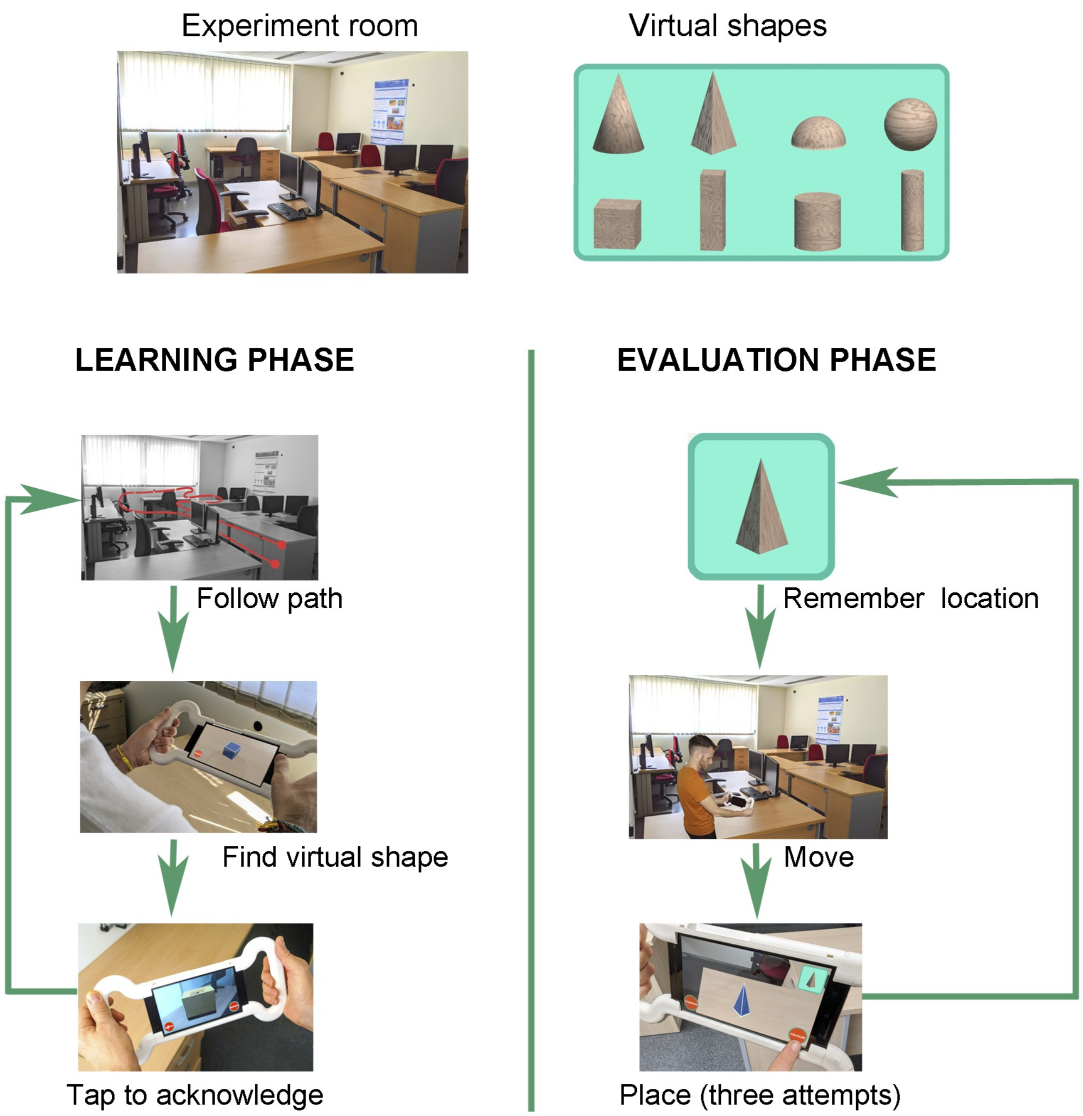


Figure 4.2: The steps followed by the users in the visual condition.

acknowledges it by tapping the screen. In the evaluation phase, subjects are requested to place each of the eight virtual shapes in its original location. Subjects have three attempts to place each shape.

The learning phase. The main objective of this phase is to allow the subject to explore the room searching for virtual geometrical shapes and to remember their locations. The supervisor guides the users through the room. The users see the shapes in the same order and follow the same path. The established order, which was the most suitable for seeing all of the shapes in a continuous tour, was: cone, narrow cylinder, cube, pyramid, sphere, rectangular prism, wide cylinder, and semi-sphere. The participants have to indicate on the application that they have seen a shape by tapping on it. At that moment, a box appears to show that this shape has been marked as seen. Once the shape has been marked by the user, it cannot be seen anymore.

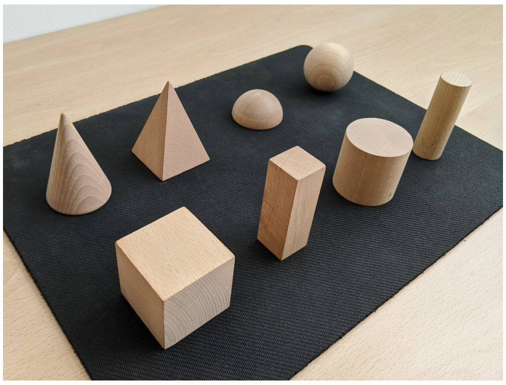
The evaluation phase. This phase evaluates the participants' ability to remember the location of the virtual geometrical shapes in the real room. The users are asked to place all of the eight shapes in their correct locations using the application. The shapes have a pre-established random order so that all of the participants carry out the placement in the same order. This order is different from the order followed in the learning phase: cube, rectangular prism, wide cylinder, narrow cylinder, sphere, semi-sphere, cone, and pyramid. The placement of the shapes does not have to be exact. There is a proximity tolerance. The point where the shape is placed by the user can be up to half a meter away from the exact point. The participants have three attempts to place each shape correctly. They are informed of whether or not they have placed the shape correctly in each try. On the last attempt, the shape remains fixed in the last position where it was placed, and the user is informed whether it was a success or failure. The participants are not helped regarding where the shapes are located.

4.4.3 The tactile condition

The task related to tactile stimuli combines the use of the AR application with touching real geometrical shapes inside opaque boxes. The geometrical shapes used are the ones already mentioned: cube, rectangular prism, wide cylinder, narrow cylinder, sphere, semi-sphere, cone, and pyramid (Figure 4.3a). The dimensions of the geometrical shapes are between 4 and 25 cm^2 at the base and between 3 and 10 cm in height. The boxes are closed. Their size is 31x22x25 cm with a capacity of 18 liters. The interior of the box is accessed through two small windows on the lower-left and lower-right sides, which are covered with strips of fabric. The subjects can introduce their two hands inside the box and touch the geometrical shapes, but they cannot see inside. Figure 4.3b shows the box. There are eight boxes. Each of the eight boxes had a different shape inside, and each box was identified using a barcode. The phases are the same as in the visual condition. Figure 4.4 graphically shows the steps followed by the users in the tactile condition.

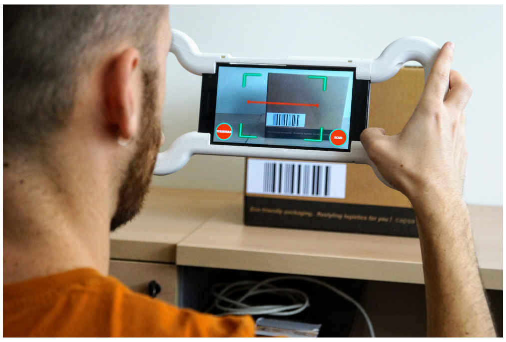
The study with the tactile condition is performed in two phases: learning and evaluation. During the learning phase, the subject has to follow a predefined path with eight physical boxes. Each box has a different geometrical shape inside. For each box, the subject has to inspect the shape inside by touch through two holes in the sides of the box. Then, the AR application is used to scan the barcode and to store a timestamp of the moment that the shape was examined. In the evaluation phase, the boxes are removed from their initial position and shown to the subject one by one. After inspecting its shape, the subject has to place a virtual box with the AR application in the position where the shape was located during the learning phase. The subjects have three attempts to place the virtual box correctly.

The learning phase. The boxes are placed in the room in the same locations as the virtual geometrical shapes were placed in the visual condition. In other words, the box



(a)

(b)



(c)

(d)

Figure 4.3: Materials used in the tactile condition. (a) Physical geometrical shapes used in our study. (b) Box used in the learning and evaluation phases of the tactile condition. (c) An example of the AR application for scanning the barcode. (d) An example of a participant placing a virtual box in the evaluation phase using the AR application.

containing the real sphere is placed in the same location where the virtual sphere was in the visual condition. The main goal of this phase is to allow the subject to walk around the room, to explore the real geometrical shapes by touch and to remember their locations. Since the real shapes are the same as the virtual ones used by the visual condition, they are located in the same locations. The subjects follow a pre-set tour, and they all perform the same task. When a subject reaches a box, he or she puts his/her hands in it and touches the shape to identify it and to remember its location. The AR application is used to scan the barcode and to store a timestamp of the moment that the shape was examined (Figure 4.3c).

