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Development and Evaluation of an Outdoor Multisensory AR System for Cultural Heritage

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ABSTRACT Enhancing tourist visits to cultural heritage sites by making use of mobile augmented reality has been a tendency in the last few years, presenting mainly audiovisual experiences. However, these explorations using only visuals and sounds, or narratives, do not allow users to be presented with, for example, a particular smell that can be important to feel engaged or to better understand the history of the site. This article pursues the goal of creating an experience that puts the user in a scene planned to evoke several stimuli with SensiMAR prototype – a Multisensory Augmented Reality system that aims to be used in cultural heritage outdoors. When using SensiMAR, the user will be involved with visual reconstructions, surrounded by the soundscape of ancient times, and is exposed to a particular smell very common that time. Given the novelty of this proposal, ascertaining the usability of such a system was raised as a foremost demand. Thus, in addition to its development and implementation specifications, an experimental study was conducted to evaluate the usability of the system in end-users' perspective. The results obtained from random visitors of an archaeological site were analysed according to their sex, age, previous experience with augmented reality technology, and provided condition – audiovisual condition, and multisensory condition, with visual, audio, and smell stimuli. Results were collected from a total of 67 participants and show that this multisensory prototype achieved good usability results across all groups. No statistically differences were found, demonstrating good usability of the SensiMAR system regardless of their sex, age, previous experience with the technology or provided condition.

INDEX TERMS Mobile augmented reality, multisensory in cultural heritage, usability of multisensory AR outdoors.

I. INTRODUCTION

Literature supports the use of augmented reality (AR) for enhancing visitors' experiences in cultural heritage (CH) contexts for multifarious reasons. It has been demonstrated to evoke feelings of pleasure and arousal [1], to promote cultural heritage [2], to increase multicultural place meaning and openness to other cultures and traditions [3], to enable enjoyable informal learning [4] and, in addition to these social, epistemic and educational values, many other benefits came across such as economic, experiential, cultural and historical value [5]. Among the diverse AR solutions proposed and implemented in CH contexts, many of them are found as being mobile approaches, such as in urban heritage for tourism in Dublin, Ireland [6]; in travel guides like in Corfu, Greece [1], or in Brno, Czech Republic [7]; in museums, as in Deoksugung Palace, South Korea [8], or as in Cornwall, UK [9]; or in outdoors ruins such as in Knossos, Greece [10], or as in Conimbriga, Portugal [11]. The conducted researches reveal good feedback from the users' perspective, being recognized as an excellent solution to use with a positive impact to users [12].

Multisensory systems, as being solutions that evoke more than visual or audiovisual stimuli on users, have also been

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stated as valuable in CH for their contributions in users' satisfaction [13]–[16], in interpretation improvements on the heritage topic [17] or in the engagement with the experience [16], [17]. These benefits, known and supported by literature mainly found with virtual reality (VR) technologies, are valuable contributions for further implementations in CH sites, providing interesting insights regarding several fields of interest, in particular, when dealing with a novel approach, regarding usability and satisfaction of their systems close to end-users.

While analysing previous work, it was observed that, when evaluating multisensory systems, the literature provides results mainly obtained in environments relatively controlled by selecting participants or by being tested with expert users [13]–[16], [18], [19]. As mentioned in a previous survey regarding virtual museums [20], we reinforce the need for more evaluation studies involving end-users in order to better understand further implementations, especially, considering that typical users of these technological conditions among CH are non-experienced and non-trained people, who aim to find meaningful and pleasant experiences in a very limited amount of time, precluding them from having slow learning curves [21].

Hence, one must obtain results from end-users as this sample will better represent the population of the target users: visitors of cultural heritage sites. When developing such AR applications for CH, there are several usability issues to have into account. For instance, an usability issue that may occur during end-users' experiences is related to the tracking, since it is required to explore the surroundings slowly in order to keep the position of the virtual elements accurate to the real scene. The speed of exploring the environment differs on each user's willingness and their ability to detect if they are moving too fast or not, by observing the virtual positioning when exploring, which might lead to less accurate experiences for less skilled users.

Due to these uncertainties, the current research aims to ascertain that the addition of more stimuli to an AR experience, in particular, audio and smell, does not affect the usability and satisfaction of the user when exploring a CH site, even when the added smell is an unpleasant smell – a fish market smell. Accordingly, we firstly conducted a background research and, to support the development of a prototype, we performed an acceptance of technology study across several archaeological sites and across online platforms to better understand the behavioural intention to use AR in these sites. Then, the system requirements were established, the case study to implement SensiMAR was selected and regular meetings were carried out with the director and the archaeologist of the museum, allowing to select the needed historical data for the prototype deployment. Following a novel theoretical proposal that combines AR with multisensory [22], a mobile AR application was developed, sounds and smells were added to enhance the multisensory experience. Following a in-between subjects experience design, random visitors from the selected archaeological site, namely Conimbriga Ruins, part of the Monographic Museum of Conimbriga-National Museum – an ancient Portuguese Roman city –, were invited to test the application *in loco* and to fill-in a questionnaire in order to perceive their satisfaction with the usability of the system. To ascertain and compare the usability of the multisensory approach, two groups of participants were evaluated: one group that tested a audiovisual condition; another that tested the multisensory condition (visual + audio + smell). This evaluation is of paramount importance in order to verify any usability issues before further evaluations of the prototype being performed, namely the impact of the different stimulus on the user experience. For analysing the results, participants were also grouped according to their sex, age, and their previous experience with AR technology.

The added value of this research is remarkable since very little is known about AR and multisensory implementations. Also spotted as a lack of knowledge relates to the fact that previous multisensory systems found in literature, presented mainly solutions to be used indoors, remaining unclear the understanding of outdoor multisensory approaches, where the usability from end-user's perceptive when experiencing it outdoors remains unclear. Proper attention must be dedicated to open-air scenarios, whereas some factors may interfere with the quality of the experience, as the environment is not controlled, and users shall use the implemented system in different possible conditions that can vary from one experience to another – for example, if the weather has changed. Sunlight is one of the uncontrolled conditions often pointed out as a factor that may hamper the experience and users' satisfaction when viewing the virtual content under the sun [10], [11]; also the wind can affect other stimuli perception, as the sound, the smell, or the touch; or the temperature that, in addition to affect the touch feeling, influences the intensity of the smell [23].

In addition to the usability and satisfaction insights for further multisensory experiences for outdoor CH sites, these results allow to implement an AR multisensory system to be tested *in situ* and to evaluate it deeply, to explore more insights related to end-users' feelings and the impact of adding stimuli in AR experiences across cultural sites. The relevance given in the current study to different groups of participants organized by sex, by age groups – taking into consideration generations –, and by their previous experience with AR technology, in the conducted usability evaluations, allows to support and understand how different individual characterises could influence, or not, the usability perceived by participants.

