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A survey of multisensory VR and AR applications for cultural heritage

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ABSTRACT

The use of technology in cultural heritage sites for end-users, like virtual audio-visual reconstructions, has become a common solution to improve the communication and perception between these spaces and their visitors. Since humans perceive the world with different senses and in real-time, to evoke more than one or two senses at a time can bring benefits for the user perception. Accordingly, some very different implementations unleashing multisensory experiences have been made. Aiming to understand how different stimuli are being evoked in multisensory experiences to enhance cultural heritage experiences, and how these implementations are being evaluated, this paper presents a systematic review of technological multisensory applications in cultural heritage. Thus, the collected and analyzed data, focused on technologies used, purpose of the experience, stimuli explored, evaluation process, main findings obtained, and limitations found, will provide valuable information for further implementations. The overall results unleash the wide diversity available for multisensory implementations, from technological solutions to available content for users. Covering the pros and cons of such diversity, this study sustains the use of multisensory applications in cultural heritage as a powerful tool to enrich users' visits.

1. Introduction

The use of technologies to enhance experience in cultural heritage (CH) contexts has seen fast growth in the last few decades. Benefits of using technology in CH are demonstrated for a long time, keeping track of technological advances in a large set of studies and implementations in different contexts. Following these insights, is stated that if institutions develop this type of applications, they can benefit from focusing on both the fun and usefulness of their applications [1].

Virtual reality (VR) and augmented reality (AR) applications, given their wide possibilities to entertain and to educate are being developed and diffused for a long time, becoming more and more common in CH sites as technology evolve. VR solutions are found to enhance heritage visits since the late 80's [2,3] while AR, despite its early appearance in the 60's [4], has seen a slower diffusion being found as pioneer solutions in CH since around year 2000 [5,6] later followed by other research projects. Benefits of VR and AR in CH are remarkable at exhibition enhancement, reconstruction and exploration [7].

These implementations are mainly visual experiences. However, multisensory has also being stated as a trigger for enhanced experiences in literature. In fact, the creation of virtual experiences stimulating the different human senses have demonstrated the high potentiality to create the experience of the sense of "being there" [8]. Since humans perceive the world with all five senses (visuals, audio, smell, touch and taste), a perception equation was formulated to understand the precision of each of the sensory stimuli [9]. Thus, in addition to audiovisual contents, haptics [10–12] or smells [13–15] are found.

1.1. Survey motivation

VR experiences, whereby users can interact and have a sense of presence in computer-generated environments [8], have been explored as a solution to a vast sort of areas, focusing on diverse purposes. When in cultural heritage contexts, they have played a significant role enhancing these experiences [16–18], being pointed as a very effective means to communicate cultural content [19].

AR, integrated in the Virtuality Continuum concept presented by Milgram et al. as a form of virtual reality where users can also, in real time, have a clear view of the real world while perceiving the virtual elements [20], has conquered prominence among the last decades, being stated as a successful solution for CH experience enhancement [21]. In fact, AR has been demonstrated as preferable for exhibition enhancement when compared to VR [7,22–24].

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For the purpose of the current study, mixed reality (MR) is considered as a variation of AR, since the specifications of MR found in literature fit in the overall definition of AR: an experience where user perceives and interacts with virtual content and the real environment in real-time. Note some MR definitions from different types of sources: in scientific community is found to merge the real and virtual environments which coexist and interact at the same time [7]; in expertise glossaries, is presented as an experience that always gives the user of their real surroundings, but uses a headset [25] or being similar to AR except virtual objects are integrated into natural world [26]; in professional companies, is stated as a mixture of the real world and virtual worlds in a way that they understand each other in a way that the virtual contents interact with the real world and with the user, such as defended by the chief creative officer at Magic Leap, Graeme Devine [27].

Minding previous surveys to better understand what was addressed so far, most relevant and related literature was scanned. A survey from 2009 covers advantages and limitations in technology approaches in virtual museums, namely, web3D exhibitions, VR and AR exhibitions, haptics as an extension of visual displays, and the use of handled devices [28]. They highlighted significant advantages but also denoted relevant drawbacks, underlining the need of evaluation studies involving real users in order to better understand further implementations. An update has been made in 2018 [7], focused on a literature review of VR, AR, and MR from a cultural heritage perspective, pointing out technological aspects of these technologies. These studies aimed to identify what has been implemented and to point out limitations found, according to each time window, tracing suggestions for further implementations. The latest, from Bekele et al. classified the purpose of VR technologies in CH as exhibition enhancement, reconstruction, virtual museums, education, and exploration. The devices more frequently used for VR applications in CH found were desktop screens (non-immersive), projection screens (semi-immersive), CAVEs, and HMD (head-mounted display) devices (both fully immersive). Regarding to AR applications, the more common devices are mobile, HMD, and less commonly used, smart glasses. Despite the clear valorization of technologies among the reviewed implementations, immersive technologies are stated as unlikely to have a widespread adoption. Relevant insights considering the use of VR in real museums are evidenced in a previous study which covers and highlights relevant issues related to using these technologies in CH contexts [19].

Following these relevant studies, the current systematic review provides a novel approach to generate knowledge that allow to researchers, designers and practitioners to identify the benefits and research perspectives of the adoption of multisensory technologies in CH contexts.

1.2. Research questions

Despite the diversity of technological solutions available on cultural heritage contexts, the closeness between museums and visitors is found to not being always fulfilling where contents are predominantly shaped for visual consumption. The opportunity to use more human senses than visual or even the audio-visual approach (i.e. smell, touch and taste) encourages new ideas, feelings and thoughts, which spark curiosity, questioning, exploration and discovery [29].

Choosing the technological devices or specific solutions has been noticed to be floating options over time due to technological advances — what is now a good solution may be overpassed by a brand-new technological device as a better solution, in a short period of time. Thus, more than identifying which specific hardware or software can lead to successfully solutions in CH, understanding how to take advantage of their features is believed to be more relevant knowledge for further implementations. Therefore, regardless the technology at issue, using technologies to promote multisensory approaches, which consider the different human senses and their interrelations in a given experience [30], appear in the literature revealing several advantages among different areas such as medicine [31–33], social sciences [34,35], education [36], industry [37–39], among other areas. Its advantages are also highlighted for CH, such as providing a strong presence to better create the experience of the sense of "being there" [8], influencing visitors' attention and also their perception [10,40]. However, despite the great expectations, no studies covering guidelines for multisensory implementations were found. Sensorial stimulus can be implemented in many manners through various types of devices, and regardless the technologies used, it can be difficult to quantify and to evaluate. Therefore, when planning to develop a multisensory approach for enhancing visitors' experience in CH sites, having a deep overview of multisensory implementations for CH is valuable and useful for any further applications.

Thus, the current work presents a systematic review of multisensory approaches among CH contexts, aiming to analyze previous solutions, providing relevant information for further implementations. This research, which expose the benefits of using multisensory technologies in CH, also aims to ancillary and update the last relative surveys. Given the literature gap regarding to multisensory implementations in CH, the current study intends to cover it, answering the following questions:

Q1. When using multisensory virtual or augmented reality, which senses are being evoked?

Q2. When using multisensory virtual or augmented reality, how are the stimuli being evoked?

Q3. What is the role played by each stimulus when evoked in the experience?

Q4. Based on how previous works implemented their systems, is it possible to trace a guideline to implement a multisensory approach in CH?

Q5 How to evaluate a multisensory system from the users' perspective?