The evaluation phase. After finishing the learning phase, the subject is invited to leave the room for a moment. Meanwhile the supervisor removes every real box from its place and piles them altogether on a working table in a given order. The working table is another table that is not used in the learning phase. The subject comes back

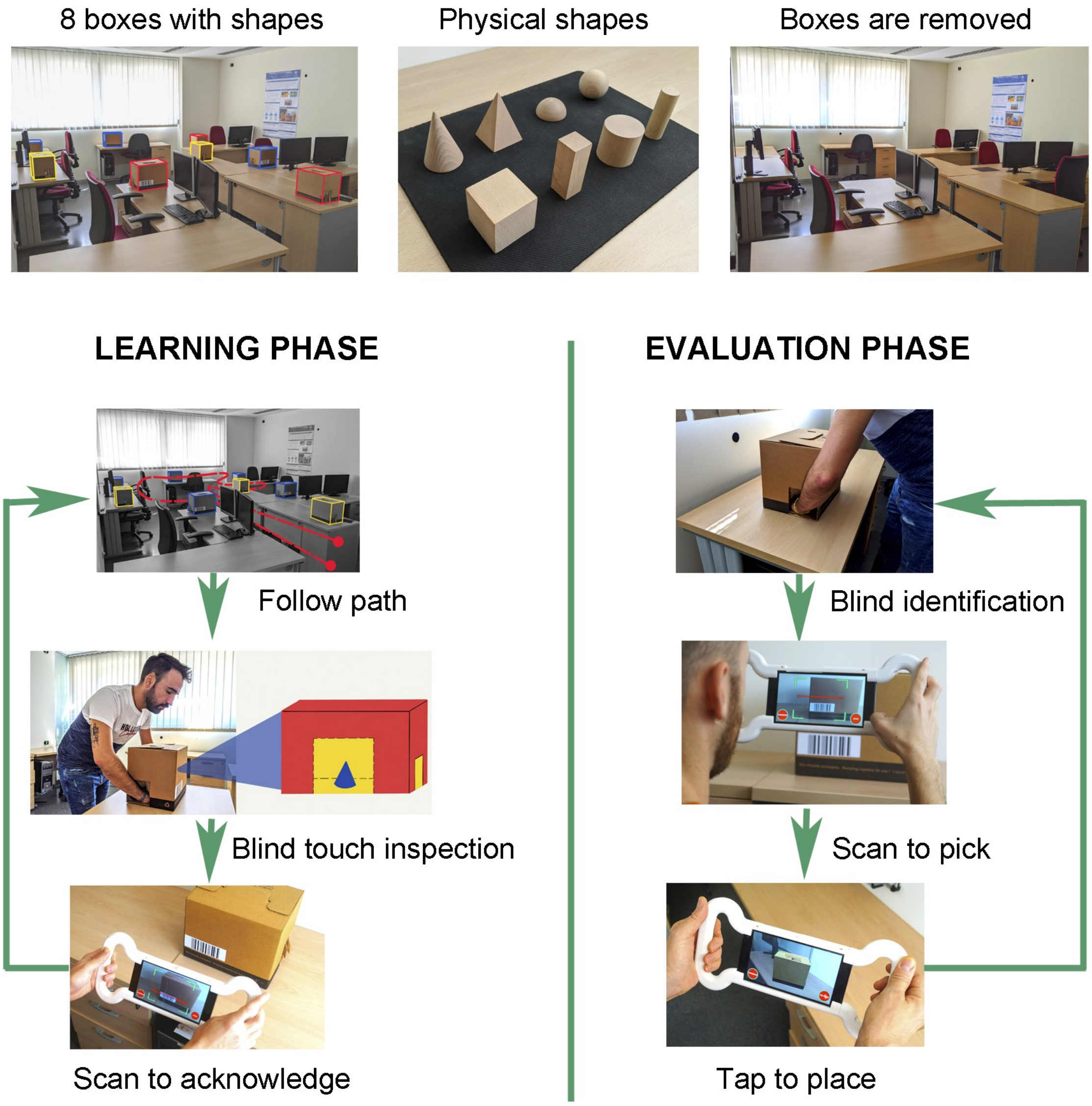


Figure 4.4: The steps followed by the users in the tactile condition.

to the room again and stands in front of the working table. The supervisor takes a real box (working box) and puts it on the working table. The subject touches its shape by introducing his or her hands inside of the working box without seeing the shape. Using the AR application, the supervisor scans the barcode that is attached to the box being used, thereby informing the AR app of the shape inside. Then, the supervisor gives the AR application to the subject. The subject has to place a virtual box in the real position where he or she had touched that shape before. There are no physical boxes on the tables. The virtual boxes are only seen through the screen of the mobile device.

While the user is performing the placement of the box, the supervisor takes the current working box and puts it on a new pile. Then, the supervisor takes the next working box and puts it on the working table for the next evaluation step. When the user has placed the current box at the desired place, he or she returns to the working table with the AR device. The process is repeated for all eight boxes. The order is the same for all of the subjects. Figure 4.3d shows a subject placing a virtual box in the room.

4.4.4 The shape-recognition application

The shape-recognition application allows the participants to select the shapes memorized in the previous tasks from among different shapes. The participants are asked to identify the geometrical shapes that they have touched or seen among a collection of different 3D shapes that appear on the screen of a tablet (Figure 4.5a). To facilitate the recognition of the shapes, they are animated and rotate around their vertical axes. The subjects can select and deselect as many shapes as they desire. Once the subjects have finished with the selection of shapes, they notify the supervisor, who ends the test. The application shows fifteen objects on the screen, of which our study uses eight objects. The order used to present the shapes on the screen is always the same.

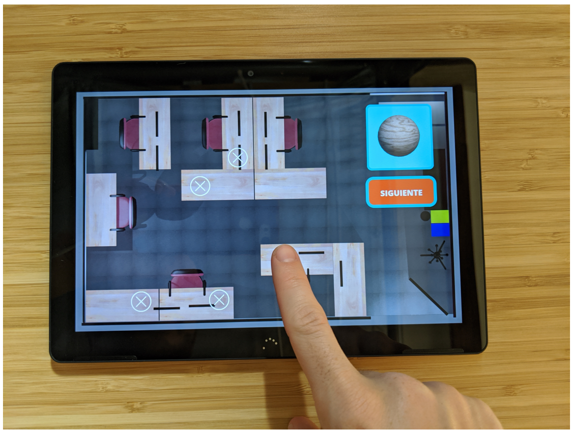
4.4.5 The map-pointing application

The map-pointing application shows an empty map of the room. This map is a two-dimensional simplified map of the room in which tables, chairs, computers and office furniture are displayed. The participants must place the geometrical shapes that they have touched or seen in the right place. For the visual condition, the eight shapes are presented on the top right of the screen one at a time (Figure 4.5b). Once a given shape is presented to the subject, he or she has to place it on the map. For the tactile condition, the participants insert their hands into a box and touch a shape without seeing it. They place that shape (represented as a box) on the virtual 2D map using the tablet. The maximum distance between the position selected by the subject and the real position is also 0.5 meters (scaled to the map). The subjects have one chance to place the shape in the right place, and they are not notified whether or not they have placed it correctly. It is not possible to change the position of a shape that has already been placed.

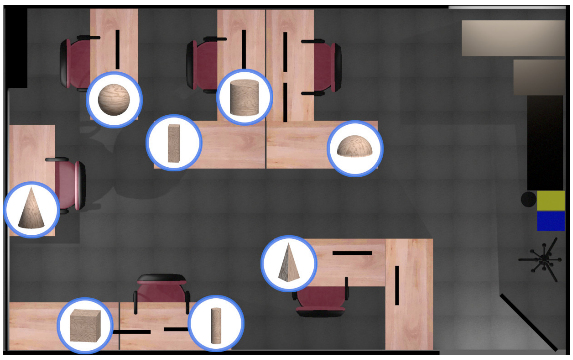
4.4.6 Spatial orientation application

The spatial orientation application is a computer version of the PTSOT (Perspective Taking/Spatial Orientation Test) test (Hegarty, 2004). The PTSOT test is a traditional paper-and-pencil spatial orientation test. The PTSOT test consists of twelve items that evaluate the users' ability to orientate themselves spatially and think about different perspectives. The application shows one PTSOT image at a time. It presents a circle around a given object placed in the center. A vector that joins the center of the circle with a point on the circumference indicates the position of a different element. The user is asked for the related position of another object using a second vector. The user has to move this second vector with his/her finger to place it in the desired position. Once the

(a)



(b)



(c)

Figure 4.5: Other applications and a schematic top view of the room used. (a) Shape-recognition application for selecting geometrical shapes. (b) Map-pointing application used in the visual condition to place the geometrical shapes. (c) Schematic top view of the room and the location of the eight virtual geometrical shapes.

user has set the vector in the desired position she or he can move to the next orientation question.

4.4.7 Hardware and software

All of the developments were developed using the Unity real-time development platform. Unity was chosen because it allows the integration of practically all of the AR SDKs. The device used for the development and study was a Lenovo Phab 2 Pro. The main features of the smartphone are: resolution (1440 x 2560 pixels); dimensions (179.8 x 88.6 x 10.7 mm); screen size (6.4 inches); and weight (259 grams). This smartphone can run applications developed with Tango SDK, implementing the SLAM technology, which is possible thanks to its three built-in cameras (a depth camera, a wide-angle camera, and a color camera with 16 MP). Another device that can be used to develop a similar version is the iPad Pro, which includes a LiDAR scanner.

A PC convertible was used for all tests in which the subjects had to be seated (the shape-recognition task, the map-pointing task, and the PTSOT test). This PC was a 13" HP Pavilion X360 with a resolution of 1366 x 768 pixels. To fill out the questionnaires, the participants used a 13" Macbook Pro laptop.

4.4.8 Architecture of our SLAM-based AR framework

To facilitate the development of the AR application used in this work and other different applications, we designed and implemented a SLAM-based AR framework. This section describes the functionalities that are specific to our framework and that have been explicitly developed for it. Our framework uses some specific services that the AR SDK used must provide; in this case, it is the Tango SDK, but it could be ARKit or any other. There are two specific services: recognition of an environment and positioning of the device in it. The framework facilitates access to these two services by providing an interface with specific functions that are common to all of the SDKs used. The developer abstracts from the different specific mechanics of each SDK. Moreover, the framework offers high-level AR functions that are not implemented in the AR SDKs such as: management of environments where AR is used, placement of virtual objects in the environment, generation of files to store the configuration of objects anchored to the environment, etc. The framework also offers functions outside the AR SDK, such as user management or data storage during sessions. Therefore, in the design of the architecture of our framework, two groups of functionalities were defined: functionalities related to AR technology and other functionalities.

The following functionalities were identified for AR technology:

- scanning of 3D geometry of real environments,
- storage, recovery, and management of 3D geometry in real environments,
- importation of 3D models to be used in the augmented environment,
- configuration of the scanned environments by adding the desired visual elements.

The following functionalities were identified for non-AR technology:

- management of user sessions,
- management of the times set for the different tasks,
- storage of the events produced by users during the task. The information stored includes direct interactions with the environment (e.g., the position of the device) or interactions through the interface (e.g., selected objects, pressed buttons, or placed objects).

Additionally, the following goals in the design were defined:

- building a modular architecture, which allows adding or removing features in a simple way. This modularity also facilitates team development since each team member can work on different modules.
- implementing the inter-module communication in a simple and efficient way. This communication should be as robust, efficient, and simple as possible.
- focusing on the AR-related functionalities. The framework must be able to work with different AR SDKs/engines. The architecture of this framework was designed in three layers as shown in Figure 4.6.
- The core layer. This is the central layer of the framework. This layer is in charge of managing the subscription of the different modules to the framework. It controls the communication between the different modules and allows the scene layer to access the interfaces of the modules. This layer also manages the life cycle of the different framework components in order to ensure consistency in their updates and calls.
- The module layer. This layer consists of the different modules that are available in our framework. Each of these modules implements a different functionality that can be added to the applications. Each module must have at least one available interface (module interface) that can be called from the scene layer or from other modules. Handler interfaces, which manage the asynchronous outputs of the module, are also implemented.
- The scene layer. This layer contains the different scenes of the applications. Each scene has access to all of the modules. The scenes access the modules through the core layer. The scenes can also implement handler interfaces to receive asynchronous callbacks from modules.