II. BACKGROUND

A literature research was made to follow-up how multisensory applications are being implemented and evaluated in CH contexts. Following the goal of the current research, for developing and evaluating usability of AR multisensory implementation in CH, some insights on acceptance of technology and usability are outlined.

A. MULTISENSORY SYSTEMS IN CH

Despite the earlier appearance in the '60s of a multisensory system with the Sensorama simulator – a system capable of displaying 3D stereoscopic images, reproducing stereo sound, simulating wind, and delivering aromas [24] – this multisensory approach was not widely adopted.

A literature review was conducted focused on multisensory applications in CH, with VR and/or AR, among the last decades. Most common multisensory applications are indoor and based on VR [19], [25]–[27], but some interesting AR installations alluding to multisensory experiences are found, such as the "Multisensory Art Gallery", at the Tate Britain art gallery in London, United Kingdom [28], the "Refugi 307" bomb shelter, from the Spanish Civil War [29], and the mobile multisensory AR project M5SAR in Faro, Portugal [30].

The literature review reveals that monitors were the most frequent device used for visual stimulus. These devices were used in The Haptic Museum [31], in The Fire and the Mountain [14], in The Gold Museum in Bogotá [15], in the Museu3I [32] and in the National Archaeological Museum of Marche [19]. More immersive approaches such as CAVE systems (a small room where at least three walls act as huge screens) and HMD (head-mounted display) devices also emerged, for instance in Museum of Pure-Form [33], the CREATE project [34], and in the Gion Festival in Kyoto [35], using CAVES; and The Feelies [36], the Interactive Haptic System for Archery [16] or the Tanning in Medieval Coventry [26], using HMDs. We may notice that the Zelige Door on Golborne Road [37] and the M5SAR project [30] were the only studies detected, so far, which had used mobile devices for providing visual exploration in multisensory applications in CH.

For audio delivery, speakers were the most common approach for this type of applications, being identified in cases such as The Museum of Pure-Form [33], the CREATE project [34], the Gion Festival in Kyoto [35], or the in the Gold Museum in Bogotá [15]. Experiences which aimed to provide a more individual experience, such as the Tate Sensorium [28], or The Feelies [36], used headphones for the audio experience.

When diffusing smell, the few examples detected presented olfactory displays developed by their own, as found in the Emotion Organ [38], in the Zelige Door on Golborne Road [37] or in the M5SAR project [30]; perfumes were also used, which was the case of the Tate Sensorium [28] and The Feelies [36]; or, in a more technological approach, a Computational Fluid Dynamic (CFD), was used in the Tanning in Medieval Coventry [26].

Haptic sensations are being provided mainly through the use of haptic interfaces, like the Gion Festival in Kyoto [35], the Gold Museum in Bogotá [15], the Museu3I [32], and the Tate Sensorium [28]; fans and heaters are also a frequent approach, such as provided in The Feelies [36], in the tanning in Medieval Coventry [26], and in the M5SAR project [30].

Results coming from these analysed experiences are stated as being very positive, both, multisensory AR and multisensory VR approaches, being projected as technologies to have potential to be one of the most engaging experiences, regarding the use of technology in CH.

1) MULTISENSORY EVALUATIONS

Across the several multisensory implementations found in the literature, some carried out usability tests such as the CREATE project [34], the Museum of Pure-Form [18], the Fire and the Mountain [14], the Gold Museum in Bogotá [15], the National Archaeological Museum of Marche [19], and the Interactive Haptic System for Archery [16].

These evaluations were all conducted indoors, in more or less controlled environments – museums [13]–[15], [19] or in laboratory [16], [18] – not being discerned any outdoors evaluations for multisensory systems. Only in a few cases, the participants are found to be random visitors from the CH site from where the system was targeted for, such as the 62 young visitants in The Fire and the Mountain museum [14], the 46 adult inexperienced and experienced users, and young novice users in the CREATE project [13], and an unspecified number of observations performed over a period of 20 days at the Gold Museum in Bogotá [15]. The remaining cases were expert users or selected participants who tested the system.

General conclusions related to usability and satisfaction were obtained through usability concerns [13], [18], [39], where the main findings pointed out usability issues, such as the system being suggested to be improved regarding comfort issues [18], or for being too heavy [16]. In some multisensory approaches, users expressed feelings described as scary and invasive (referring to taste stimulus) [28]. Although users expressed their satisfaction, such as in [13], [15], [40], it was proved that these systems are still far to be used with non-experts users [13] and these studies do not present a comparison between the use of the multisensory system and the use of a conventional visual or audiovisual approach.

According to each case, as noticed in the previous section, multisensory implementations are very distinct from each other, depending on the devices used for each stimulus, leading to a wide range of methodologies, and, consequently, to some diversity of evaluation procedures as well. These evaluations were carried out with sample sizes from 6 participants [18] to 123 [15], having as tools questionnaires, direct observation, and informal interviews. Despite the fact that it was not identified any standard for usability evaluations across multisensory implementations, they presented usability understandings, valuable for similar further VR multisensory implementation indoors. Some of their insights were related to navigation efficiency [39], successfully adaptability to the developed system [16], and good usability during the interaction with the system [41]. Some limitations raised in literature are related to expectation of more satisfactory haptic interaction [18], the need for more usable, easy to learn, and efficient systems [13], some discomfort [16], and the need for evaluating these systems with non-expert users and in real-world context [13], [21].

Although some AR multisensory systems were found in the literature research [28]–[30], the usability and satisfaction of these systems are still evinced as a concern for future multisensory AR implementations. Furthermore, even considering AR strongly linked to VR as some authors suggest [42], none of the evaluated systems in VR environments supplied useful data for outdoors experiences, and it is important to understand how usability and satisfaction are perceived from an end-user's point of view. An outdoor environment lays participants in some uncontrolled conditions, which is not an issue in indoors scenarios, a remark that can interfere with the overall satisfaction and the use of the system itself. For this reason, it is considered unreliable to extend previous usability evaluations from indoor experiences to outdoor implementations

B. USABILITY EVALUATIONS

Since literature does not provide a standard guideline for usability evaluations of multisensory systems, the need for a brief research intending to select a suitable instrument to evaluate usability and satisfaction of SensiMAR arose.

User evaluation, defined as the ease of using an interface [43], is known to be a key factor for any user centred application [15]. Frequently referred to as usability tests, in short, these evaluations are linked to effectiveness, efficiency, and satisfaction [44], [45]. Since these measures can vary widely depending on the system itself or depending on the tasks at issue, robust and reliable instruments has been proposed towards usability assessments. As a relevant attribute that affects user's adoption and experience [46], the literature provides several approaches aiming to validate the usability of new digital solutions in the user's perspective, such as the IBM questionnaires focused on measuring user satisfaction with computer system usability – e.g., the Software Usability Measurement Inventory (SUMI) [47], the After-Scenario Questionnaire (ASQ) and the Post-Study System Usability Questionnaire (PSSUQ) [48] –, the System Usability Scale (SUS) [44], the usability scale for handheld augmented reality (HARUS) [49], or the Mobile Phone Usability Questionnaire (MPUQ) [50].