The strategy adopted for finding proper answers for all questions is to make a detailed analysis from previous works. For the first two questions, the procedure of identifying which senses were added to the environment as well as spotting which technologies are being used to provide the added contents regarding to each stimulus evoked, should provide the answers.

To better understand multisensory advantages, this study aims to comprehend the role of each stimulus on each implementation, as proposed in the third question. The importance of this question arises from observing that several implementations add stimuli all together in the same experience and, for someone who intends to implement a multisensory system, it is unclear which senses they must evoke to cause a certain impact. This problem can emerge when the results obtained from these all-in-one experiences became unclear if a given advantage was triggered by a specific sense of all together. The importance of this understanding is related to the main purpose of a certain implementation in a way that will provide insights related to understand what specific senses can trigger certain emotions, avoiding a full setup for example, or adapt the setup for the main goal of that given implementation. Accordingly, this reflection will help to identify the purposes and the intentions that motivated researchers and/or entities to develop these experiences are identified.

The answer for question four is linked to the answers found for the previous three questions in a sense that the current study is also focused on identifying key steps that contributed to successful approaches of multisensory implementations in CH. This

Table 1
Inclusion criteria.

Inclusion criteria	Description
Inclusion criterion 1	The paper has the one of following terms in the title, abstract, or keywords: *"virtual", "augmented reality", "mixed reality" or "mixed-reality", "VR", "AR", "MR", "XR";* along with one of the terms: *"multisensory", "multi-sensory", "multisensorial", "multi-sensorial", "stimuli", "senses";* and with one of the terms: *"cultural heritage", "museums", "museum", "historic city", "historic cities", "archeological", "archeological", "archeology", "archeology".*
Inclusion criterion 2	The study provides an experience where the several senses are evoked simultaneously.
Inclusion criterion 3	The paper is published as a journal article or as a conference paper.
Inclusion criterion 4	The paper is written in English, Portuguese or Spanish.

is the most aspirational question from which an ideal outcome for these questions would be a framework that could be used as a tool for further multisensory implementations in CH.

In order to disclose a relevant answer for the last presented question, considering studies with users' evaluations, the evaluation process and the main evaluated variables will be reviewed. From here, it is intended to extract the impact and the main findings of multisensory experiences in CH contexts, and to disclose the limitations found across the processes.

2. Methods

The current literature review followed the PRISMA method [41] as a guide to the development of systematic reviews to ascertain a transparent and complete reporting of the surveyed topics.

2.1. Eligibility criteria

A randomized search that implemented multisensory VR and AR solutions in CH was addressed aiming to provide relevant data taking into account its implementations, usage, and evaluation. The inclusion criteria are specified in Table 1, whereas exclusion criteria are outlined in Table 2.

2.2. Search strategy

The strategy followed to obtain a full survey regarding to the specified topics, included two search stages: a search through online searches, and a search when analyzing the records obtained from the previous search stage.

For the first search stage, the literature was identified through online searches, by conducting an extensive search in well-known databases for their publications related to Virtual and Augmented Reality, namely Science Citation Index on Web of Science (Clarivate), Elsevier Scopus, ACM Digital Library, and IEEE Xplore. Following the need to better comprehend multisensory implementations across CH contexts, a first search was run on 28th of November 2018, being updated on 21st of December 2018 to ensure informed results. Later, aiming to keep an up-to-date survey, this search was again updated on July 10, 2021. The search was performed to be equivalent to the following logical expression: Title/Keywords/Abstract containing ("virtual" OR "augmented reality" OR "mixed reality" OR "mixed-reality" OR "VR" OR "AR" OR "MR" OR "XR") AND ("multisensory" OR "multi-sensory" OR "multisensorial" OR "multi-sensorial" OR "stimuli" OR "senses") AND ("cultural heritage" OR "museums" OR "museum" OR "historic city" OR "historic cities" OR "archeological" OR "archeological" OR "archeology" OR "archeology").

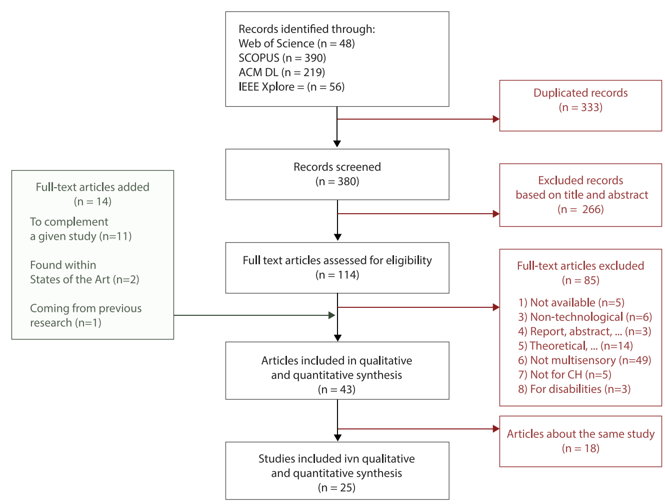

Fig. 1. Flow diagram of study selection.

For the second search stage, carried out when reviewing full-text articles (see Fig. 1 for a better context in relation to the several steps proposed in PRISMA method), a search was performed for eligibility when analyzing the full-text articles, due to the fact that some articles did not provide enough information for qualitative either quantitative analysis. In addition, previous studies, coming from a previous research, or studies which met the inclusion criteria established for this systematic review were found in the state of the art of these full-text articles and added to the current systematic review. Thus, Google Scholar platform was used to make an oriented search for these titles.

2.3. Study selection

Following the aforementioned search strategy, whereby a total amount of 380 records were obtained, an eligibility assessment was performed independently in a conventional unblinded standardized manner. Each paper was reviewed by two reviewers to decide its eligibility, based on the title and abstract of each study, taking into consideration the exclusion criteria. When a record was rejected by one reviewer and accepted by the other, that record was kept for eligibility.

When performing this task, 266 records were discarded, remaining 114 full text papers assessed for eligibility.

Table 2
Exclusion criteria.

Exclusion criteria	Description
Exclusion criterion 1	The paper is not available.
Exclusion criterion 2	The paper is written in another language than English, Portuguese or Spanish.
Exclusion criterion 3	The paper does not consider the use of technology.
Exclusion criterion 4	The paper is a technical report, an abstract, editor note, call for paper, or thesis.
Exclusion criterion 5	The paper is only theoretical (e.g. information system proposal, literature review), not presenting any implementation.
Exclusion criterion 6	The system described in the paper provides only an audio-visual experience, or only an one-stimulus-experience. E.g. haptic experience solo
Exclusion criterion 7	The system described in the paper it is not applied to a CH context.
Exclusion criterion 8	Stimuli are explored specifically for disability reasons.
Exclusion criterion 9	Access to read the paper denied.

2.4. Data collection process

The eligibility assessment performed across 114 full text papers, aimed to collect all data needed for the current systematic review. Among this process, some articles were dropped – considering the exclusion criteria – and other were added — coming from the second search stage.

The selected papers for full-text assessment were reviewed, and the data collection process was conducted using piloted forms. The variables considered were the stimuli considered in the study, technologies used to exploit the senses, context (indoors/outdoors), the evaluated variables for the experience, sample size, evaluation instrument, the main findings, and the limitations found. The evaluated variables for the experience correspond to the contribution of the multisensory system, such as satisfaction, added knowledge, sense of presence, usability, or quality of the experience (QoE).

Some considerations of collected data are relevant to highlight, in particular, related to type of immersion and to the purpose of each study.