This architecture is centralized. All of the elements involved in the framework subscribe to the core layer. All of the processes that occur in the framework go through the core layer. All of the updates are triggered by the core layer in an orderly way. This layer manages the order in which processes must be executed. In other words, no element can

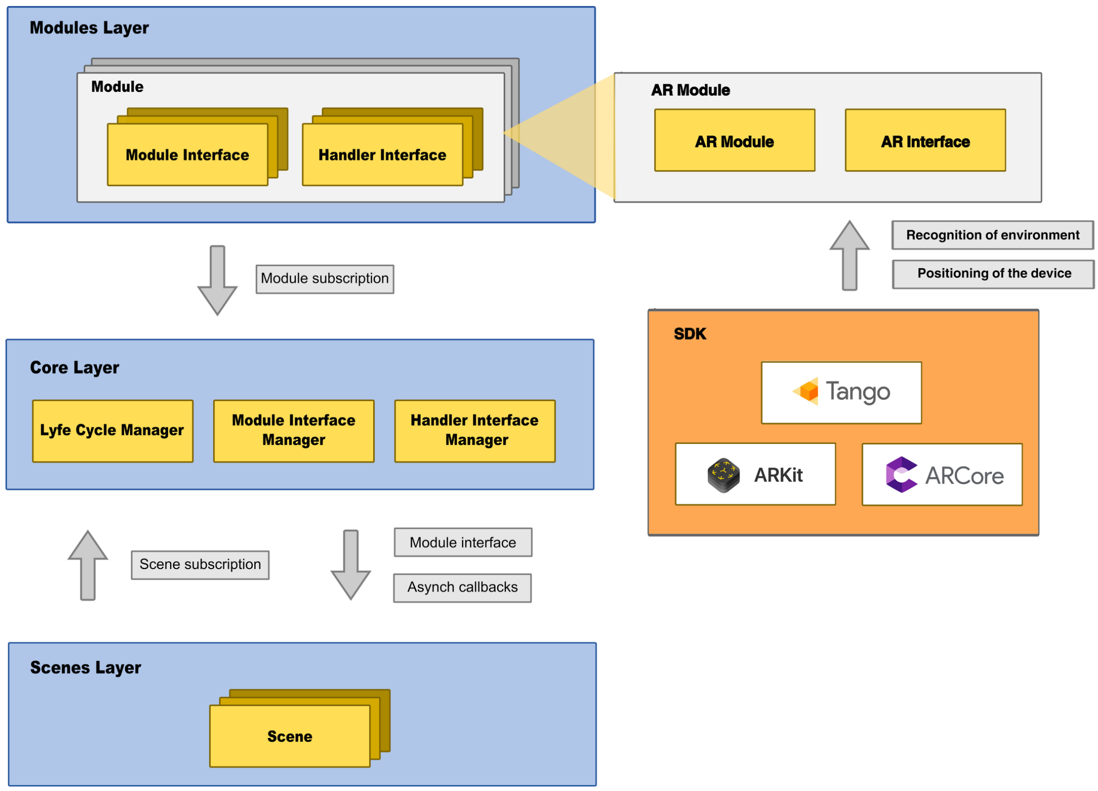


Figure 4.6: Architecture of our SLAM-based AR framework.

manage its own processes in isolation from the core. Therefore, there is no background computation that can affect the performance of the application. The access to the modules is achieved through the core layer. In addition, this architecture is modular. It is distributed in independent modules that can communicate with other modules, but always through the core layer and by interfaces. The core layer manages the integration of the different modules. A module only has to subscribe to the core layer, indicating what its module interfaces and its handler interfaces are. The core layer manages all subscriptions and allows the scene layer to access those interfaces. The core layer is also in charge of managing the subscription of the scenes to the module callbacks once the interfaces are implemented.

Specific modules have been implemented for AR. These modules can be used with different AR engines/SDKs in a simple way and without altering the rest of the code. The core layer also has an event-handling system. The events can reach a multitude of components that are subscribed to the core layer. This communication system is useful for sending broadcast messages with different content. There are templates for different events with different objectives. There are broadcast messages regarding the interface to indicate, for example, which system component is allowed to receive interface events. There are also messages indicating the status of the AR service.

The AR application used in this study was implemented using our framework. There is a scene in the application for each of the phases of the task. These scenes subscribe to the core layer of the framework and can use the different modules. The modules used in this application are: the AR module, the user interface module, the configuration storage module, the event and data storage module, and the time control module.

The AR module is the module that is in charge of providing all of the AR functionality. This module encapsulates the initialization and configuration of the AR engine. It offers different simple methods that are common to different AR engines. Some of these functionalities are: scanning, storage, and management of environments where AR is used, detection of planes in the environment, placement of virtual objects in the environment, generation of files to store the configuration of objects anchored to the environment, etc. It also offers user interface events for the management of augmented objects. It should be noted that this module facilitates the switch among the different AR engines.

The user interface module manages everything that is displayed on screen as well as the interactions between the user and the application. This module is divided into two sub-modules: an AR interface sub-module that manages the part involving AR elements, and the standard interface module. The AR sub-module implements functions to manage the user's interaction with augmented objects in the environment and also with the current environment shown on the screen. The standard sub-module controls features that are common to all applications and allows the creation of menus, buttons, selection screens, etc.

The configuration storage module is in charge of storing and retrieving the configuration files of the scenes. The geometry of the environment, the selected objects and their respective locations in the environment are stored for each scanned environment. The module for storing events and related data is in charge of managing the identifiers of the session and the user. In addition, this module stores all of the information that is relevant to the tasks performed by the user, all of the user's interactions with the application, and the outcomes. It also stores the physical paths that users have taken during their tour in the real environment. The time control module manages the time specified for each task and provides configuration options. It also allows interface elements (e.g., countdown timer) to be incorporated.

Three more applications were developed to carry out the study presented in this paper: the shape-recognition application, the map-pointing application, and the PTSOT application. These three applications were developed with a model-view-controller architecture, using the user interface tools offered by Unity. The storage of outcomes, events, times, etc. was carried out using the same storage structure as defined above.

4.5 Study

4.5.1 Participants

The initial sample included 53 adults (60% undergraduates and 40% graduates). The gender distribution was 70% men. The participants were recruited at the Universitat Politècnica de València (Spain), through campus advertising. The participants received a small reward consisting of a USB stick. The final sample was selected after applying two inclusion criteria that are explained in section 4.2. The final sample considered for our study included 47 adults. The gender distribution was 70% men. The minimum age was 20 and the maximum age was 56. The mean (standard deviation) age of the participants was 30.18 (9.25) for males, and 32.86 (11.22) for females. Two of the participants were left-handed. None of the participants were under medical treatment that could affect their cognitive functioning. None had suffered a brain injury, or had any sensory or motor impairment. None of the participants were familiar with the environment where the study was carried out. The participants gave written informed consent prior to the study. The individuals who appear in the images of this manuscript gave written informed consent to publish their case details. The study was approved by the Ethics Committee of the Universitat Politècnica de València, Spain. The study was conducted in accordance with the declaration of Helsinki.

4.5.2 Statistical tests

The Shapiro-Wilk test was used to check the normal distribution of the variables (Patrício et al., 2017). None of the variables followed a normal distribution. Therefore, non-parametric tests were used with the whole dataset. A descriptor of each group is presented in the format (median (Mdn); interquartile range (IQR)). All of the tests are presented in the format (statistic U/W, normal approximation Z, p-value, r effect size). The results were considered to be statistically significant if $p < .05$. We used the R open source statistical toolkit (https://www.r-project.org) to analyze the data (specifically, RStudio 1.2.5033 for Windows).

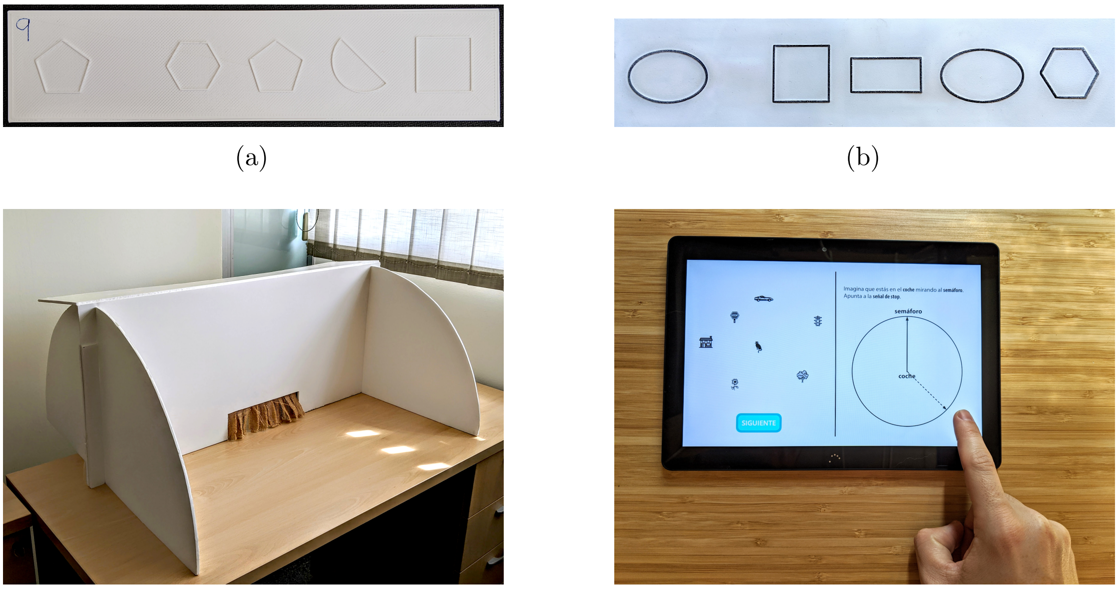
4.5.3 Inclusion criteria

We built a battery of haptic tests to assess tactile abilities. These tests were used as inclusion criteria to select participants with similar tactile abilities. Our battery of tests is based on the battery of haptic tests (Haptic-2D) proposed by Mazella et al. (2016). Their complete battery consists of eleven haptic tests divided into five categories to measure short-term memory, scanning skills, spatial comprehension skills, tactile discrimination skills, and picture comprehension. Two-dimensional raised stimuli (lines, dots, patterns, shapes, or pictures) were printed on swell paper for their tests. They used a wooden structure to enable subjects to introduce their hand behind the curtain to explore the stimuli through active touch, thus preventing subjects from seeing the materials. Our battery of tests consisted of tests for spatial orientation, shape discrimination, and spatial location built in plastic and in swell paper. Our plastic tests were printed on a Rapman 3.1. 3D printer that used an additive process, where successive layers of material are laid down according to the desired pattern. Our 3D printer used ABS white material. The items were printed in pieces of two different sizes, 26 x 6 cm and 30 x 7 cm. We also used swell paper to raise stimuli and create items equivalent to those used in the plastic items. The size of the paper items was the same as the size of the printed items, 26 x 6 cm and 30 x 7 cm. To prevent the users from seeing the tests, we built a structure of cardboard with a thickness of 5 mm and an open area with a curtain made of fabric so that the users could introduce their hands, but not see inside (Figure 4.7c). The three tests using the plastic items are described below.