Questionnaires are frequently used, particularly, in usability research because they provide evaluators with feedback from the users'perspective quickly and economically [51]. However, selecting questionnaires for end-users (non-experts) should consider some known limitations from this subjective tool, such as the attempts of users to guess what the researchers are examining [52], or the fact that they frequently get frustrated when answering long questionnaires, especially when they notice several questions addressing the same issue in different ways [53], affecting the reliability of their answers. While analysing usability questionnaires, it was noticed that some were too long – e.g. 72 items [50] or 50 items [47] –, or had questions that are not suited for the SensiMAR application – e.g. questions related to input data [49], or with too many allusion to work environment, like ''complete tasks'' and ''become productive'' [48]. Known to be a highly robust and versatile tool for usability evaluations [45], the SUS approach came over as being one of the more versatile and suitable for a wide diversity of technological systems. The main reasons that stand out by using SUS instead of other excellent alternatives (such as SUMI [47], ASQ [48], or MPUQ [51]) are for being technology agnostic, quick and easy to conduct, for having a single score that cames out of the questionnaire analysis, and for being nonproprietary, making it a cost effective tool [45].

When evaluating the usability of a new system, age and sex differences appear to affect the reaction of users towards technologies [15], [54]. Woman appear to more strongly refuse to wear technology [55] or to take longer time to perform tasks [56], reporting higher levels of technology-related anxiety [57]. Not all adults know how to handle new technological conditions and have difficulties gauging just by how much they can alter the convention [58]. Older adults have shown more unwilling for adopting new technological solutions, such as increased problems expressed by older participants using mobile devices [59]. In fact, better usability scores were found for younger adults than for older adults [60] who are generally more reluctant to technology usage [55].

Age is frequently divided according to generations, as they appear to exhibit similar characteristics, preferences, values and perspectives. Back in 1952, Karl Mannheim addressed the problem of generations as a group of the same age people who are united by some memorable historic event and made one of the biggest contributions to the theory of generations [61]. Over the years, the generations gaps have been suffering some adjustments as big events in society happen. Since then, it appears that the defined intervals are not consensual [62]–[66] and, given the fast development of technological gadgets, to establish a classification of generations that somehow has been proved to be suitable in recent studies when evaluating a technological system such as SensiMAR seems reasonable. Such classification should take into account world events, ethic origins, the location of conducted studies for classifications, and recent validations of the generation classification at issue. A brief research unveiled a recent study [67] that identified significant individual characteristics differences across Strauss-Howe's generations [62]. Hence, combining these two classifications, we have: Greatest Generation (born between 1901 and 1924) Silent Generation (between 1925 and 1942); Boom Generation (born between 1943 and 1960); Generation X (born between 1961 and 1981); Generation Y (born between 1982 and 2004); Generation Z (born after 2005). The mentioned study revealed significant differences between three generations, namely, Boom Generation, Generation X, and Generation Y, wherefore it may be interesting in current studies to organize participants according to these age intervals.

III. PROTOTYPE DEVELOPMENT

Following a theoretical proposal on outlining a multisensory AR system to be used outdoors in CH [22], we present an overview on the deployment of SensiMAR to further validate the system usability with end-users. The development of SensiMAR was focused in keeping it easy and simple for all types of potential users, always considering the user as the centre of the system, aiming to develop an application as user-friendly as possible. As the literature suggests, to build a simplistic user interface is essential to have the minimum stages as possible, to allow users to find it intuitive and engaging in order to successfully experiencing the system [68]. SensiMAR prototype was developed and tested with expert users at three moments of deployment. One after the AR application development, without sounds nor smell added, another with all stimuli added tested inside a laboratory, as figure 1 illustrates, and a last evaluation stage *in situ*. At each stage of evaluation, four participants evaluated the system individually and in group – a maximum of 3 individuals was tested because this was the established limit for the final experiences. The researcher observed each participant when interacting with the system to observe any usability issues and, after each experience, informal interviews were conducted focusing on usability issues reported by participants.

FIGURE 1. Photograph taken during one of the conducted tests during the development of SensiMAR.

All developed contents – visual, audio, and smell – were subjected to exhaustive research according to the Roman period and were validated by the director and by the archaeologist of the museum where the experience took place.

A. SensiMAR PLANNING

The process of planning SensiMAR prototype included, in a first stage, an acceptance of technology study, then the requirements identification, and the architecture. Since a previous design of this system was already outlined in a previous study, we suggest for further information related to SensiMAR design, to refer to [22].

1) ACCEPTANCE OF TECHNOLOGY STUDY

We conducted an acceptance study of AR technology based on the UTAUT model [69]. With this study we aimed to understand the relations between Performance Expectancy (PE), Effort Expectancy (EE), Social Influence (SI), and Facilitating Conditions (FC), on Behavioural Intention (BI) when using AR in archaeological sites. This establishing included the monitoring of moderators such as Sex, Age, Technological knowledge, and Archaeological knowledge.

Venkatesh *et al.* defined Performance Expectancy as the degree to which a person believes that using the system will help each individual to obtain gains related to something [54]. Effort Expectancy has been defined as the degree of ease associated with the use of the system [54]. Social Influence was defined as the degree to which a person perceives that important others believe each individual should use the new system [54]. Facilitating Conditions have been defined as the degree to which an individual believes that an organizational and technical infrastructure exists to support the use of the system. According to Venkatesh *et al.*, it is expected that Behavioural Intention will have a significant positive influence on technology usage [54].

The conducted acceptance study at this stage aimed to provide feedback helpful for some requirements gathering of our AR multisensory prototype. Thus, correlations between constructs and moderators analysis were performed according to the normal distribution of the variables under study. Parametric Pearson's correlation coefficient tests were performed for normally distributed variables, and for free distribution non-parametric Kendall's tau-b correlation coefficient test were conducted as it has been shown to be more robust and slightly more efficient than Spearman's rank correlation [70].

The results obtained revealed that the BI to use AR in archaeological sites is influenced by PE, EE, FC, and SI. Results also showed that PE on behavioural intention was not moderated by gender neither by age, but was moderated by archaeological knowledge and technological knowledge, such that the effect was stronger for higher archaeological connoisseurs, and for higher technology connoisseurs. The influence of EE on BI was revealed as not being moderated by age, but was moderated by gender and by technological knowledge, such that the effect was weaker for male, and particularly for higher technology connoisseurs. Regarding the influence of SI on BI, results showed that was not moderated by age, but was moderated by gender and by technological knowledge, such that the effect was stronger for men, and particularly for lower technology connoisseurs. From the analysed results, it was observed that the influence of FC on BI was not moderated by age, but was moderated by gender and technological knowledge, such that the effect was stronger for man, particularly with high levels of technological knowledge. BI was revealed as not being moderated by gender neither by age, but was moderated by archaeological knowledge and by technological knowledge, such that the effect was stronger for higher archaeological connoisseurs and, for higher technology connoisseurs. For further details please refer to [69].