2.4.1. Type of immersion

A classification into three categories – non-immersive, semi-immersive, and immersive – was made for VR systems. This classification, as literature suggests [7,19,42,43], identifies as non-immersive systems the usage of desktops; semi-immersive systems with large surfaces to display the visual-scene, such as projection-based screen displays, or sets of several wide screens; and immersive systems that almost, or completely, fills the user's field of view, such as CAVEs or HMD devices. The presented VR classifications do not include AR systems, which will not have a classification regarding to its immersive level, remaining classified as AR. In addition, some studies propose multisensory experiences without having a visual stimulus added – not VR nor AR –, which should be classified as not applicable (NA) considering this type of immersion classification. Accordingly, relating to type of immersion, a system may be classified as non-immersive, semi-immersive, immersive, AR, or NA.

2.4.2. Purpose of each study

Based on the survey of augmented, virtual and mixed reality for CH previous made [7], the purpose of each study is identified as:

- Education — focusing on tools and applications where learning is the primary goal;
- Exhibition enhancement — aiming to enhance a visit experience at physical museums and CH sites, not replacing it with virtual views;
- Exploration — applications primarily focused on the historical aspects of tangible archeological CHs leading to knowledge creation and new insights based on their discovery, exploration, and manipulation of the content;
- Reconstruction — applications allow users to visualize CH assets that existed in the past or that partially exist;
- Virtual Museums — Simulations of physical museums and CH sites, frequently extended to represent users as virtual-human characters inside the simulated environment.

2.5. Quality assessment items

The method followed to review all records takes into consideration quantitative analysis, revealing the amount of studies where a given item was identified. A quality assessment is carried out to identify the most suitable records towards the raised questions for the current study. Due to the intention of the current study to present a survey on multisensory implementations in CH contexts, a quality assessment was carried out. Following the guidelines to create a quality assessment checklist [44], and based on STROBE checklists [45], a set of questions was created to which predefined answers were settled – Yes (weight of 1), Partially (weight of 0.5), No (weight of 0). The questions established for this quality assessment are the following:

1. Clearly define all outcomes.
2. Clearly describe used technologies.
3. Report numbers of individuals at each stage of study.
4. Present variables to be handled in the study.
5. Describe all statistical methods.
6. Show and discuss results.
7. Report outcome events.
8. Discuss limitations of the study.

3. Results

The search made in the identified databases returned a total of 713 records, of which 333 were identified as being duplicates – and were consequently removed –, exposing a total of 380

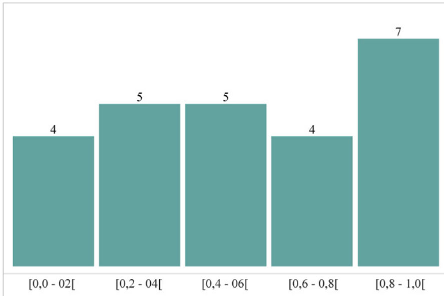

Fig. 2. Quality assessment scores, from 0 to 1, within intervals of 0,2 each bar.

records to screen. The title and abstract of the unique 380 records were analyzed, taking into account the eligibility criteria, from were 266 records were excluded for not meeting such criteria. As result, 114 records were obtained as being eligible for full-text analysis. From those 114 records, more 85 records were excluded based on the previously defined exclusion criteria. During the analysis, a search update was made in which 14 articles were added to the search, resulting in a total of 43 records for the qualitative synthesis. From these 43 articles, since some of them refer to the same implementation, they refer to a total number of studies included in this survey of 25. Please refer to Fig. 1 for a detailed overview of the study selection.

3.1. Quality assessment results

According to the aforementioned checklist of 8 items for quality assessment, having as possible answers 1 (for "Yes"), 0.5 (for "Partially"), and 0 (for "No"), a scoring regarding to the 25 studies was performed. An average score of 0,6 was obtained, having as average deviation of 0,2. The quality assessment scores histogram is observable in Fig. 2. The high-quality papers having into account this quality assessment are marked with an asterisk in the table which summarizes the 25 multisensory applications found in CH contexts, in the qualitative analysis section (Table 3).

This quality assessment shows that the scoring average of each study is disperse among the scale, where eight of these studies got an average score equal or above 0,8.

3.2. Qualitative analysis

Among the 380 results screened, from where 25 were studies carefully analyzed under the related 43 articles, Table 3 presents a summary of this review, being implicit the type of experience according to the immersion type — which can be related to VR, as being immersive, non-immersive, or semi-immersive, or AR. All studies provided indoors experiences.

Table 3 summarizes the 43 articles analyzed, aiming to characterize the 25 studies found. The description of each study is presented, as well as the type of immersion provided, and the quality assessment score assigned.

3.2.1. Summary of analyzed studies

The "Haptic Museum" was a pioneer research which aimed to give the opportunity to visitors to explore three-dimensional works of art by "touching" them over-the-network exploration of museum objects [46]. At this stage, the main contributions of this research were related to the development of low-level force-control algorithms for haptics rendering and techniques for haptic exploration of museum objects.

A virtual system was created through touch and sight senses in the "Museum of Pure Form" [47], a virtual museum of digital art in Italy. The overall system, in a CAVE and with an exoskeleton-supported with one arm as haptic interface, allowed to interact with a selected art piece standing in front of them.

The CREATE project was created to enable highly interactive real-time construction and manipulation of virtual worlds based on real data sources and including senses such as sounds and haptics [51].

"The Fire and the Mountain", a temporary museum exhibition at the Civic Museum of Como, Italy, conceptualized as a learning opportunity for visitors, was an exhibition implemented aiming to enforce emotions via technology, to promote active and social learning in a multi-modal way engaging multiple senses (visual, auditory, and tactile) [53].

"SenSpace" project, tested in the United States of America, uses visual, audio and tactile cues to convey the Greek myth of Narcissus to the user within a physical space [54]. This research proposes interaction between visitors and ambiguity as an important component of meaning-making.

A restored parlor organ from 1895 was able to produce varying combinations and intensities of sound, light, color, scent, vibration and movement. The "Emotion Organ" aimed to stimulate a highly subjective, cause-and-effect sensory immersion [55].

MediaEvo project is a didactic game aiming to explore the reconstructed heritage environment and learn about the Middle Ages through a virtual experience [56]. Inside MediaEvo Project has also been implemented a module to manage the interactions with artificial intelligence, the principal key for retrieving knowledge and experiences from the virtual reality [60].

One of the applications of "Ultra-realistic Communication Research", Japan, included a multisensory interaction system with vision, sound, touch and smell [61]. This research focused on digital museums consisting of a multisensory interaction system and two other systems, to provide a good impression to visitors.

"Virtual Kyoto" was a system developed for users to experience the things and events related to Gion Festival, in Japan, where users can experience high-defined decorations of Yamahoko with visual and haptic senses, the high-quality sounds of the Festival music and the virtual Yamahoko float ceremony in the 3D vision environment [62,63].

Focused on novel digitizing techniques to create virtual exhibitions in the context of the "Gold Museum in Bogotá", Colombia, commercial haptic devices into a new virtual installation that allows visitors to touch, hear, and see virtual approximations of the real objects was also integrated [64].

"Museu3I" is an immersive, interactive, and itinerant virtual museum which was developed in order to allow users to perform virtual visits and, with the use of haptic when visitors have available a haptic device [66].