Spatial orientation test. The stimuli in the spatial orientation test are raised-line figures made up of one, two, or three rectilinear segments. Each segment has a specific orientation (vertical, horizontal, or oblique). Each segment is 3 cm long. Each test includes a practice item and six items with increasing complexity. Our test includes two items with one segment, two items with two segments, and two items with three segments. The subjects must explore the figures with the index finger of their dominant hand. We used the instructions proposed by Mazella et al. (2016). Each item consists of a reference element and four similar elements. The participants must inspect the reference element by touch, and then touch the following four elements one by one, without being able to go back. For each of the four elements, the participants must indicate verbally whether or not the figure has the same spatial orientation as the reference. The supervisor writes down their answers without giving any feedback. Two points are awarded for each correctly completed item. The maximum score is 12 points. Shape discrimination test. The protocol is similar to the spatial orientation test. The only difference is the type of figures, which are geometrical shapes. The size of the shapes is adjusted so that they occupy the maximum size in an area of 9 cm^2. These 2D shapes are: square, rectangle, rhombus, sphere, semi-sphere, ellipse, pentagon, hexagon, right triangle, equilateral triangle, and five-pointed star. Figure 4.7a shows an item used in this test. As in the previous test, the participants must inspect the reference element by touch. Then, for each of the four elements, the participants must indicate verbally whether or not the shape of the figure is the same as the reference element. Spatial location test. The protocol is similar to the two previous tests. The only difference is the type of figures. The stimuli in this test are raised-line figures inside a circle (diameter = 4 cm). The circle may contain one, two, or three small elements inside (circle, star, or square). The size of these small elements varies from 7 to 10 mm. Three of the items have one inner element, two items have two inner elements, and one item has three inner elements. As in previous tests, the participants must inspect the reference element by touch. Then, for each of the four elements, the participants must indicate verbally whether or not the spatial location of the inner elements is the same spatial location as in the reference element.

The swell paper test contains a practice item and six items (Figure 4.7b). This test includes two items for spatial orientation, two items for shape discrimination, and two items for spatial location. The protocol is similar to the three previous tests. However, there are two differences: the type of material used to build the test, and the total number of items (6).

After building a box plot with the scores obtained by the participants in all of the haptic tests, five outliers were identified. These five outliers were removed from the sample (N = 48). We checked whether or not there were differences for the haptic test battery and for gender. To determine whether or not there were differences for the total score of the three plastic tests of our battery between the group of women (Mdn = 28; IQR = 3.5) and the group of men (Mdn = 28; IQR = 2), we applied the Mann-Whitney U test



(a) (b) (c) (d)

Figure 4.7: Tests used as inclusion criteria. (a) An example of one item included in the shape discrimination test (printed using ABS white material). (b) An example of one shape discrimination item included in the swell paper test. (c) Structure to prevent the participant from seeing the items used in the battery of haptic tests. (d) An example of a user interacting with the PTSOT application.

(U = 200, Z = -.740, p = .467, r = .108). To determine whether there were differences for the total score of the swell paper test score between the group of women (Mdn = 10; IQR = 0) and the group of men (Mdn = 10; IQR = 4), we applied the Mann-Whitney U test (U = 246.5, Z = .381, p = .712, r = .056). These results indicate that the women and men of our sample had the same tactile abilities.

We checked the total score of the participants in the PTSOT test as an inclusion criterion (Figure 4.7d). We used the previously published PTSOT scores as the upper limit for men and women (Munoz-Montoya et al., 2019b). These upper limits are 57.61° for men and 92.03° for women. One male was excluded from the sample (N = 47). We checked whether or not there were differences for the PTSOT variables and for gender. To determine whether or not there were differences for the PTSOT score between the group of women (12.65; 10.555) and the group of men (12.86; 11.56), we applied the Mann-Whitney U test (U = 212, Z = -.442, p = .671, r = .064). To analyze the unattempted items on the PTSOT for the group of women (33.333; 20.833) and the group of men (33.333; 16.667), we applied the Mann-Whitney U test (U = 243, Z = .284, p = .785, r = .041). These results indicate that the women and men of our sample had similar spatial orientation abilities.

4.5.4 Measures

Performance with visual and tactile conditions.

The visual application and the tactile application store the following variables: the total number of shapes located correctly during the evaluation phase (LocShapes); the total number of attempts made while placing the shape in the correct location (AttemptS); and the total time required to complete the learning phase (TTimeL) and the evaluation phase (TTimeE).

The shape-recognition task.

We developed the shape-recognition application to test the ability of the participants to recognize the shapes that they inspected during the task. The shape-recognition task stores two variables: the number of shapes that the participants selected correctly (RecogS), and the number of shapes that the participant selected incorrectly (RecogI).

The map-pointing task.

We developed the map-pointing application to test the ability of the participants to read a bi-dimensional map of the room in which the main task with the visual/tactile application occurred. The map-pointing application stored one variable: the number of shapes that the participant placed correctly on the map (MapShapes). A shape is considered to be correctly located on the map when the participant places it within a radius of what would be half a meter in the real world, which is the equivalent of 3 cm on the virtual map.

Questionnaires.

The participants filled out a questionnaire about their subjective experience with the AR application. The questionnaire consists of 21 questions that we group into the following variables: enjoyment, concentration, usability, competence, calmness, expertise, non-mental effort, non-physical effort, presence, and satisfaction. This questionnaire was designed specifically for this study, and some of the questions were adapted from commonly used questionnaires (Witmer et al., 2005; Brooke et al., 1996; Regenbrecht & Schubert, 2021; Slater et al., 1994) and based on our previous experiences (Munoz-Montoya et al., 2019b; Valencia et al., 2019; Keil et al., 2020; Chu et al., 2017; Rehman & Cao, 2017; Peleg-Adler et al., 2018; Hegarty, 2004; Patrício et al., 2017; Mazella et al., 2016; Witmer & Singer, 1998; Brooke et al., 1996). The items were on a 7-point Likert scale, ranging from 1 “Totally disagree” to 7 “Totally agree”. All of the items were formulated in a positive manner except for items #9 and #10. Scores for the variables were obtained by calculating the mean value of the associated questions. This questionnaire is available in the S1 Appendix.

4.5.5 Procedure

The study was carried out in a room of 37.5 square meters. The room had the furniture commonly found in an office or in a university laboratory. Figure 4.5c shows a schematic top view of the room and the location of the eight virtual geometrical shapes.

The participants were involved in the two conditions (tactile and visual). Both conditions were tested in sessions that were held more than two months apart. After more than two months, it was very difficult for the participants to remember the location of the shapes. Furthermore, the room was not familiar to the participants since they had not had previous access before the study. The two conditions were the following:

The tactile condition: participants who learn the location of the physical geometrical shapes that were placed inside of physical boxes distributed throughout the room. In the learning phase, the boxes were placed in the room as shown in Figure 4.3d. The participants had to touch the shapes inside the boxes. The application was used to store which shapes were touched and when. In the evaluation phase, the boxes were not distributed throughout the room. The boxes were all on a table. The users had to touch the shapes one by one, in the same order. After touching a physical geometrical shape, the users were asked to place a virtual box using the AR application in the location that they thought they had touched the real object in the learning phase. The visual condition: participants who learn the location of the virtual shapes placed in the real room using our AR application. The participants used the AR application for the learning and evaluation phases. The location of the geometrical shapes (real or virtual) was the same in both conditions (Figure 4.5c). The administration protocol was comprised of two sessions. In the first session, the participants completed the battery of haptic tests and the PTSOT test. Then, they performed the tasks in the tactile condition: the short-term memory task for the location of geometrical shapes, the shape-recognition task using the shape-recognition application, and the map-pointing task using the map-pointing application. After more than two months, the participants completed the tasks again using the visual condition: the short-term memory task with the AR application, the shape-recognition task, and the map-pointing task. Finally, the participants filled out an online questionnaire about their subjective perception regarding the use of the AR application.

4.6 Results

4.6.1 Performance outcomes

We compared the performance outcomes between the two conditions (TactileCondition vs. VisualCondition) (within-subjects analysis) to determine how the use of tactile or visual stimuli affects memory of the location of stimuli. Figure 4.8 shows box plots for the performance outcome variables and for the tactile and visual conditions. First, we analyzed the variable that indicates the total number of successes for the eight stimuli used. This variable counts the number of shapes placed correctly (up to eight shapes). To determine whether or not there were differences in remembering and placing shapes in their correct locations between TactileCondition (Mdn = 7; IQR = 1) and VisualCondition (Mdn = 8; IQR = 1), we applied the Wilcoxon Signed-rank test (W = 123, Z = -1.739, p = .098, r = .179). This result indicates that there are no statistically significant differences between the two conditions.