2) GENERAL SYSTEM REQUIREMENTS

Aiming to identify system requirements, this subsection clarifies what the SensiMAR prototype should provide to users, and how. From a functional perspective, this multisensory AR application for CH contexts provides to the user, when exploring a given local in ruins, the ability to perceive, in real-time, relevant virtual elements, including virtual humans, that complement the existing structures or objects which were damaged or destroyed. Given our goal for understanding the impact of adding stimuli to an AR experience in CH, in addition to visual information, SensiMAR prototype provides synchronized audio, and specific smells. The sounds are delivered in a 360-degree amplitude for better immersion, in the ambisonics format, i.e., a sphere of sounds that recreates a 3D sound scene, in such manner to give the user the sensation that sounds are coming from different directions and various distances, therefore providing a spatialized soundscape which is more engaging and realistic [26]. These sounds represent a soundscape consisting of all events heard – not only objects seen [71]. Diegetic sounds, whose source are related to the actions that were performed in the ancient times for that given spot, complement the soundscape available of the experience. Thus, the prototype should:

- Place virtual images overlaid in their ruins;
- Explore the virtual scene combined with the real scene in a 360-degree;
- Play an animation, also overlaid in the real scene, when order by the user;
- Have 3D soundscape delivered in ambisonics format;
- Have another soundscape synchronized with the animations;
- Release smell at specific moments.

3) FUNCTIONAL REQUIREMENTS FOR CONIMBRIGA

Considering our case study of the Ruins of Conimbriga, specific functional requirements for this particular implementation were collected. More specifically, users that experiment SensiMAR, were able to see a reconstruction of an interior garden that was known by the Romans as a peristyle. This garden, with flowers, water and fountains was surrounded by ionic[1] columns. They should also listen to a soundscape with bird sounds, people working, wagons travelling around, people talking, and other sounds that correspond to the soundscape of an activea ancient Roman city. Also available to the user, when he or she turns around, is the virtual reconstruction of the entrance of the house, where an animation occurs: two figures dressed as Romans walk from the right to left, appearing from behind a folding screen. These human figures were used as part of the animation in order to better engage the user in this mixed reality scenario, aiming to assist the immersion and complete the overall experience [72]. The user heard them talking in Latin with each other and, at a given moment, a wagon passes outside the house, also visible in the user's field of view. At this moment, the two Romans greet the charioteer who also greets them back. Then, a smell of a fish sauce that used to be frequently carried back then – the *garum* – is delivered to the user and the two Romans keep walking and talking until they disappear behind another folding screen.

Experiencing this system allowed the users to perceive the described added elements, but also to perceive the real scenario. That is to say, in addition to the virtual scenario, they were able to view the current ruins in place, to listen to the present soundscape, sensing the surrounding ambient smell, feeling the wind, the temperature, and all the other natural elements. SensiMAR intended to evoke into the real scene three stimuli, namely, sight, hearing and smell.

[1] The Ionic order is one of the three canonical orders of classical architecture. This style is easily identified by the volutes of its capital.

4) NON-FUNCTIONAL REQUIREMENTS

From an overall non-functional perspective, our AR multisensory application has collected the following non-functional requirements:

- Computing platform: Keeping in mind the importance of facilitating conditions on the intention to use an AR technology in CH from the conducted adoption of technology study briefly presented in subsection III-A1, SensiMAR has been developed for Android and planned to be easily suited to multiplatform such as iOS systems.
- Integrability: SensiMAR is compatible with any Android device starting from Android 4.0.3 (Ice Cream Sandwich), any four speakers that enable the ambisonics sound format, and a smell dispenser connected to a laptop via USB.
- Performance: As observed in the conducted adoption of technology study, the performance expectancy affects the behavioural intention to use the system wherefore performance as well as response time without delay to keep a good performance of the system is very important. A system as SensiMAR must enable exploring a 360-degree scenario in real time without delay. The virtual information must be presented at the correct position, orientation and scale, to provide an accurate and credible perception of the ancient scenario. It is also necessary to keep these settings according to the user movement, by tracking the user's motion. The soundscape added to the scene is also created in a 360-degree to increase the immersion in the user by deploying the sounds from various directions and at different distances. The sounds must be synchronized with the animations provided in the visual scene. The smell must be delivered at specific moments with a specific duration to release enough quantity to be scented close to the user at the right time.
- Portability: Albeit being preferable to stay at one single point and rotating for exploring SensiMAR, portability

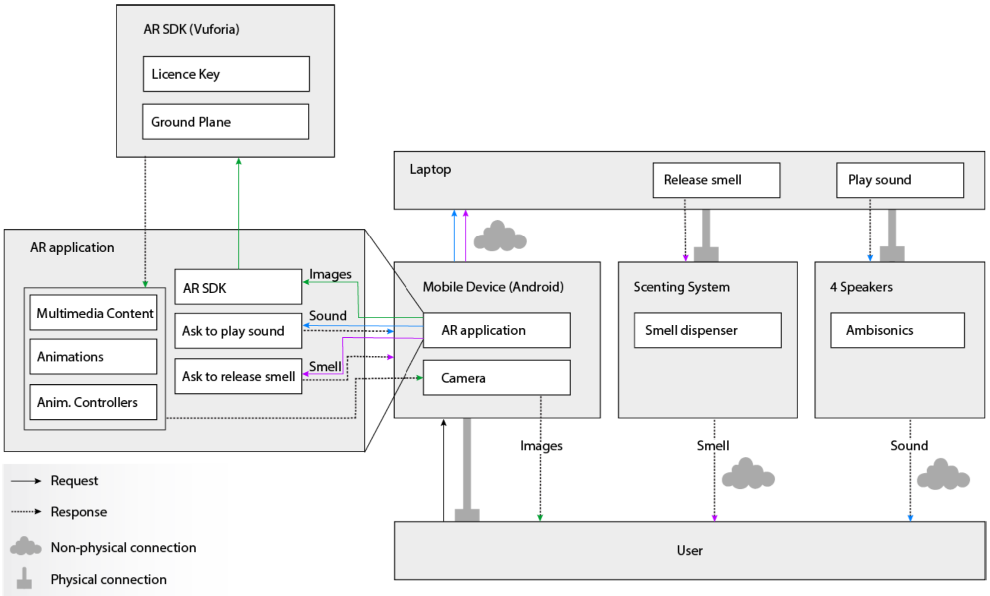


FIGURE 2. SensiMAR architecture, targeted for mobile AR, when adding stimuli to engage sight, hearing, and smell.

was required for the AR application, as the user would be free to walk around to explore.