A proxy-based rendering system was designed combining visual, auditory, and haptic senses [67,68], here presented as "Hapto-visual and Auditory Rendering". This multi-modal visualization of digitally preserved heritages aiming to enrich user's experience in the virtual world.

"The Reconstructed Historical City of Tomis", now Constana (Romania), a multisensory study, focused on haptics was developed to identify to what extent different types of assistance methods are natural, intuitive, and efficient [69].

Aiming to create a new combination of real and virtual scenarios in order to enrich the experience, the knowledge and the multi-sensory perception of museum visitors, an interactive solution was proposed in the "National Archaeological Museum of Marche", Italy [71]. According to this study, due to the technological solution proposed, learning of historical and cultural content increased and greater user involvement during the visit to the museum can be accomplished.

Table 3
Summary of the analyzed studies referring to the immersion type, and the quality assessment score assigned.

Reference	Designation	Immersion type	Quality assessment
[46]	The Haptic Museum	non-immersive	0,5
[47–49]	The Museum of Pure-Form *	immersive	1,0
[50–52]	CREATE project *	immersive	1,0
[53]	The Fire and the Mountain	non-immersive	0,6
[54]	SenSpace project *	semi-immersive	1,0
[55]	The Emotion Organ	non-immersive	0,4
[56–60]	MediaEvo project	semi-immersive	0,2
[61]	Ultra-realistic Communication *	immersive	0,8
[62,63]	Gion Festival in Kyoto	semi-immersive	0,4
[64,65]	The Gold Museum in Bogotá *	non-immersive	0,8
[66]	Museu3I	non-immersive	0,3
[67,68]	Hapto-visual and Auditory Rendering	non-immersive	0,4
[69,70]	Historical city of Tomis	non-immersive	0,6
[71]	National Archaeological Museum of Marche	immersive	0,7
[72,73]	Tate Sensorium *	*n.a.*	1,0
[74]	SensArt Demo: Art Gallery	*n.a.*	0,6
[75–77]	The Feelies	immersive	0,3
[78,79]	Zelige Door on Golborne Road	AR	0,4
[13]	Tanning in Medieval Coventry	immersive	0,6
[80]	Haptic System for Archery *	immersive	0,9
[81]	The Shanghai style jade carving	non-immersive	0,3
[82]	Road Grader Simulator *	semi-immersive	0,9
[83,84]	M5SAR	AR	0,6
[85]	Thresholds: VR in museums *	immersive	0,8
[86,87]	SensiMAR *	AR	1,0

* high-quality papers with an average of 0,8 or higher in the quality assessment score. *n.a.* stands for "not applicable".

Part of "Tate Sensorium" (developed by Flying Object, the winning project of IK Prize 2015) at Tate Britain, London (England), experts in sound, taste, scent and touch as well as lighting and theater draws together a small sensory exhibition among art paintings, conducting a pioneer case study on how to design art experiences whilst considering all the senses, to provide a new view on those exhibits by creating a new emotion [72,73].

An art gallery enhancement in Canada, was proposed by the authors of "SensArt" [74] by exploring the sense of hearing and haptics.

"The Feelies" developed a multisensory experience in 2015 with virtual reality productions within theatrical settings [75,77], focused on writing, shooting and delivering original content. This experience was found to be temporary available in New York, United States of America, and also in São Paulo, Brazil.

Published as a workshop, visitors to Coventry's Herbert Art Gallery and Museum were transported back to the 15th century and visit a "Tanning in Medieval Coventry", England, through a recreation of authentic multiple senses to enable the visitors to experience what the past may have been like [13]. The explored senses were visuals, audio, smell, and temperature — being exposed to stimulate the sense of touch.

Aiming to make explicit the relationship between interaction design and people's perception, the installation "Zelige Door on Golborne Road", London, provided an AR application with olfactory technologies to superimpose pre-recorded video and smells [78].

Intended to develop engineering systems for training using simulations in virtual reality, the "Interactive Haptic System for Archery" was developed and presented in several technological exhibitions, for experiencing traditional archery [80].

Having the "Shanghai style jade carving" in China as an example, the technical means to achieve a multiple senses experience was designed [81]. A design of a multisensory system was presented, showing what the system may provide to users.

Based on Omnidirectional video (ODV), audio, and haptic feedback, a "Road Grader Simulator" installation was built in Finland [82]. Although not focused on the multisensory approach evaluation, a seat with haptics feedback from their first experience suggests that it may represent a statistically significant improvement to the user experience.

Aiming to develop an AR system to be a guide in cultural and historical events and museums, the mobile five senses augmented reality system for Museums is proposed in the M5SAR project [83]. Presently, the tests made in this study, from Portugal, are related to the system performance, not providing an evaluation respecting to the visit enhancement.

Aiming to fuse virtual and physical realities, "Thresholds" created a virtual world to be explored inside a room, physically replicated in accordance to the virtual scenario, already exhibited at locations in the United Kingdom and in Turkey. Thus, the users were able to touch real elements that were aligned with the virtual objects [85]. Accordingly, a series of iterations of both physical and virtual model were available in the experience. The results, by tracking the visitors experiences, provided interesting data related to the way that visitors explore a site virtual and physically.

To better understand the role that each stimulus can play during an experience with AR, SensiMAR proposed a mobile experience outdoors, while exploring an archeological site in Portugal, that will provide added information to the visit [86]. A virtual reconstitution was provided for the AR experience, as visual stimulus, being then complemented with audio and smell. The results of this study provided insights related to the role that each stimulus play in the visitor's perspective, in relation to their sense of presence, the acquired knowledge, their sanctification and the value of the experience.

3.2.2. Implementation characteristics

The described multisensory studies applied to CH sites included all works found regarding to the use of technologies for stimulating several stimuli at the same time in a given experience. Table 4 resumes the characteristics of the analyzed studies such as the purpose and explored stimuli.

The setting where the experience took place was identified (indoors or outdoors) was also considered but, since all application took place indoors, this info is suppressed.

Table 4
Summary of the analyzed studies referring to implementation characteristics.

Designation	Purpose	Visual	Audio	Smell	Haptics	Taste
The Haptic Museum	Exploration	Screen display			Haptic Interface	
The Museum of Pure-Form	Virtual Museum	CAVE	PC Speakers		Haptic Interface	
CREATE project	Education	CAVE	Speakers Stereo display		Haptic Interface	
The Fire and the Mountain	Education	Screen display; Projector	Speakers		Touch Screen	
SenSpace project	Exhibition enhancement	Screen display; Projector	Speakers		Haptic interaction (with water)	
The Emotion Organ	Exploration	Screen display			Haptic Interface	
MediaEvo project	Education	Projector	Speakers		Haptic Interface	
Ultra-realistic Communication	Exhibition enhancement	Screen display; Stereoscopic glasses	Headphones	Olfactory display	Haptic Interface	
Gion Festival in Kyoto	Virtual Museum	CAVE	omni-directional loudspeaker		Haptic Interface	
The Gold Museum in Bogotá	Exploration	Screen display	Speakers stereo display		Haptic Interface	
Museu3I	Virtual Museum	Screen display			Haptic Interface	
Hapto-visual and Auditory Rendering	Exploration	Screen display	Speakers		Haptic Interface	
Historical city of Tomis	Reconstruction	Screen display	n.d.		Haptic Interface	
National Archaeological Museum of Marche	Education	Screen display; HMD HTC Vive		Haptic Interface		
Tate Sensorium	Exhibition enhancement	*(paintings)*	Polar Audio Headphones	*(parfums or oils)*	Haptic Interface	(chocolate)
Art Gallery	Exhibition enhancement	*(paintings)*	Headphones		Haptic belt	
The Feelies	Exhibition enhancement	HMD	Head-phones binaural	*(parfums or oils)*	Haptic Interface	
Zelige Door on Golborne Road	Exhibition enhancement	Mobile device	Tablet Speakers	Olfactory display	*(real objects)*	
Tanning in Medieval Coventry	Reconstruction	HMD Oculus Rift DK2	Head-phones Oculus Rift DK2	CFD	Fans; Heater	
Haptic System for Archery	Exploration	HMD	Headphones Ambisonics		Haptic Interface	
The Shanghai style jade carving	Exploration	Screen display	n.d.	n.d.		
Road Grader Simulator	Virtual Museum	Projector	Speakers		Haptic seat	
M5SAR	Exhibition enhancement	Tablet	n.d.	Fans and fragrances	Heaters on device handlers, device vibration, and fans for air flow	electronic vaporizers
Thresholds: VR in museums	Exhibition enhancement	HTC Vive	Headphones		Heater *(and real objects)*	
SensiMAR	Reconstruction	Smartphone	Speakers Ambisonics	Olfactory display		