Second, we analyzed the variable that represents the total number of attempts made when placing the shape in the correct location. Note that a maximum of three attempts

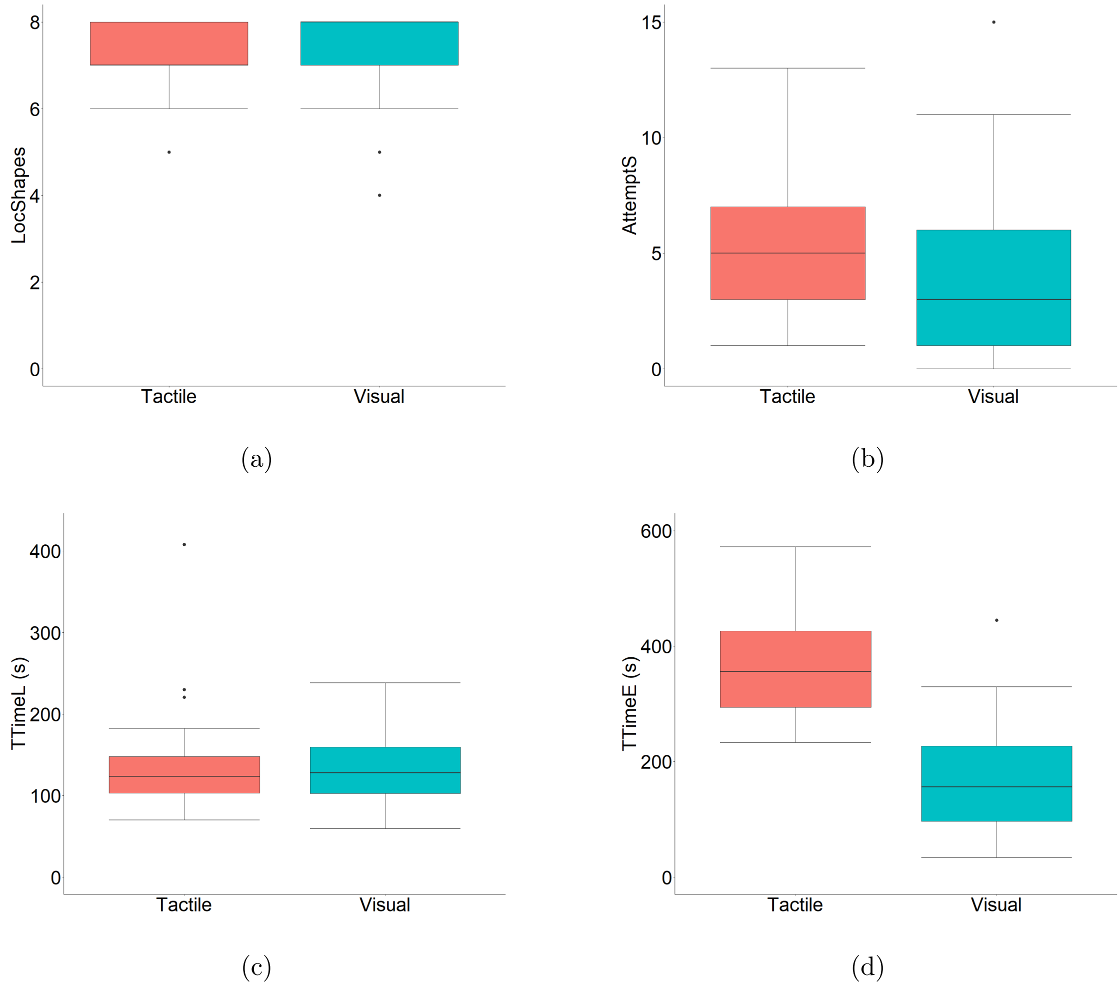


Figure 4.8: Box plots for the performance outcome variables and for the tactile and visual conditions. (a) Total number of shapes placed correctly (LocShapes variable). (b) Total number of attempts required to correctly place the shapes (AttemptS variable). (c) Total time in seconds required to complete the learning phase (TTimeL variable). (d) Total time in seconds required to complete the evaluation phase (TTimeE variable).

were allowed to place a shape in the correct location. To determine whether or not there were differences for this variable between TactileCondition (Mdn = 5; IQR = 4) and VisualCondition (Mdn = 3; IQR = 5), we applied the Wilcoxon Signed-rank test (W = 492, Z = 2.860, p = .004, r = .295). This result indicates that there are significant differences between the two conditions in favor of the visual condition, which required fewer attempts to place the shape correctly.

Third, we analyzed the variable that represents the total time required to complete the learning phase. To determine whether or not there were differences for this variable between TactileCondition (Mdn = 123.54; IQR = 44.64) and VisualCondition (Mdn =

128.02; IQR = 56.84), we applied the Wilcoxon Signed-rank test (W = 454.5, Z = -1.159, p = .249, r = .120). This result indicates that there are no significant differences between the two conditions.

Fourth, we analyzed the variable that represents the total time required to complete the evaluation phase. To determine whether or not there were differences for this variable between TactileCondition (Mdn = 356.23; IQR = 132.325) and VisualCondition (Mdn = 156.11; IQR = 130.44), we applied the Wilcoxon Signed-rank test (W = 1127, Z = 5.958, $p < .001$, r = .614). This result indicates that there are significant differences between the two conditions in favor of the group with visual stimuli, who spent less time to complete the evaluation phase.

We also analyzed the variable of the shape-recognition test that represents the number of shapes that the participant remembers after performing the task. To determine whether there were differences for this variable between TactileCondition (Mdn = 8; IQR = 0) and VisualCondition (Mdn = 8; IQR = 0), we applied the Mann-Whitney U test (W = 28, Z = -1.387, p = .178, r = .143). This result indicates that there are no significant differences between the two conditions. We also analyzed the variable that represents the number of shapes that the participant selected incorrectly for TactileCondition (Mdn = 0; IQR = 0) and VisualCondition (Mdn = 0; IQR = 0), and we applied the Wilcoxon Signed-rank test (W = 15, Z = 2.236, p = .037, r = .231). This result indicates that there are significant differences between the two conditions in favor of the group with visual stimuli, which selected fewer incorrect shapes.

We also analyzed the variable that represents the number of shapes that the participant placed correctly in the map-pointing task. To determine whether there were differences for this variable between TactileCondition (Mdn = 4; IQR = 3) and VisualCondition (Mdn = 6; IQR = 1), we applied the Mann-Whitney U test (W = 127, Z = -4.250, $p < .001$, r = .438). This result indicates that there are significant differences between the two conditions in favor of the group with visual stimuli, which placed more shapes correctly.

4.6.2 Gender analysis and subjective perception

To determine if gender influences the variable that indicates the number of correctly selected shapes, we analyzed the group of women (Mdn = 8; IQR = 1) and the group of men (Mdn = 7; IQR = 2) for TactileCondition, and we applied the Mann-Whitney U test (U = 289, Z = 1.438, p = .154, r = .210). For VisualCondition in the group of women (Mdn = 8; IQR = 1) and the group of men (Mdn = 8; IQR = 1), we also applied the Mann-Whitney U test (U = 221, Z = -.262, p = .803, r = .038).

We then analyzed the total number of attempts. For TactileCondition in the group of women (Mdn = 4; IQR = 3.5) and the group of men (Mdn = 5; IQR = 4), we applied the Mann-Whitney U test (U = 151, Z = -1.874, p = .063, r = .273). For VisualCondition in the group of women (Mdn = 3; IQR = 5) and the group of men (Mdn = 3; IQR = 6), we applied the Mann-Whitney U test (U = 235, Z = .094, p = .934, r = .014).

We analyzed the time required to complete the evaluation phase. For TactileCondition in the group of women (Mdn = 343.915; IQR = 64.173) and the group of men (Mdn = 395.23; IQR = 162), we applied the Mann-Whitney U test (U = 203, Z = -.651, p = .527, r = .095). For VisualCondition in the group of women (Mdn = 166.255; IQR = 105.653) and the group of men (Mdn = 123.83; IQR = 132.58), we applied the Mann-Whitney U test (U = 252, Z = .489, p = .637, r = .071).

Since no statistically significant differences were found in any of these analyses, we can conclude that the performance results were independent of the participants' gender.

The questionnaire about subjective experience was used to measure the participants' subjective perception of the AR application and their performance in the Visual Condition. The questions were grouped in the following variables: enjoyment, concentration, usability, competence, calmness, expertise, non-mental effort, non-physical effort, satisfaction, and presence. No statistically significant differences were found in any of these variables; therefore, we can conclude that the subjective perception was independent of the participants' gender ($U \geq 169.5, Z \geq -1.513, p \geq .134$).

4.6.3 Correlations

This section presents the significant correlations obtained after the application of the Spearman rank correlation and the Bonferroni correction for the visual condition. For the tactile condition, no significant correlations were found between the AR spatial task and other tasks.

We used the Spearman rank correlation to test the associations among variables for the performance in the visual condition (LocShapes, AttemptS) and among variables in the shape-recognition task (RecogS) and the map-pointing task (MapShapes). As there are multiple comparisons, the Bonferroni correction was applied. If we apply the Bonferroni correction to the matrix formed by these four variables, LocShapes correlates with MapShapes (r = .49, p < .01), and AttemptS also correlates with MapShapes (r = -.48, p < .01). This sensibly means that participants who placed fewer shapes correctly during the evaluation phase or required more attempts to place the shapes correctly also made more mistakes on the map-pointing task. Figures 4.9a and Figure 4.9b show these two correlations graphically.

If we apply the Bonferroni correction to the matrix formed by the four variables (TTimeL, TTimeE, LocShapes, and AttemptS), the TTimeE correlates with the LocShapes variable (r = -.51, p < .01) and with the AttemptS variable (r = .48, p < .01). This means that participants who required more time during the evaluation phase placed fewer shapes correctly and required more attempts. Figures 4.9c and 4.9d show these two correlations graphically.

We also used the Spearman rank correlation to test the associations among the ten subjective variables (enjoyment, concentration, etc.) and the variables of the performance outcomes (LocShapes and AttemptS). If we apply the Bonferroni correction to the matrix formed by these 12 variables, the LocShapes variable correlates with perceived competence (r = .49, p = .03), and the AttemptS variable correlates negatively with perceived competence (r = -.50, p = .03). This means that participants who placed a greater number of shapes correctly felt greater competence. In contrast, the greater the number of attempts, the less the perceived competence. Figures 4.9e and 4.9f show these two correlations graphically.