- Usability: Performing the tasks safely, effectively, and efficiently while enjoying the experience and meeting user expectations, was also a must. As observed in the adoption of technology study conducted, the effort expectancy affects the behavioural intention to use the system wherefore the ease of use is essential. A multi-sensory AR system such as the proposed for the current research, considering the wide-ranging target group of potential users from CH sites, needs to be user-friendly. As literature suggests, to deploy a simplistic user interface is essential for the experience and system purpose, by having the minimum interactions possible, in order to allow users to find it intuitive and engaging [68].
- Reliability: As observed in the adoption of technology study conducted, trust expectancy is also an important construct for influencing behaviour intention to use AR. Thus all added elements were accurate and historically correct, being validated by the archaeologist responsible for the CH space.
- Interoperability: SensiMAR architecture envisaged some specific limitations of many archaeological sites, such as the absence of wi-fi and electrical current.
- Preventing failures during the experience was also addressed among all development process.

5) PROTOTYPE ARCHITECTURE

This subsection updates the previous study that aimed to outline the design of SensiMAR in CH sites [22]. The experience should start in a specific place by opening the AR application on a smartphone and, by touching the screen, the virtual information is overlapped. Sound and smell are triggered by a signal at specific moments, sent by the AR app, in order to activate these stimuli. A local network must be created for this purpose, so the signals received by a laptop enable the giving order to play the sounds and to release the smell. All added elements at a given CH place must be accurate and historically correct. Thus, all data was validated by the archaeologist responsible of the CH space.

Figure 2 illustrates the architecture of SensiMAR, and how different elements should connect with each other. This solution was achieved after some updates regarding the prior solution for a multisensory AR system [22].

SensiMAR was mainly built using the Unity 3D platform. All visual contents are merged using this software, including animations and all functionalities needed for SensiMAR visual performance. The integrated Vuforia SDK was used to implement the AR application for mobile devices, benefiting from one of its feature named *ground plane*[2] to trigger the AR experience. The communication between the Vuforia portal and the application developed in Unity is wireless and, once installed in the mobile device, no wi-fi connection is required.

Carrying the smartphone, the visitor should perceive a correct visualization of the virtual content of the experience over the real scenario while a soundscape is already playing. Another sound track and smell are triggered by a flag when the animation starts, meaning that the system sends a signal at specific moments. To make it happen, the app, running on a smartphone, sends the UDP signals that are received by a laptop through a local network. This action will play an audio track – sending the output to the speakers, through an audio interface also connected to the laptop – and enables the smell dispenser – releasing the aromas.

[2]Ground plane enables digital content to be placed on horizontal surfaces in the real environment, such as floors and tabletops.

The user, carrying only a mobile device in their hand (as noticeable in figure 7), surrounded by the speakers, is exposed to all three senses of this multisensory experience, in addition to the natural five stimuli coming from the surrounding real environment.

B. SensiMAR IMPLEMENTATION

The experience occurs in the remains of a wealthy Roman house, a *Domus* – named House of Cantaber – located in Conimbriga Ruins, part of the Monographic Museum of Conimbriga-National Museum (Portugal). The house of Cantaber is a big and wealthy house which has occupied a very central position regarding the urban area of Conimbriga [73], as illustrated in figure 3.

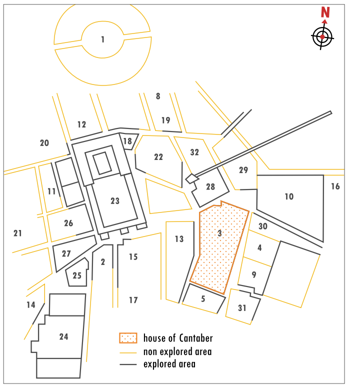


FIGURE 3. House of Cantaber highlighted in the city map of Conimbriga.

FIGURE 4. Peristyle of the House of the Cantaber, the more representative scenario of SensiMAR experience.

Nowadays, the ruins of the House of Cantaber are next to the defensive wall built during the Low Empire to protect the city. The experience took place in front of the main peristyle, as figure 4 shows. A 360-degree photo of the space can be explored in the following link: https://roundme.com/tour/445106/view/1531953/.

1) VISUAL CONTENTS

The role of the visual stimulus in this experience is to provide information that should include domestic architecture features, people appearance as well as their behaviour, and transportation means. Thus, virtual reconstitution of house walls, columns, flowers, water, decorative elements, humans, cows, a wagon, and domestic objects were obtained.

Most of these virtual elements were modelled and textured using Maya software, with exception of one of the humans and the water fountains that were created using Poser Pro Software and Unity. Almost all animations were also created in Maya, apart from the water flowing that was animated in Unity.

The animation includes also two Romans walking and talking at each other. For this, a 2D footage was captured with real actors, who dressed like Romans, and performed the proposed actions – talking between each other, walking and, at some point, stopping to wave at someone – in front of a green screen. This footage was later edited and post-edited, using the following software: Adobe Premiere Pro, Adobe After Effects, and Unity 3D.

The human figure who rides the wagon is a 3D recreation and has two animations created: one when he is ridding (a loop animation), and another when he looks to the side, and waves at someone. Using Unity, these two animations are synchronized with the AR application and with the animation action of the two other humans that will appear in the overall animation. The wagon has one loop animation and the walking animations of the cows is actually a single one, being replicated for each other in Unity 3D, with a different starting point, to avoid a perfect synchronism between the two animals.

A previous AR prototype, with all these virtual elements was developed having this experience divided in two parts: the first was related to the garden explorations; the second was focused on the animation that took place while facing the main road outside the house – the Romans and the wagon passing. However, this approach was not used because, after conducting some tests with experts carried out in laboratory, usability issues were identified due to the fact that it was not clear to users how or when they could go to the second part of the experience. Another noticed problem was that, having two different experiences in the same process, users got confused about what was happening in each one of them and how to interact with it. These issues were observed when changing to the second experience, where it seemed that users had to start a new process of learning how to interact with the system again. Thus, a single experience in 360-degree was developed.

Once implemented *in situ*, holding a given smartphone, visitors are first presented to a virtual reconstitution of the garden in front of them – they start the experience facing the main peristyle of the house. In figure 5 it is possible to observe some information of this reconstitution, such as the flowers, the columns that surrounded the peristyle, and the fountains.

While navigating, when at a 180-degree position, users were able to play the animations, as illustrated in figure 6.