n.d. stands for "not defined". CFD stands for Computational Fluid Dynamics.

With reference to smell implementations, in some cases as visible in the presented table, technology did not play a role when adding it because parfums or oils are being used, having the smell always present in the experience without an interaction between the user and the sense. For visual, audio, and haptic stimulation, all presented studies adopted technologies on, at least, one of the explored stimuli.

3.2.3. Analyzed studies with user tests

Aiming to answer the questions raised for the current research, the multisensory studies that performed user studies related to the experience impact on participants are more meaningful for looking into. Thus, regarding to users' evaluation of the analyzed implementations, Table 5 summarizes some evaluation details, experimental design notes, and variables under consideration.

The presented "dependent variables" were gathered from authors' intentions on their multisensory proposals, including cases where user tests were not found to evaluate those given variables.

When searching for the role played by each stimulus when invoked in each experience, the collected data does not provide clear information to understand the changes of adding each stimulus. Experimental or quasi-experimental designs that covered as independent variable the addition of one or more stimuli, providing positive impact on the analyzed dependent variables, such as enabling the haptic render to the experiment [49], activating the stereoscopic display [65], changing the visual

Table 5
Summary of the analyzed studies focusing on conducted user tests and evaluations.

Designation	Sample size	Evaluation Instrument	Experimental design	Independent variables	Dependent variables
The Haptic Museum	No user tests found				
The Museum of Pure-Form	6	Questionnaires	Quasi-experimental	Haptic rendering (enable/disable)	Satisfaction; Sense of Presence; Usability; QoE.
CREATE project	46	Questionnaires; Interview; Direct observation.	Non-experimental		Satisfaction; Knowledge; QoE; Effectiveness and Efficiency.
The Fire and the Mountain	62	Interview; Direct observation; Video recording.	Non-experimental; Ethnography design.		Usability; Social Interaction.
SenSpace project	24	Questionnaires	Pre-experimental	Fore-knowledge; Filling the questionnaire (alone/jointly).	Physical Interaction; Interpretation
The Emotion Organ	No user tests found				
MediaEvo project	No user tests found				
Ultra-realistic Communication	200	Questionnaires	Non-experimental		Satisfaction; Usability; Acceptance.
Gion Festival in Kyoto	No user tests found				
The Gold Museum in Bogotá	42	Questionnaires; Direct observation.	Pre-experimental	Stereoscopic display type (active or auto)	Satisfaction: Usability; QoE; Metaphor.
Museu3I	No user tests found				
Hapto-visual and Auditory Rendering	10	Questionnaires	Non-experimental		QoE
Historical city of Tomis	No user tests found				
National Archaeological Museum of Marche	27	Video Recording	Quasi-experimental	Visual apparatus (3S screen; 3D red/blue glasses; 2D in HD)	Knowledge
Tate Sensorium	2500	Questionnaires; Interview; Direct observation.	Experimental	Haptic pattern	Satisfaction; QoE.
SensArt Demo: Art Gallery	12	Questionnaires	Pre-experimental	Stimuli (Visual, multisensory)	Emotion
The Feelies	600	*n.d.*			*n.d.*
Zelige Door on Golborne Road	n.d.	Interviews (in groups)			Memories; Artistic outcomes.
Tanning in Medieval Coventry	No user tests found				
Haptic System for Archery	20	Questionnaires	Pre-experimental	Shooting type (real bow or haptic bow)	Satisfaction; Sense of Presence; Usability; QoE; Overall Experience.
The Shanghai style jade carving	No user tests found				
Road Grader Simulator	215	Questionnaires	Experimental	Installation types (baseline; haptic; 23 screens; inverted steering)	Sense of Presence; Usability; Overall Experience.
M5SAR	72	Questionnaires	Pre-experimental	Two modules (audio-visual and five senses)	Acceptance

(*continued on next page*)

Table 5 (*continued*).

Designation	Sample size	Evaluation Instrument	Experimental design	Independent variables	Dependent variables
Thresholds: VR in museums	200	System logs			Time spent; Interaction choices.
Thresholds: VR in museums (continuation)	12	Questionnaires			Enjoyment; Immersion.
SensiMAR	60	Questionnaires; Direct observation.	Experimental	Added stimuli conditions: (1) none (2) visual (3) visual + audio (4) visual + smell (5) visual + audio + smell	Usability; Sense of Presence; Enjoyment; Acquired knowledge; Value of the Experience.

n.d. stands for "not defined". QoE stands for "Quality of the Experience".

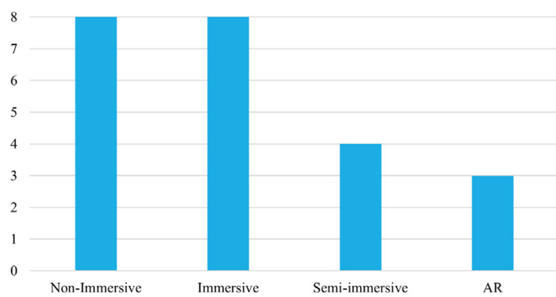

Fig. 3. Level of immersion across multisensory studies.

apparatus [71], adding multisensory setup instead of only the visual stimulus [74], or changing the installations types [82].

3.3. Quantitative synthesis

The quantity of senses evoked in the analyzed studies are presented in this section, as well as the setups used for the implementations. Proposed variables for evaluate the multisensory impact are also quantified.

3.3.1. Level of immersion across multisensory studies

Following the characterization presented in Table 3, according to the type of visual device used as previously explained, the experience can be non-immersive, semi-immersive, immersive, or AR — note that AR is classified as a type of immersion itself due to the variant levels of virtual content that can be added in such experiences. Note that experiences where visual stimulus was the real scenario [72,74] were indicated as "not applicable", thus they are not considered as a type of immersion. Fig. 3 summarizes the distribution of the analyzed studies according to the type of immersion provided.

3.3.2. Multisensory stimuli and setups used

Counting the number of times which each stimulus was added to the CH site experience in multisensory applications, it is noticed that sight is the more frequent sense explored, as illustrated in Fig. 4.

When exploring haptics among multisensory experiences, Fig. 5 resumes how many studies used haptic interfaces or other solutions — including fans, heaters, screen vibration, or interaction with water.