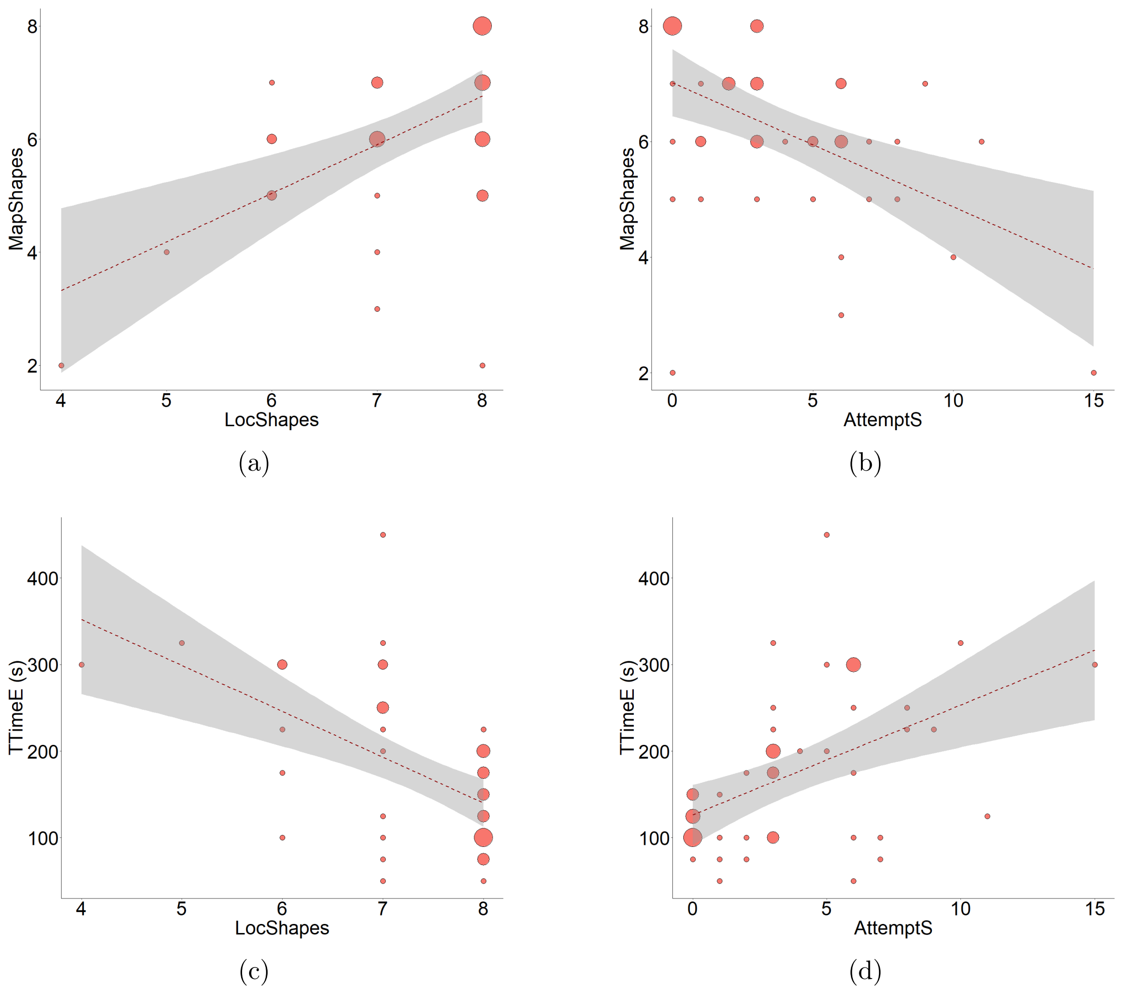
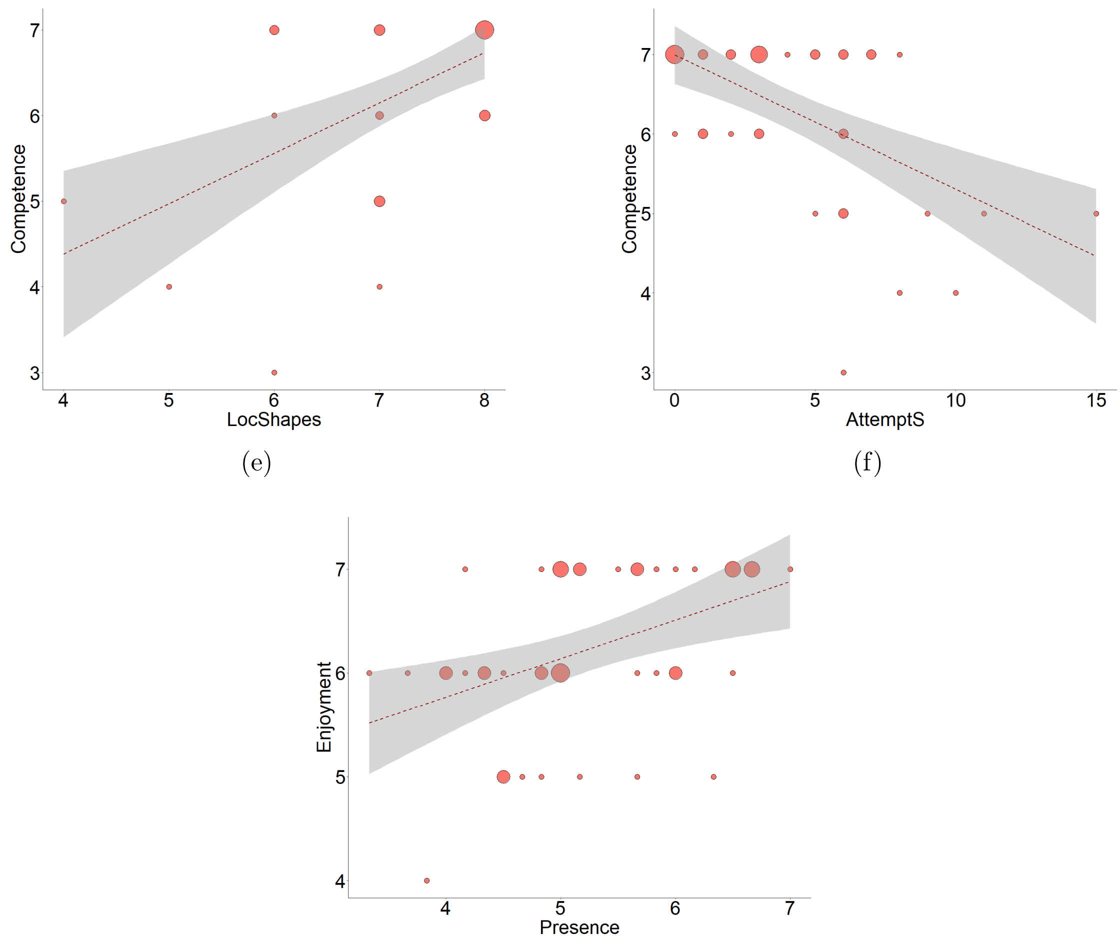


Figure 4.9: Scatter plots for significant correlations for the visual condition (n = 47). (a) Scatter plot for the total number of shapes placed correctly (LocShapes variable) and the score obtained in the map-pointing task (MapShapes variable). (b) Scatter plot for the total number of attempts to place the shapes correctly (AttemptS variable) and the score obtained in the map-pointing task (MapShapes variable). (c) Scatter plot for the total number of shapes placed correctly (LocShapes variable) and the time spent in the evaluation phase (TTimeE). (d) Scatter plot for the total number of attempts to place the shapes correctly (AttemptS variable) and the time spent in the evaluation phase (TTimeE).

If we apply the Bonferroni correction to the matrix formed by the ten subjective variables, there is only a significant correlation that corresponds to the enjoyment and presence variables ($r = .47$, $p = .04$). This means that participants who experienced more enjoyment reported a higher sense of presence. Figure 4.9g shows this correlation graphically.



(e) (f)

(g)

Figure 4.9: (e) Scatter plot for the total number of shapes placed correctly (LocShapes variable) and the perceived competence variable. (f) Scatter plot for the total number of attempts to place the shapes correctly (AttemptS variable) and the perceived competence variable. (g) Scatter plot for the presence and enjoyment variables. Three sizes of circles appear in the plots that represent a low number of occurrences, an intermediate number of occurrences, and a high number of occurrences. The dashed red lines are best fitting linear regression lines. In panels C, D and G close values were grouped for clearer visualization. The grey area represents a 95% confidence level interval for predictions from a linear model.

4.7 Discussion

In studies related to working or short-term spatial memory, mainly visual or auditory modalities have been considered (Juan et al., 2014; Rodríguez-Andrés et al., 2016; Mendez-Lopez et al., 2016; Valencia et al., 2019). In this work, we contribute with a study in which the tactile modality is considered. To our knowledge, this is the first study in which tactile stimuli are used for the assessment of short-term spatial memory for shape-location in a three-dimensional array. In our study, the participants navigated the environment to learn the spatial location of each tactile stimulus.

There are substantial differences in terms of the studies carried out in our previous AR works and the study presented in this paper. In the study of Munoz-Montoya et al. (2019b), only four objects were used and the participants were divided into two groups in which the learning phase was different (AR vs. Non-AR). The participants who used AR learned the placement of the virtual elements in the real world using AR. The participants who used Non-AR learned the location of the virtual elements through photographs. The augmented photographs showed the real environment with the virtual objects superimposed on it. In the study of Munoz-Montoya et al. (2019b), eight virtual objects were used (horse, wall clock, telephone, toy car, bust, fountain pen, sailboat, and screwdriver). The objects were distributed in a building on two different floors. That study analyzed the correlations between the results of the performance outcomes with the AR app taking into account gender and different measures of emotional and spatial factors. These measures were the levels of trait anxiety, wayfinding anxiety, and different spatial strategies for wayfinding.

From our results, there was no significant difference for the number of shapes placed correctly between the two conditions (visual vs. tactile). However, the participants in the visual condition required significantly less time to complete the evaluation phase and also required significantly fewer attempts. There was a significant difference in the number of shapes that the participants placed correctly in the map-pointing task after performing the task in favour of the visual condition. There was no significant difference for the shape-recognition test, which represents the number of shapes that the participants remember after performing the task between the two conditions (visual vs. tactile). However, the variable that represents the number of shapes that the participants selected incorrectly showed that the participants in the visual condition selected fewer incorrect shapes. From all of these results, we can conclude that visual and tactile stimuli can be used to assess spatial memory and that visual stimuli positively affects short-term, spatial memory outcomes. This supports previous research stating that the sense of sight is the dominant sense in humans, and, consequently, this dominance facilitates the learning of spatial-visual associations (Cattaneo et al., 2008; Papadopoulos & Koustriava, 2011). Our results also indicate that visual and tactile stimuli are suitable for the assessment of spatial memory in navigation regardless of the gender of the participants. These results are in line with previous works (Juan et al., 2014).

The following correlations were identified between the total number of shapes correctly remembered and located using visual and tactile stimuli (LocShapes) and the total number of shapes correctly placed in the pointing-map task (MapShapes). For the Visual Condition, LocShapes correlated with MapShapes. This result shows that spatial-visual associations were learned and transferred from the three-dimensional array of the real room to the bi-dimensional array of the map. In contrast, spatial-tactile associations were learned, but failed to achieve this transfer. These results are in line with previous works, in which the memory for the location of virtual objects in the visual modality in a navigational space correlated positively with the pointing of these objects on a map (Munoz-Montoya et al., 2019b).

We also studied the correlations between the subjective perception and the performance measures of the participants for the AR spatial task (Visual Condition). The total number of shapes (LocShapes) correlated with perceived competence, which indicates that the greater the number of correctly placed shapes, the greater the perceived competence. The AttemptS variable (attempts required for placing the shapes) correlated negatively with perceived competence. This correlation indicates that the more attempts required, the less competence was perceived.

For the AR application, the subjective perception of the participants was independent of their gender. On a scale from 1 to 7, the medians were very high: equal to or above 6 in all cases (except for one with a value of 5.3). The correlations among the subjective variables were analyzed for the whole sample, and thirteen positive correlations were found. It is worth highlighting that the sense of presence correlated with the enjoyment variable. The participants that reported a higher sense of presence also experienced more enjoyment.