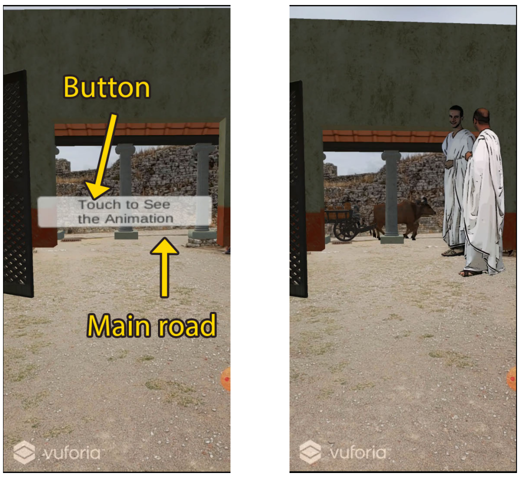
2) AUDIO CONTENTS

The sounds of SensiMAR, emmited in the ambisonics surround sound format through four speakers, intended to

(a) View of the beginning of the experience.

(b) Beginning of the experience with SensiMAR.

FIGURE 5. Virtual reconstitution of the main peristyle of the House of Cantaber.



(a) SensiMAR experience when users were facing the main road.

(b) SensiMAR animation.

FIGURE 6. Virtual reconstitution at the entrance of the House of Cantaber and in the main road.

recreate the soundscape of ancient times, when the Roman city was in activity, including sounds from people talking in Latin (the Romans' native language) and walking around in the streets, wagons passing by, and working sounds coming from the nearby surrounding activities – such a blacksmith and some shops that used to be close to the House of Cantaber. The animation also has their own sound such as dialogues – also in Latin –, steps, animal sounds, and more wagon noises – wood grate, the mooing of the cows, and the sound of containers – where goods were transported – between each other while moving.

All tracks, composed by captured sounds and by other tones downloaded from open-source sound libraries, were assembled in the digital audio workstation Reaper, for creating the tracks and to distribute the sound positioning according to the sphere of sounds, in order to give each sound positions and animations across the time. Two sound files were generated, a background soundscape that is playing repeatedly in loop, and other that is triggered when the animation starts.

Max/MSP/Jitter software was used to play these audio tracks and a patch was created enabling the synchronization between animations and sounds, as well as some manual controls such as the volume for the different channels (speakers) that were tested in place before the user tests.

3) SMELL CONTENTS

The smell is added to the augmented scenario at specific moments, depending on the timeline of the experience. Dry crystals were acquired to spread the smell, in particularly, the ''fish market'' aroma. This smell represented the *garum*, one of the most common and typical products consumed by the Romans, and broadly exchanged between people. During the animation, when the wagon passes in the main road, a signal sent by the AR application triggers the smell release.

In order to assure that it would be successfully delivered to participants, the smell was released in the vicinity of the user. After some laboratory tests, the duration time in which the system valve is open was settled to 500 milliseconds. However, while testing this system outdoors, since it was an open space and the smell was not intense enough to feel it, *in situ*, the duration time was increased to 800 milliseconds.

IV. SensiMAR EVALUATION METHODOLOGY

SensiMAR evaluation was held *in situ*, aiming to obtain the results to provide accurate interpretations regarding visitors usability when using this prototype.

A. VARIABLES

The dependent variable studied was usability of the SensiMAR prototype. To analyse how usability scores would vary across different groups, we have labelled participants according to their sex, age, previous AR experience, and the condition they tested – from the two conditions available: audiovisual (visual + sound) or multisensory (visual + sound + smell).

For the sex groups, two categories were considered: Male and Female. Age was segmented according to Strauss-Howe's classification [62] of generations:

- Generation Y: age between 37 and 15 years old;
- Generation X: age between 58 and 38 years old;
- Boom Generation: age between 76 and 59 years old.

Regarding participants' previous experience with AR technology, two groups were determined: no previous experience (participants who stated they never had an AR experience before the one they just evaluated), and with previous experience (participants who claimed that they had already experienced AR at least once).

B. PARTICIPANTS

All participants were volunteers that were visiting an archaeological site (Conimbriga, Portugal), who accepted to be

TABLE 1. Groups of participants involved in the evaluation of SensiMAR usability.

Condition	Size	Sex	Age			Previous AR exp.
			Interval	Mean	Std. dev.	
Audiovisual	35	19 female	[21-68]	40	14	17 Yes
		16 male	[26-74]	48	15	18 No
Multisensory	32	17 female	[23-75]	50	16	17 Yes
		15 male	[24-74]	51	17	17 No

part of an experience to whom SensiMAR was explained as a research project to apply technology within these sites. A total of 67 people participated in this study and, as table 1 resumes, it was observed a balanced number of people across all defined groups.

C. INSTRUMENTS

To evaluate the SensiMAR usability, the SUS 10-item questionnaire was used to obtain usability scores. Since visitants of Conimbriga come mainly from Portugal (the host country of the site), the European Portuguese validated questionnaire of SUS for Portuguese native speakers was used [74]. Apart from the Portuguese speakers, target-audience has a lot of other nationalities, most including non-native English speakers – according to a report provided by the museum regarding the sale of tickets during 2019, apart from England, EUA, and Canada (native English speakers), a great number of visitants come also from France, Spain, Italy, Japan, among others. Hence, in order to avoid comprehension difficulties with the word ''cumbersome'', as reported by Finstad in 2006 [75], this word was replaced to clarify the term by defining it as ''awkward''. Also Bangor *et al.* (2008) [45] and Lewis and Sauro (2009) [76] have both confirmed that the word ''cumbersome'' can be replaced by ''awkward'', making this item easier to understand. Moreover, it has been confirmed that rather than using the term ''system'' using other terms such as ''product'', ''application'', or ''website'' does not change the results. Accordingly, the questionnaire used in this study used the term ''application''. French native speakers are also noticed in great number across the visitants' statistics but, since no validation study was found neither proposed by SUS authors, it was used a common French version that has being applied across software development companies [77]. Following the approach implemented in the English version, the expression ''ce système'' was replaced for ''cette application''.

For collecting participants' socio-demographics information, a generic questionnaire inquiring sex, age and previous experience with AR was given to participants as being the last part of the survey, as suggested in the literature [78], [79].

D. MATERIALS

The AR application evaluated was the SensiMAR prototype briefly described in this article, were two different conditions were considered:

1) *Audiovisual* – this condition allowed the participant to receive visual and audio stimuli for the experience. They carried a smartphone with them, and four speakers were placed around them;

2) *Multisensory* – this condition allowed the participant to receive visual, audio and smell stimuli for the experience. They carried a smartphone with them, four speakers were placed around them, and a tripod was placed close to the user to release the smell, as illustrated in figure 7.

FIGURE 7. Photograph taken during one of the experiments, while one participant was exploring the surroundings with SensiMAR.

The visual stimulus of the AR application was delivered via a Samsung Galaxy S9 smartphone that features a 5.8'' AMOLED display that supports 16 million colours with a resolution of 1440 × 2960 pixels. The audio stimulus was delivered via an ambisonics surround sound system based on four Mackie CR4 speakers. The smell was delivered via a custom-made smell dispenser machine based on an Arduino that controlled an electrovalve attached to a compressed air system. When activated, the eletrovalve opens the compressed-air system and the air circulates via a vacuum chamber where a bag of dry crystals from *SensoryCo.* with the ''fish market'' aroma is stored. The smell was released in the vicinity of the participants to ensure that it was felt by them.