When providing images for visual stimulus, Fig. 6 resumes the setups found, namely, Screen monitor, video projections, HMD or shutter glasses, CAVEs and mobile devices — tablets. or smartphones

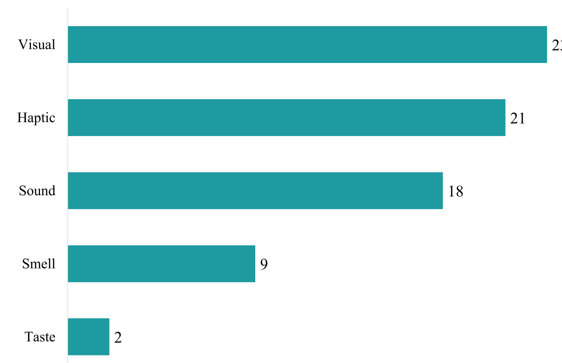

Fig. 4. Graphic representation of added stimuli to the multisensory implementations applied to CH found in literature.

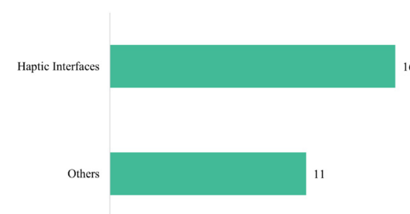

Fig. 5. Summary of haptics devices used in multisensory implementations analyzed.

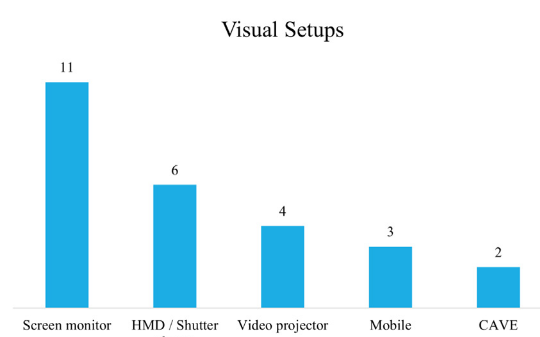

Fig. 6. Identification of setups used for sight stimulation amid multisensory studies found.

Regarding to audio technologies, two technologies were found as solution to evoke this sense – speakers and headphones – and its usage is illustrated in Fig. 7.

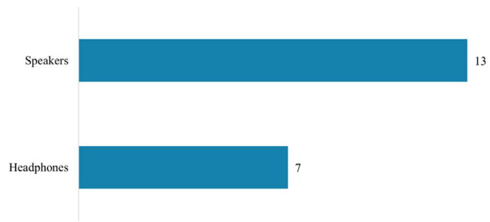

Fig. 7. Summary of audio devices used in multisensory implementations analyzed.

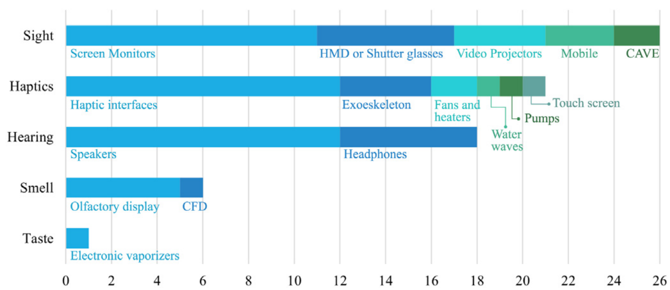

Fig. 8. Displays in use for each stimulus explorations among the analyzed studies.

Fig. 9. The amount of studies found classified according to their purpose when installed in CH.

In the overall, the diversity of used devices to explore sense, are resumed in Fig. 8.

The chart expresses the variety of devices used according to the different gray tonalities of each stimulus bar, specifying the most common displays implemented. Despite the fact of haptics being also very frequent in the multisensory implementations found – as Fig. 4 suggests –, there are much more visual devices found because some studies used more than one device to stimulate vision in their experiments. Regarding to smell devices, olfactory displays refer to custom devices developed for the experience. Perfumes also include the use of fragrances and oils.

When analyzing the exploration of taste stimulus in multisensory implementations in CH, only one display was found — in particularly, electronic vaporizers.

3.3.3. The aim of multisensory applications

The following sections group the studies according to their purpose and according to the variables that were intended to be validated across these implementations.

The Purpose of the Implementations

The motivation behind the multisensory studies found in CH differ between five categories and Fig. 9 illustrates the number of studies in each category as to their purpose in the implementation found.

The main reason for implementing multisensory in CH is for exhibition enhancement (9 implementations), followed by exploration, virtual museums, education, and, last of all, reconstruction.

Variables Proposed for Evaluation

The search made aiming to provide the answers for the proposed questions, found some studies that did not have enough information to provide all needed data, such as the studies that did not present user tests aiming to understand how stimuli can change people perceptions in CH. Concerning to the evaluated variables found among user evaluations, a search overall is presented in Table 5. The variable presented as "usability", also includes interaction issues, ease of use, ease of understanding, manipulability – 7 studies proposed this variable for evaluation. Likewise, "satisfaction" variable encloses arousal, liking, enjoyment, and also general reactions such as frustrating/excellent, boring/exciting, rigid/flexible – 6 studies proposed this variable for evaluation. For quality of the experience ("QoE"), was also included into this variable, studies which aimed to evaluate sense of touch (for haptic experiences), quality of contents, and realism subjects – 6 studies proposed this variable for evaluation. "Sense of presence" includes the variables presented as engagement and as immersion – 3 studies proposed this variable for evaluation. Also 3 studies referred to knowledge as a variable to study, the overall experience is referred twice, as well as interaction outcomes. Acceptance, emotion, memories, metaphor, and artistic outcomes appear once as variables to be evaluated among participants. Given the lack of information regarding to the evaluating process, some studies did not present clearly the results regarding to the variables that are initially targeted to be evaluated. In some cases, the variables are proposed to be evaluated but the collected information is not enough to support its evaluation. Thus, the most commonly variables efficiently evaluated among the analyzed studies were usability, followed by satisfaction and sense of presence.

4. Discussion

The current survey aims to synthesize qualitatively and quantitatively the literature focused on the use of technologies for multisensory applications when targeted for CH contexts. The purpose of the current discussion is to provide valuable data for better understanding of multisensory AR applications in CH — debating about what stimuli were explored, how were these experiences implemented, in what conditions were they used and tested, for what purposes, and discuss about impacts and limitations of multisensory applications nowadays. The clear divergence between the uncovered solutions is a central key to highlight. All records have in common the aiming for improve users' experiences among CH, but their approaches are so distinct that each study, even after a carefully analysis, did not provide all information needed for a full understanding of the multisensory results. Each approach is described differently, not following a guideline to present and expose their implementation, not providing all needed information for a detailed analysis and review, leading to difficult – or, sometimes impossible – replications of the implementations.

Observing the assigned quality assessment for each study on the aforementioned Table 3, it is noticed that higher values obtained in the quality assessment are found in immersive systems, meaning that these types of studies have been providing more answers to the questions raised for the current analysis. Therefore, too little information was obtained regarding AR multisensory as an emergent solution in CH [21–23,88].

Previous literature highlighted the need of evaluation studies [28]. More recently, users are again in the scope of these implementations due to the need for curators to provide users with a new perspective on their collections [7], pointing out the need for further research to cover tracking and registration, realistic rendering, and human–computer interaction. The following discussion, based on the multisensory studies found in CH, provides relevant insights regarding to evoked senses, their role in the experiences, and user evaluation found.