The developed framework allows different AR engines/SDKs to be used. For example, these different AR engines could be ARCore or ARKit, which are wrapped in a module with the same interface offering, and therefore have the same functionalities. This design allows the rest of the application to be independent of specific AR SDKs. To take into account that different AR engines may have different functionalities, we have defined a set of basic functionalities. Another set of optional functionalities was also defined, which can be activated or deactivated depending on the engine used. We have tried to minimize this last set of functionalities so that the impact on the rest of the application code is minimized. At this time, the Tango SDK could be changed for another equivalent engine without altering the application code. Until the release of ARKit 3.5 in March 2020, neither ARKit nor ARCore offered enough functionalities to afford the development of applications like the one presented in this work. ARKit 3.5 incorporates the possibility of using the new LiDAR scanner and depth-sensing system that are built into the iPad Pro. Thanks to these new sensors, it is possible to use the geometry of the scene, just as is done with Tango SDK. Therefore, applications such as those presented in this work can be created by using ARKit in supported devices. Tango SDK has been deprecated since March, 2018. Since then, with the discontinuation of compatible devices on the market (Lenovo Phab 2 Pro and ASUS Zenfone AR), there has been a gap that was not covered. Therefore, the appearance of the iPad Pro is especially relevant because it opens up many possibilities for developers.

Our proposal and other similar tools can greatly help in training short-term spatial memory. Difficulties in spatial memory are usually associated to disorders or diseases (e.g., Koen et al. (2016); Hampstead et al. (2011)). For example, several studies have reported that hippocampal damage may provoke impairments in short-term memory (e.g., Koen et al. (2016)). Patients with amnestic mild cognitive impairment have difficulty remembering where the objects are located (e.g., Hampstead et al. (2011)). In an ongoing work, patients with acquired brain injury perform a task with visual stimuli with our AR application. From the preliminary results, we have observed that these patients can perform the task with the AR application. Therefore, our AR application could be used as a help tool for groups with impairments in short-term memory.

This work studies the differences in seeing and touching objects and recognizing their shapes by touch. To our knowledge, no work has been presented in which a haptic system allows the recording of user responses related to a navigational task for the learning of spatial-tactile associations. However, different commercial haptic devices or prototypes developed by researchers have been presented for their use in VR and help users to have a higher level of presence. Wang et al. (2019) classified the paradigm of haptic HCI into three stages (desktop haptics, surface haptics, and wearable haptics). They presented a taxonomy of desktop haptic devices and also a classification of tactile feedback devices. One of the most widely used wearable haptic devices are haptic gloves. These gloves can include hand motion tracking and provide distributed force and tactile feedback in the palm and in the fingertips. They compared 10 existing commercial haptic feedback gloves. Existing commercial VR controllers (e.g., HTC Vive) only provide global vibrotactile feedback, which greatly limits the haptic experience. The existing haptic technology does not allow a user to touch a virtual object and recognize its shape. An open challenge is how to efficiently include localized and diverse spatial-temporal vibrotactile patterns, thermal feedback, texture feedback, contact, softness, skin tightening, etc. in a haptic device (Wang et al., 2019). In the study carried out in this work, the participants touched real objects, and the use of haptic devices is proposed as future work.

We built a haptic test battery to assess tactile abilities. We used this battery as an inclusion criterion in order to assure that the participants involved in our study had similar tactile abilities. We checked whether or not there were differences in the haptic test battery (plastic and swell paper) and for gender. The results indicated that the haptic test battery was independent of the participants' gender.

We developed applications for the tasks and tests that are traditionally done on paper. Specifically, we developed the shape-recognition application, the map-pointing-application, and the PTSOT application. The supervisor's work is facilitated by being able to perform these tasks or tests on the computer. The applications themselves control the times and also store successes and errors. The applications are particularly useful in making precise calculations (e.g., the angles for the PTSOT test). One of the advantages of using software tools is that the process of data analysis is facilitated (Heintz et al., 2018). In a paper-based approach, the data must be digitized for analysis, which can be time consuming depending on the amount of data to be digitized. When using software tools, the data only has to be exported to spreadsheets. While the paper-based approach can take hours, using software tools is a matter of minutes. Our applications automatically create the spreadsheets. Other authors have argued that the replacement of traditional paper-based neuropsychological tests by computerized neuropsychological tests offers other advantages since the traditional tests are expensive and time consuming (Zhang & Feinstein, 2016). It might be interesting to complement the information about the recognition memory task with a free-recall task. However, in our case, we used geometrical shapes and many participants would have had problems correctly describing the eight shapes they had to memorize. Therefore, we decided to evaluate the ability of the users to identify the eight memorized shapes with a recognition task involving seven additional shapes in order to monitor the strength of the memory formed about the shapes.

A limitation of our study is that the two sessions were carried out in the same order (first the tactile and then the visual). The design of our study could have influenced the better performance in the vision session due to participants remembering shape locations from the previous session. Nevertheless, we would like to highlight that the participants carried out the second session more than two months later, the type of objects used were not remarkable to induce a long-term memory, and the room in which the study was carried out was not familiar to the participants. These three aspects lead us to argue that it would be very difficult for a participant to remember the specific location of a certain geometric shape in the room. However, this limitation could have been removed if the order of the sessions were counterbalanced.

4.8 Conclusions

This paper introduces the architecture of our framework for the development of SLAM-based AR applications. Our framework allows the use of different AR engines/SDKs and allows the development of applications that do not depend on these engines/SDKs. An AR application for the assessment of short-term spatial memory was developed. Our application works in any indoor environment and can even be used in several rooms or on several floors of the same building. The supervisor can configure the environment and include as many virtual shapes as desired and place the shapes in any position of a real space.

For the first time, we have carried out a study in which tactile stimuli are used for the assessment of short-term spatial memory in a navigational space. A SLAM-based AR application was used to compare visual and tactile stimuli. From the results, we can conclude that visual and tactile stimuli can be used to assess spatial memory. The number of shapes placed correctly was similar for both conditions. The tactile condition required more time and more attempts to complete the task. The performance outcomes were independent of gender, but a tendency of women requiring fewer attempts than men was found for the tactile condition. Therefore, the tactile stimuli are stimuli that can be used to assess the ability to memorize spatial-tactile associations. However, more research is needed to further investigate how the sense of touch and other sensory modalities (excluding visual and auditory) can be used to assess spatial memory and identify the groups that can benefit from them.

Chapter 5

Discussion

This chapter discusses the main contributions of this thesis. Each of the three publications included in this thesis has its own discussion section, which completes the discussion presented in this section.

5.1 Discussion

This thesis is part of the AR3Senses project (TIN2017-87044-R) and the Generalitat Valenciana grant (ACIF/2019/031). As mentioned in the introduction section, in this thesis and in AR3Senses new indoor location techniques were developed in the field of SLAM-based AR to assess spatial memory. The main contribution of this thesis and AR3Senses is the use of SLAM-based AR for spatial memory assessment. All applications developed in AR3Senses include physical movement of the user in real space, including the applications developed in this thesis. In previous works by the research group, the stimuli received by the user were either visual (Cárdenas-Delgado et al., 2017; Juan et al., 2014; Mendez-Lopez et al., 2016; Rodriguez-Andres et al., 2018; Rodríguez-Andrés et al., 2016) or auditory (Juan et al., 2022b; Loachamin Valencia et al., 2019). Furthermore, traditional methods consider each sense (e. g., visual, auditory) separately (Brancal, 2009; Reynolds et al., 2012). However, this thesis explores the sense of touch for the assessment of spatial memory.

XR has experienced considerable growth in recent years thanks to the emergence of both hardware (e.g., Microsoft HoloLens 1 and 2, LiDAR-enabled mobile devices (e.g., iPad Pro, iPhone 12, 13, or 14 Pro)) and software (e.g., Tango SDK, ARKit, ARCore) with enough power to create applications unimaginable 5 years ago. All these advances have enabled the developments of this thesis, which is the first work using SLAM-based AR for spatial memory assessment.

The framework that has been developed allows to use different AR engines or SDKs (e.g., Tango SDK, ARCore or ARKit). There are different interfaces incorporated in the framework through which the different AR modules can be connected. This enables a modular and independent use of the AR engine for developers. This technology works similarly to ARFoundation which works with different plug-in packages supported by Unity for each AR platform: Apple ARKit XR plug-in on iOS, Google ARCore XR plug-in on

Android and OpenXR plug-in on HoloLens. Our design allows the rest of the application to be independent of specific AR engines/SDKs. As different AR SDKs/engines may have different functionalities, we have implemented a module with basic functionalities which is common to all engines. Additionally, another set of optional modules with extra features was also implemented, which can be enabled or disabled depending on the engine to be used. In the authoring applications developed so far, Tango SDK could be replaced by another equivalent SDK or engine without modifying the code of the application.

Neither ARCore nor ARKit offered enough functionality to allow the development of applications like the one presented in this thesis until ARKit 3.5 was released in March 2020. ARKit 3.5 introduced the use of the LiDAR scanner that is built into the iPad Pro, and later in iPhone 12 Pro, iPhone 13 Pro, and iPhone 14 Pro. These sensors allow to work with the geometry of the environment, just like the Tango SDK. Therefore, the authoring applications created in this thesis could also be developed using the framework and this new ARKit technology with a compatible device. In March 2018 Tango SDK was deprecated. From that moment, devices that worked with Tango SDK (ASUS Zenfone AR and Lenovo Phab 2 Pro) were no longer manufactured, which created a gap in this area covered by the release of the iPad Pro. In addition, the appearance of this device and the successors iPhone 12 Pro, iPhone 13 Pro and iPhone 14 Pro was especially relevant because it opened up many possibilities for the development of different types of applications.

To date, few works have explored the potential of AR for spatial memory assessment, being the research group in which the present thesis is framed the one that has presented most of these works (Juan et al., 2014; Mendez-Lopez et al., 2016). The main difference is that those works (Juan et al., 2014; Mendez-Lopez et al., 2016) use AR based on image targets, which must be physically placed in the real world. The inclusion of such image targets makes the environment no longer as natural as it could be without such inclusion. Therefore, our proposal is less intrusive than previous work.

Physical movement is an important aspect to consider for spatial ability (Ruddle & Lessels, 2009). Such movement allows tasks to be similar to those of daily life. Physical movement is important as previous applications of AR (Juan et al., 2014; Mendez-Lopez et al., 2016) or VR (Cárdenas-Delgado et al., 2017; Rodriguez-Andres et al., 2018; Rodríguez-Andrés et al., 2016) have shown.

This thesis also includes physical movement, which, moreover, can be in any selected environment, allowing the location tasks to be similar to those of daily life.