E. PROCEDURE

To assure ecological validity in the evaluation of this system, all participants of this study were random visitants of the archaeological site that, along their visit, were invited to test the SensiMAR system. Each participant that accepted the invitation and consented to participate in this study was informed about the context of the current research and how they would participate in the study.

The experience with end-users took place at the ruins of the vestibule of the House of Cantaber and started with some explanations, as illustrated in figure 8, regarding the

TABLE 2. Summary of collected data from SensiMAR experiments *in situ* presenting the average of usability scores and respective quarter grades according to SUS analysis, presented by sex, age groups, AR experience, and condition.

Participant group	Sample	Average Usability Score*	Average SUS Quarter Grade#
Female	36	80.0	Good
Male	31	80.6	Excellent
Boom Generation (age 76-59)	18	76.5	Good
Generation X (age 58-38)	24	82.1	Excellent
Generation Y (age 37-15)	25	81.2	Excellent
No previous experience	35	77.9	Good
With previous experience	32	82.9	Excellent
Condition 1 (audiovisual)	35	81.8	Excellent
Condition 2 (multisensory)	32	78.6	Good

*Usability Scores of SUS goes from 0 to 100. #The grade of SUS quarter goes from Awful, Poor, Okay, Good, and Excellent.

FIGURE 8. Photograph taken during one of the experiments, while some explanations were provided to participants before testing SensiMAR prototype.

surroundings of this house when inhabited by the Romanized locals.

All the information regarding the context and the SensiMAR usage was provided in Portuguese, English, or in French, depending on the language of participants' preference. A script was followed to ensure that the information given to the visitors was the same for all participants. The AR experience was initially triggered by the researcher that was conducting the experience. Immediately afterwards, the smartphone was handed to the participant. The experience could be tested individually or in group in a maximum of 3 individuals – due to the visibility of the smartphone's camera. When undergoing the AR experience, participants were free to explore it by themselves, as illustrated in figure 7. Only when requested by them, the researcher intervened in the experience, mainly for answering questions or to exchange comments related to what participants wanted to share at that moment of the experience.

After using the SensiMAR prototype, the participants were asked to fill in the SUS questionnaire. The following step was to have participants filling the generic socio-demographic questionnaire at the end of the survey. All the collected data was anonymous and confidential, used only for purposes of sampling. The whole procedure took approximately 10 minutes per experiment.

F. STATISTICAL PROCEDURE

To calculate the SUS scores, the contribution of each item of the questionnaire was obtained according to literature [44]. For correlations between variables, conducted for the acceptance study briefly described in the previous subsection III-A1, and for the correlations between usability scores and groups of participants, ahead presented in section V, the normality of the data was assessed by using a Shapiro-Wilk test, conducted using the statistics software SPSS, version 23.

Parametric Pearson's correlation coefficient tests were performed for normally distributed data. For free distributions, non-parametric Kendall's Kendall's tau-b (τ_b) correlation coefficient tests were conducted as it has been shown to be more robust and slightly more efficient than the Spearman's rank correlation [70].

V. SensiMAR RESULTS

The presented results arose from 67 participants, previously described in subsection IV-B. The usability scores were calculated according to literature [44]. Table 2 presents an overview of the collected data from SensiMAR prototype usage *in situ*, and figure 9 illustrates the average usability across the groups of participants analysed.

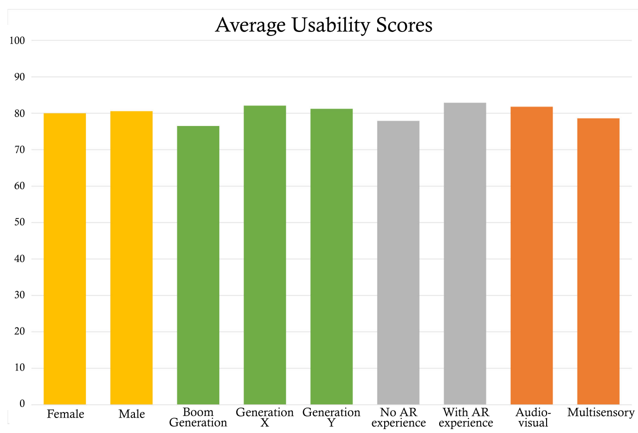


FIGURE 9. Chart illustrating the average usability scores obtained by end-users while testing SensiMAR *in situ*.

The analysis between usability scores obtained across all the aforementioned variables – sex, age, AR experience, and

TABLE 3. Summary of non-parametric correlations, based on Kendall's correlation coefficients, made between usability scores and sex, age groups, previous experience with AR (AR xp), and condition.

		Sex	Age group	AR xp	Condition
Usability Score	Kendall's tau-b (τ_b)	-0.004	0.067	-0.150	-0.077
	Sig. (2-tailed)	0.970	0.497	0.151	0.461
	N	67	67	67	67

condition – and table 3 depicts that there are no significant differences between any of them.

VI. DISCUSSION OF RESULTS

In accordance with table 2, the presented data reveals good usability of this outdoor system stated by all types of participants, as all groups obtained scores above 68, which correlates with systems having high usability [80].

A. USABILITY SCORES AND SEX

Despite the fact of the behavioural intention to use a new technology being stated as significant different between gender [54], [81], the previous multisensory studies found do not provide insights relating gender with the multisensory systems usability. The current analysis reveals a slight difference between women and men when using the SensiMAR system, from 80.0 points (women) to 80.6 (men), a minimal different of 0.6 points that, for being close to 80.2, is reflected in the SUS quarter grade, being classified as ''good'' by female audience and as ''excellent'' by men. Thus, usability scores from SensiMAR are not influenced by the sex of participants since no significant difference was found as stated in table 3.

In fact, albeit literature frequently raises the sex as a moderator to use or their intention to use a technology [56], [57], our results that demonstrated no statistically significant differences between usability scores and sex, are in line with [45], [69], [82] where has been also demonstrated that these differences tend to not be identified.

B. USABILITY SCORES AND AGE

The literature does not provide objective insights relating age with the multisensory systems usability. Despite the widespread agreement across generations, the current research notices that some groups of participants present better usability scores than others, in particular, between Boom Generation and the other two generations, with minimal differences of around 5 points. According to the presented data, younger generations – X and Y – stated higher scores in a way that the quarter grade was classified as ''excellent'', instead of ''good'' as the previous age group. Though these differences between Boom Generation and the other two generations – X and Y –, according to table 3, these results do not appear to have any significance. Thus, the usability scores from SensiMAR are not influenced by the age of participants.