4.1. Evoked senses in multisensory experiences in CH

An overview regarding to which senses are being evoked in multisensory virtual or augmented reality experiences in CH is thereafter presented. The major part of studies presented their results as an overall multisensory experience, not providing results from each stimulus exploited, such as [53,54,61], or did not gathered data comparing the presence or the absence of a given stimulus [65,82].

Results evince that the most common senses evoked are sight (92,0%) followed by haptics where 84,0% of the 25 multisensory studies reviewed, provided haptics and/ or visual experiences, then followed by audio (72,0%). Smell and taste were the less explored stimuli, specially the taste — found only twice, representing 8,0%, having only one occurrence that used a technological implementation for exploring this stimulus. Smell experiences combined with, at least, one other stimulus, are found in 36,0% of the analyzed studies.

Evoked Senses: Vision

Considering visual stimulus, as discussed above, almost every implementation found provided visual content added to the experience (23 studies in a total of 25). However, mainly due to the fact that most part of technological approaches to enhance visitors' experiences in CH are providing visual content – when not focusing in multisensory experiences –, the main findings provided by these multisensory implementations did not revealed particular findings regarding to the addition of this sense. Accordingly, no results comparing an experience with and without visual content added, were spotted.

Evoked Senses: Touch

The usage of haptics is one of the predominant evoked senses, being present among 21 studies. According to this literature review, haptics has proven to bring enhanced experiences among CH. However, some aspects are pointed out that should be taken into consideration for further implementations to better fulfill participants' needs. The first multisensory application found with user tests suited for this analysis in CH contexts [47], used a skeleton as haptic device and its comfort was rated as being quite low [49]. Users felt intimidated by the exoskeleton and they did not find the sense of touch realistic.

When used as a potential tool for education, a much more detailed representation would be required [52]. However, in the overall experiences, users enjoyed the experiment more when exploring with haptics. More recent approaches regarding to haptics has appeared as being easy or relatively easy to use — users affirmed to have a great involvement in the experiment [50,80]. According to the analyzed studies, the realism of the haptic experiences was not accomplished in any reviewed studies. In addition to being stated as not comfortable [49,52], it remained clear for users to identify whether they were using haptics technologies or real objects [80], or they seemed to be afraid or too enthusiastic about expected feedback [65].

Also related to haptics, some studies suggest feelings related to wind and heat [13,81], but there was no user tests found for these situations so far. Note that a ceramic heater was found to be added to the experience in the Thresholds project [85], where user tests were found. However, this study did not evaluate the influence of the heat feeling during their experiences, being pointed out as future considerations for further implementations alike.

Evoked Senses: Hearing

Audio has also been often added to the experience (18 studies in a total of 25), without pointing particular studies aiming to understand its influence comparing the experience with and without its addition. Most part of the studies did not specify the type of installation for audio stimulus, remaining unclear the purpose of the added sound – e.g., would it be a narrative with explanation? A soundscape? Or lounge music? Each one of these can arouse a different reaction in the user and, given the collected data, it is not possible to make any advances on this analysis. However, when in multisensory experiences, audio is stated to contribute for an authentic experience [13], playing a significant role in participants' involvement from visitors perspective and their behavioral presence during the experience [86], which sparks its interest for further multisensory approaches.

Evoked Senses: Smell

Regarding to smell, explored in eight multisensory experiences in CH (32,0%), stays as uncertain which is the more stable solution to explore this stimulus. Some studies simply added parfums or oils to the experience [30,72], others present olfactory displays [55,61,78,81,83,87]. One of the studies used a simplified version of a Computational Fluid Dynamics (CFD) [13].

Its usage, has been diversified between the analyzed implementations which create curiosity about the role of each implementation in users experiences, however users' evaluations collected do not provide unanimous data regarding to participants' opinions or feelings about the smell experiences, since this was not the scope of the analyzed studies. Thus, even though the smell is proved to be essential in the perception equation [9] and presented by literature as having a key role in recollecting personal memories and to arouse visitor emotions [15] this is not clear in multisensory experiences in CH so far, being actually reported with weak importance in the multisensory experience, when compared with taste, visual, and hearing [72]. Nonetheless, when participants were submitted to experiences with and without smell without knowing, spatial presence and experienced realism was positively influenced when comparing between a visual experience and visual with smell added to the scenario [86].

Evoked Senses: Taste

Focusing on taste, in multisensory applications in CH (8,7%), was found one technological approach, using electronic vaporizers (also known as electronic cigarettes) [83], and one where chocolate was given to users as part of the multisensory exploration [72]. The first, apart from the usability tests, does not provide users' perspective about its addition yet. The second, by adding a chocolate in the experience, reported a weak importance in the multisensory experience.

4.2. Virtual and augmented reality setups used

From all analyzed studies, two of them [72,74] did not specify any virtual content added to the experience. Among the studies which implemented virtual or augmented reality setups, they were diverse among their approaches. As previously mentioned, a classification regarding to the type of immersion was made. This classification showed that, across the studies that added visual devices in their experience, an equal number of non-immersive and immersive experiences were identified, where in 69,6% of the studies were immersive or non-immersive, 17,4% were semi-immersive, and 14% were AR experiences.

Regarding immersive studies, the more frequent system used so far, is through HMD devices [13,61,71,75,80,85]. From these immersive installations, it was observed that, apart from the stereoscopic glasses used in 2010 [61], all other HMD devices used for multisensory implementations among CH, appeared after 2017, in contrast with screen monitors, video projections and CAVEs, that were much more frequent before 2017. More specifically, 81,2% of screen setups are found in studies from 2015 or earlier, 100% of the CAVEs were used in 2010 or earlier, and 75,0% of the projections made are found in 2009 or earlier. Regarding to HMD usages, they are all found in 2017 or later, and AR solutions, all of them mobile, are found in 2018 or later.

In short, the variety of setups found is wide. Note that, in several cases, were not tested neither evaluated by users. An interesting insight is related to the frame window that clearly appears to influence these setups across the time.

4.3. The role of multisensory in VR and AR experiences in CH

To discuss the role of multisensory VR and AR experiences in CH is helpful, since the studies did not follow a common guideline for implementations neither for evaluation, to understand the purpose of its implementation, as well as to understand the impact on the dependent variables of its usage.

4.3.1. Purpose of its implementation

Aiming to observe the reason for appealing to multisensory experiences were targeted, according to the aforementioned classification proposed by Bekele et al. [7], it was found a larger number of experiences aiming to exhibition enhancement (36,0%), when compared to other purposes. Namely, 20,0% of the implementations were classified as exploration, the same amount of studies virtual museums and education (16,0%), and 12,0% focusing on reconstruction.

Bridging the results and revealing a significant difference between the current survey and the latest found [7], which did not dwell into the multisensory approaches, they identified VR being applied, mostly, for virtual museums. According to the current study, when analyzing VR in a multisensory environment, it is the exhibition enhancement that is the main purpose for the implementation. The referred survey of VR and AR in CH [7] revealed AR as preferable for exhibition enhancement which sparks interest for multisensory AR applications. However, as observed in the current survey, the three AR implementations found are not enough to discuss this issue.

When analyzing the impact of multisensory experiences, it is meaningful to highlight the lack of user tests found. When reviewing the studies, in some of them, no user evaluations were found, others, were tested with expert users [52] or with users that do not represent end-users [65] – which should be visitants from CH sites. In total, only 68,0% of the reviewed studies alluded to user tests as final users, remaining 32,0% multisensory setups with a lack of user test and evaluation. Among the studies that referred to user tests, only 28,0% presented – or partially presented – the statistical methodology and discussed their results.