For validation, three studies were conducted with healthy adults. The first study used visual stimuli in a small environment. A total of 55 users (36.53 ± 15.78) participated and were divided into two groups, one group in which participants memorized the location of virtual objects in the real environment in a memorization phase using AR and a second group in which participants memorized the location of objects by looking at photographs of the augmented environment using the device. The second study used visual stimuli in a large environment (a two-story building). A total of 46 young adults (24.65 ± 8.54 years) participated in this study in which participants had to memorize the position of a total of eight virtual objects while they were walking through a two-story building, traditional tests were administered for verbal recall of information (verbal enumeration of objects seen), spatial orientation and perspective taking exercises on paper (from the revised version of the test Perspective Taking/Spatial Orientation Test (PTSOT), Hegarty (2004)), and map interpretation (placing the objects seen on a paper map of the two floors of the building) and trait anxiety levels were measured with the Spanish version (Guillén-Riquelme & Buela-Casal, 2011) of the Trait Anxiety Inventory (STAI-T, Spielberger et al., 1970). The third study used visual and tactile stimuli in a small environment. A total of 53 subjects participated, to whom the exclusion criterion was applied and the final sample studied was 47 subjects. The participants performed the task with the AR application and traditional tests (placing the stimuli on a map) were also administered. The general conclusions of these three studies are discussed below and are complemented by the enumeration of general conclusions in the Conclusions section. Specific conclusions from each of the three studies are listed in the Conclusions section.

Regarding object location, the applications developed in this thesis have proven to be effective for memorizing and placing objects in remembered locations, regardless of the stimulus used (visual or tactile) or gender. Moreover, they work in any environment (small and large environment) and without the need to add real elements to the environment for registration. The developed applications allow an assessment of spatial memory with great ecological validity. Ecological validity can be defined as the "functional and predictive relationship between the participant's performance on a set of neuropsychological tests and the participant's performance in a variety of real-world environments" (Spooner & Pachana, 2006). The environments are real-world settings. They could be the participant's own home, a hospital ward, or any other place familiar to the participant. All of this corroborates the hypothesis GH1.

Correlations were found between our task using visual stimuli and traditional methods in studies 2 and 3 (study 1 did not use traditional methods), showing that our task has demonstrated to be a valid tool for the assessment of spatial memory, which corroborates hypothesis GH3. Specifically, correlations were found in studies 2 and 3 between the task that used visual stimuli and placement of memorized objects on a physical map. In study 3, no significant correlations were found between the task and traditional methods when tactile stimuli were used. The significant correlations when using visual stimuli are in line with results obtained in previous work to assess spatial memory that also obtained correlations between AR/VR tasks and traditional methods (Cárdenas-Delgado et al., 2017; Juan et al., 2014; Mendez-Lopez et al., 2016; Rodríguez-Andrés et al., 2016).

Regarding the subjective variables when using AR applications in studies 1 and 3 (variables not analyzed in study 2), participants rated them positively with respect to: motivation, fun, ease of use, and satisfaction. Both groups of participants in study 1 rated their experience with the application positively (averages greater than 6 on a scale of 1 to 7). The participants of Study 3 also rated their experience with the application positively, with values equal to or greater than 6 (on a scale of 1 to 7) in all cases (except one, with a value of 5.3). These results corroborate hypothesis GH2.

The sense of touch is a sense to explore for assessing spatial memory. To our knowledge, visual stimuli (Cárdenas-Delgado et al., 2017; Juan et al., 2014; Mendez-Lopez et al., 2016;

Rodriguez-Andres et al., 2018; Rodríguez-Andrés et al., 2016) or auditory stimuli (Juan et al., 2022b; Loachamin Valencia et al., 2019) have been used to date for that purpose, but not tactile. The dominant sense in humans is the sense of sight and such domain facilitates the learning of visuospatial associations (Cattaneo et al., 2008; Papadopoulos & Koustriava, 2011). Nevertheless, the human brain is capable of storing information from all sensory modalities (Schmidt & Blankenburg, 2018). In this thesis, the sense of touch is explored and tactile stimuli are combined with real and visual cues for spatial memory assessment.. From the third study, it is concluded that tactile stimuli are valid stimuli for the assessment of the memorization of tactile-spatial associations, but the memorization of visual-spatial associations is dominant.

Chapter 6

Conclusions

This chapter summarizes the main contributions of this thesis and proposes some future work.

6.1 Conclusions

New indoor location techniques have been developed in the field of SLAM-based AR, validated through the construction of a framework and applications oriented to the assessment of spatial location ability in adults; and perceptual augmentation in the visual and tactile channels has been studied. The tasks included physical movement by the user to perform them. The task supervisor can configure the environment by adding the number of virtual objects desired, as well as their location, and store as many configurations as desired for use with participants. When a user goes to perform a task, the supervisor selects the desired configuration. The application stores all performance variables for later analysis.

In this thesis, three studies were carried out that focused on studying the feasibility of using the applications in small and large environments, as well as the use of visual and tactile stimuli. Traditional methods were also used (in studies 2 and 3) to assess memory skills for comparison. Similarly, subjective variables such as usability, fun, or general satisfaction were assessed. In addition, to our knowledge, this is the first work using SLAM-based AR for the assessment of spatial memory, with physical movement by the user, and considering visual and tactile stimuli. The applications developed in this thesis and other similar tools can be used for spatial memory assessment as well as for training.

The conclusions of the three studies are described below:

Study 1: Visual stimulus and environments of small dimensions.

- The performance results regarding object location for the participants in the AR group were significantly higher than those obtained by the participants using photographs in the memorization phase (Hypothesis H1 corroborated).

- No statistically significant differences were found for performance and considering gender or age (Hypothesis H2 corroborated).
- Walking through the augmented environment helped users better remember the locations of virtual objects added to the real world compared to looking at photographs of the augmented environment.
- Both groups of participants rated their experience with the application positively (means greater than 6 on a scale of 1 to 7). No significant differences were found in the variables analyzed, except for satisfaction and presence in favor of the AR group, and mental effort in favor of the group that memorized the location of objects by looking at photographs.

Study 2: Visual stimulus and large environments.

- The application worked without any problems in a two-story building (Hypothesis H3 corroborated).
- There were no significant differences between women and men, in the performance outcomes of the AR task for the location of objects (i.e., errors and objects located), on the recall task or the map-pointing task.
- Men performed significantly better on the pencil-and-paper spatial test (PTSOT) and spent significantly more time to complete the AR learning phase.
- A positive correlation was obtained between spatial memory for the location of objects on the map and in AR.
- Trait anxiety was positively correlated to the time spent by the participants during the AR learning phase, while wayfinding anxiety was negatively correlated with the preference for directional cues for orientation (i.e., orientation strategy). Results that highlight the importance of anxiety in spatial orientation (Hypothesis H4 corroborated).

Study 3: Visual versus tactile stimuli, and environment of small dimensions.

- No statistically significant differences were found in the number of correctly placed shapes for both stimuli (visual versus tactile).
- The group that used the tactile stimulus required significantly more time to complete the assessment task and required significantly more attempts (Hypothesis H6 corroborated).
- After completing the AR task, there were significant differences in the number of shapes that participants placed correctly on the map-pointing task in favor of the

visual condition. No significant differences were found for the shape recognition test between visual and tactile conditions. The variable indicating the number of shapes that subjects incorrectly selected revealed that participants when using the visual stimulus selected fewer incorrect shapes.

- The performance results when using both stimuli were independent of gender (Hypothesis H7 corroborated).

- For the visual stimulus, a correlation was found between the number of shapes that were correctly placed using the AR application and their placement on a map, as well as between the number of attempts and their placement on a map. Results showed that participants who required more attempts to place the shapes correctly or placed fewer shapes correctly during the testing phase also made more errors on the map-pointing task.

- Significant correlations were found between performance outcomes variables using visual stimuli and subjective variables: 1) perceived enjoyment is greater when a greater sense of presence is induced; 2) the more attempts required, the lower the perceived competence; 3) the greater the number of correctly placed shapes, the greater the perceived competence.

- Tactile stimuli are valid stimuli for assessing the memorization of spatial-tactile associations, but the memorization of spatial-visual associations is dominant (Hypothesis H5 corroborated).

From the developments and the studies conducted, the following general conclusions are presented:

- SLAM-based AR is suitable for developing spatial memory assessment tasks, working in any environment and without the need to add real elements to the environment for registration.

- The applications developed in this thesis allow task customization and storage of performance variables.

- These applications have allowed an ecological assessment.

- These applications and similar tools could be used to assess and train spatial memory as an alternative to traditional methods.

- Tactile stimuli are valid stimuli that can benefit the assessment of memory of tactile-spatial associations, but memory of visual-spatial associations is dominant.

- The applications developed in this thesis and similar tools could help in the diagnosis of spatial memory impairments, including different types of dementia with disorders of orientation, stroke, traumatic brain injury survivors, and others.

6.2 Future works

This thesis can serve as a basis for the development of new tools for spatial memory assessment. For example, using hardware with higher performance than the one used in this thesis (e. g., HoloLens 2, Meta Quest Pro).

The sense of touch has been explored in this thesis, but further research is required to better understand how this sense and other sensory modalities (e.g., smell) could be exploited to assess spatial memory and identify which groups could benefit.

Although emotional factors have been studied in this thesis, more research is needed to better understand how other emotional factors, including motivational or personality traits, can affect spatial orientation.

In this thesis, only healthy participants were involved, but the applications could be used in groups with spatial memory problems, for example, patients with long-COVID syndrome, patients with acquired brain injury or other groups with spatial memory problems, both for assessment and training.

6.3 Scientific contributions

The publications derived from this thesis are the following:

6.3.1 Papers in journals indexed in JCR

- Munoz-Montoya, F., Juan, M.-C., Mendez-Lopez, M., & Fidalgo, C. (2019b). Augmented reality based on SLAM to assess spatial short-term memory. IEEE Access, 7, 2453– 2466. https://doi.org/10.1109/access.2018.2886627

- Munoz-Montoya, F., Fidalgo, C., Juan, M.-C., & Mendez-Lopez, M. (2019a). Memory for object location in augmented reality: The role of gender and the relationship among spatial and anxiety outcomes. Frontiers in Human Neuroscience, 13, 113. https://doi.org/10.3389/fnhum.2019.00113

- Munoz-Montoya, F., Juan, M.-C., Mendez-Lopez, M., Molla, R., Abad, F., & Fidalgo, C. (2021). Slam-based augmented reality for the assessment of short-term spatial memory. a comparative study of visual versus tactile stimuli. PLOS ONE, 16(2), 1–30. https://doi.org/10.1371/journal.pone.0245976

6.3.2 Other conferences

- Munoz-Montoya, F. (2017) SLAM and its possibilities for spatial orientation, IV Conference on Industrial Applications of Research.

- Munoz-Montoya, F. (2018) Augmented Reality as a Tool to Assess Spatial Ability, XIII National Congress of Psychology Students.

6.4 Other diffusions

- Munoz-Montoya, F. (2018) Augmented reality and its applicability for indoor positioning, V PhD Students Meeting (UPV).

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