The powerless attitude of adults when compared to younger users, identified in a previous study for a multisensory usability system [15], observing their willingness to approach the site experiences by themselves and to use the system, neither problems using this novel system as previously demonstrated [59] do not seem to be noticed with SensiMAR system, since both generations, X and Y, report similar average usability scores.

The irrelevance of age when using AR technology appears as a relatively new insight, as literature frequently refers to these two features as moderators for technology usability [45], [55], [59], [60] or intention to use [54], [81]. However, the tendency of observing a reduced negative impact on age towards technology usage, has been also recently reported [69]. Nonetheless, we highlight the need for being careful when generalising these results since they were obtained in a single archaeological site, while inviting people to participate in the study. It remains unclear if visitors would interact with the system similarly if they were not invited to do so.

C. USABILITY SCORES AND AR EXPERIENCE

Some differences in usability scores were also found between the two groups which reflect previous experience with AR technology. High scores were obtained from the group who stated no prior AR experience before SensiMAR prototype. This satisfaction related to usability is very comfortable from a group that had no previous experience with the technology. Individuals with prior experience with AR, appeared to express even more ease when using SensiMAR application since they scored it with even higher usability scores, raising the quarter grade from ''good'' – observed in individuals with no previous experience with AR – to ''excellent''.

Despite these variations, usability scores from SensiMAR are not influenced by the previous AR experience of participants since no significant differences were found according to presented data in table 3. We state SensiMAR, with its AR feature and multisensory approach, with high levels of usability scores, regardless their previous experience with this technology. These results are in line with the obtained results in The Fire and the Mountain museum [14], that evaluated usability of a multisensory system with touch-based technologies with children who did not exhibit any difficulties to interact with the system, even though they never used the technology before. The relevance of these findings meets the need raised in literature for evaluation studies involving end-users [20], Specially, taking into account the slow learning curves typically addressed to non-experienced users [21].

D. USABILITY SCORES AND CONDITION

Regarding conditions, it is noticed that audiovisual condition got the best usability score, rated as ''excellent'', yet the multisensory condition – the one where the smell was added – had a good performance regarding usability scores as well.

We highlight that we considered for this usability evaluation, the use of an unpleasant smell and, even so, the statistical difference, according to table 3, does not appear to have any significance. Thus, the usability scores from SensiMAR are not influenced by the condition experienced by participants.

FIGURE 10. Peristyle of the House of the Cantaber, the more representative scenario of SensiMAR experience.

We acknowledge that the peculiarity of the smell of *garum* in the experience – an unknown smell to most people – may raise some questions since smell familiarity also influences odour sensitivity [83]. Adding a more familiar smell to the experience can trigger new memories and make differences in their sense of presence during the experience, a factor that was taken into account for potential usability issues. To avoid the novelty of the *garum* smell, a context and presentation of the smell was provided before the SensiMAR experience.

VII. OVERALL DISCUSSION

We have conducted the development of an AR multisensory system, implemented and tested *in loco* with random visitors from an archaeological site that has been demonstrated to have good usability and satisfaction scores across several groups of users, namely, among sex, age, previous AR experience, and condition. No statistically significant differences were found and, according to the adjective classification available in literature for SUS appliance, all groups of participants rated SensiMAR system as "good" or "excellent", which correlate with systems having high usability [80].

Hence, we affirm that SensiMAR has been successfully implemented *in situ* in terms of usability and satisfaction among all participants. The minor variations detected in the average SUS quarter grades related to age groups are not considered a concern at all for further outdoors solutions like SensiMAR since higher results were obtained for younger generations, namely, generation X and Y, yielding good prospects for the future.

The challenges of implementing a multisensory AR experience remains, especially for outdoors. Trying to avoid getting our experiments hampered by the sunlight, or by the wind, or even by temperature, we presented some bypasses in order to collect results. Aiming at keeping an authentic ecological validity at the same time that we tried to provide the more similar scenarios as possible between participants, we constantly checked the weather conditions and set up the experience scene at the same schedules each day. Even so, some participants experienced SensiMAR when the sky was cloudy while others experienced SensiMAR with sunlight. Thus, for testing purposes, the researcher who was conducting the experiment held an umbrella close to the participants when the sun was shining, as figure 10 shows.

Concerning smell delivery, we placed the smell dispenser in the vicinity of the user to avoid its vanishing with the wind; from time to time, more precisely, twice a day, the researcher left the experiment spot for approximately one hour and returned to ascertain the intensity of the smell. Also, the time schedule for the experiments were chosen in order to avoid high temperatures – the high temperatures are known in literature for increasing the intensity of the smell.

VIII. CONCLUSION

Following the design proposal for a multisensory AR system, SensiMAR, to be implemented in an outdoor archaeological site [22], the current study presents its development, implementation, and its usability evaluation from end-users' point of view. This system provides visual AR experience by the use of a smartphone, the sounds are added to the scene with the ambisonics sound format through four speakers, and the smell is delivered by a custom-made smell dispenser.

Aiming to ascertain the system usability and satisfaction by the visitors' perspective, SensiMAR was implemented and tested *in situ* in two different conditions: as an audiovisual experience, and as multisensory experience – evoking the three stimuli (visual, audio, and smell). Random visitors of a CH site were invited to test and evaluate the system *in loco*, by using the prototype and then, by filling in a questionnaire.

Results were collected in order to perceive if the system would be revealed as having good usability according to SUS scores, across all types of participants, namely grouped by sex, age, previous experience with the AR technology, and condition used – audiovisual and multisensory. Given the small amount of usability evaluations with multisensory AR systems in literature, the current research supports this solution to be used among CH, validating its usability across different groups of participants. Presented results support the satisfaction of each group of participants while using the system, where usability scores do not suggest significant changing tendencies across the analysed groups. Hence, the distribution of all groups of participants is the same across usability scores being graded as "good" or "excellent". The small seemingly difference in scores allows to comfortably sustain the good usability of SensiMAR by all visitors, which supports the generalization of this technology outdoors across other open-air cultural heritage sites.

The challenges for implementing multisensory AR still remain: issues related to sunlight, temperature, daylight hour, and generic weather conditions – such as wind and rain – , should always be considered and taken into account when developing these sort of systems. The novelty of this AR multisensory implementation also triggers future work towards deployment strategies. Since we have now a validated system with the addition of a peculiar and not very pleasant smell of *garum*, we point for future research the addition of a more common smell by adding a familiar scent known among people.

Furthermore, since this research supports the usage of multisensory AR, new research lines are traced towards further evaluations with end-users. Demonstrating SensiMAR usability across visitants of the ruins of Conimbriga, this study inspires further research related to pursue understandings related to the impact that multisensory AR can have in visitors when exploring a CH site, and how this technology can enhance their experiences. Hence, the absence of usability issues on this multisensory AR system invites future analysis on its benefits exploring social values, epistemic, educational, economic, experiential, cultural and historical value, as literature did with AR benefits.

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