Observing the collected data from Table 5, where the lack of users' evaluations among these multisensory implementations is notorious, a very diversity of samples was identified: from only 6 participants [47], to around 2.500 [72]. From the known evaluations analyzed (a total of 16 studies since 8 of them are not found to have user tests and one did not provide enough information to know data was collected and evaluated [30]), questionnaires are the most common instrument for evaluation (81,3% of the times used), followed by direct observation (31,3% of the times), interviews (18,8% of the times) and, at last, video recording with two usages, and System logs data, once.

Dwelling on evaluated variables, Satisfaction and Enjoyment were the more frequent variables proposed for evaluation (50,0%), followed by Usability (43,8%), for QoE (proposed in 37,5% of the studies), and Sense of Presence and Immersion (considered in 31,3% of the studies). Talking into consideration evaluated variables – which means, studies where results were found –, it is noticeable that satisfaction, overall experience, and acceptance, when evaluated, were always validated. The biggest difference when validating variables is found in QoE, which presented a low rate of validation. This is related to the realism, inserted into this category, which was not accomplished among the reviewed studies.

4.3.2. The role each stimulus in multisensory experiences

As discussed above, the multisensory implementations are very distinct and this singularity reflects also in the impact obtained, depending on the main goal for each study. To identify the positive – or negative – impact of these multisensory approaches in CH, depending on the results obtained of the analyzed variables, a careful analysis on each study insights of was conducted. Based on authors' considerations in their overall analysis and based on their conclusions, 78,6% clearly stated as positive the impact caused by the multisensory experience, remaining 21,4% as not conclusive — no study was found as having a negative impact on users.

According to results and authors' conclusions, end-users are in favor of using haptic devices in CH context [49,80] and, when combined with other senses, can enhance their experiences due to the greater user involvement [71], allowing stronger emotional reactions [72,86], opening new ways of thinking and interpreting information [72]. Multisensory experiences, preferred by the major part of the participants [47,74,83,85], are also stated to be very useful [61], since is demonstrated to be effective for learning and communication [71], providing a greater feeling of involvement [80] and immersion [82] in the experience.

According to the discussed data, an answer for the question that aimed to understand what is the role of each stimulus in the multisensory experiences in CH, cannot be formulated mainly due to the disparity found between systems goals and evaluations. Further research is needed to sustain the relevance that each stimulus has in users' experiences, since it appears to have different outcomes according to the added stimuli [86]. For example, the addition of smell in an AR experience appears to positively affect users' spatial presence. However when the sound was also added, the spatial presence was no longer verified. Thus, the need for a better and deeper understanding of the role of each stimulus play in virtual experience remains.

4.4. Limitations found in multisensory experiences in CH

As noticed, the lack of user evaluations evinces some limitations regarding to results obtained amid multisensory applications in CH contexts. As mentioned in a previous survey regarding to virtual museums [28], the need of evaluation studies involving end-users in order to better understand further implementations, remains. Especially, considering that typical users of this technological setups among CH are non-experienced and non-trained people, who aims to find meaningful and pleasant experience in a very limited amount of time, precluding them to have slow learning curves [19].

In addition to the limited amount of user tests, other limitations were found among the different studied approaches, in such a way that some of these virtual installations are stated to be far from a real-world context with non-expert users on a long-term basis, calling the attention for the need to make the environments more usable [52]. Individual differences are also referred as a matter to take into considerations for further implementations [54,65,72]. It has been noticed that some of the evaluations were made having groups of participants instead of individual experiences, which may result into conditioned data collection, when trying to identify the impact of the sense on each individual participant [54,72]. Some of the experiences were not targeted for evaluating the multisensory itself, resulting in less data acquired, hampering the understandings about how multisensory can be valuable in CH when compared to a regular visit — or when compared to an audio-visual experience.

Also related to results obtained, another limitation found was the specification of used instruments for evaluation. In some studies, due to the absence of information related to the used instruments for collecting data, it is not possible to clearly identify how the variables were evaluated, remaining a slight uncertainty about how to evaluate further multisensory implementations.

A scarce number of previous studies are found in literature regarding to multisensory AR implementations. The two cases of AR are not enough to identify setups for comparison, moreover, without detailed user evaluations.

The analyzed studies did not provide enough information in order to understand the role of each stimulus in each experience. This understanding would be helpful for further implementations, since it would provide concrete data about what changes can each sense create in the participant experience. All multisensory implementations analyzed provided indoors experiences which reveals a lack of knowledge regarding to the possibility of implementing such solutions outdoors.

4.5. Overall discussion

As an overall analysis, the main limitation found after analyzing the described studies is related to the lack of standardization in relation to the process of implementing multisensory experiences. A significant mismatch was found across the studies, becoming a true challenge for further implementations to find a common thread to a successful multisensory solution.

Given the diversity of implemented systems, the collected data did not provide enough insights to trace a guideline to implement a multisensory approach in CH. Following this limitation, the fourth research question raised for this study is not completely answered. It is now possible to affirm that a wide variety of multisensory implementations for CH context is possible to conduct, mainly providing a clear positive impact on peoples' experiences.

Furthermore, the lack of deep description related to the overall variables at study for comparing the impact of the addition of each stimulus, highlights the need for deeper research regarding multisensory implementations. In fact, this need is reinforced by the inconclusive impact of the addition of stimuli in the analyzed experiences. One of the latest studies even raises new questions regarding the differences that each stimulus can make in a single experience [86].

5. Conclusion

This systematic review was focused on finding interactive multisensory implementations applied to CH contexts, unveiling what stimuli are being evoked and how they are being delivered to people who experiment them. Understandings regarding to the reasons why the senses are being evoked, as well as what previous researchers evaluated when implementing these solutions and how they did evaluate it, were also searched, presented and discussed.

According a large number references of previous studies pointing out the advantages of evoking more stimuli in experiences, this survey attempted to clarify what is already known in literature. An overview of the way that different senses may be exploited and evoked through technological approaches for CH was discussed. Despite the evident benefits found in multisensory experiences, there are also significant limitations that should be considered for further implementations. It was observed that little is known regarding the role of each stimulus in a CH experience, and the impact of these stimuli when blended, is even more uncertain. Nevertheless, highlighting the relevance of evoking stimuli aiming to enrich experiences, this research demonstrates multisensory for CH as a great chance for creating innovative applications, in order to provide more comprehensive insights regarding to the use of multisensory solutions.

In the overall, the relatively small amount of interactive multisensory implementations applied to CH found in literature was found – 25 instances –, specially, regarding to users' evaluations, evince the risks of the unknown for museums and other CH sites when attempting to provide multisensory solutions. Thus, more implementations targeted on clearly demonstrating multisensory advantages can be a great channel to understand how to truly enhance and enrich CH experiences, strengthen the relation between CH and the use of technology.

The need for guidelines to help and support the implementation of a multisensory approach in CH remains wherefore it is addressed as the most valuable further research in this area. Thus, the current review suggests for future multisensory VR or AR implementations, to accurately and actively look for answers related to what stimulus to evoke, how, and why. Once defined, all specifications of each implementation, regarding technologies used, setups, variables to be studied, providing detailed information about the evaluations made and related results, should be clearly described. Following a complete guideline for these implementations will strongly supply further implementations, in a way that will be possible to predict more accurately what could be the advantages of adding each stimulus for a given context.

CRediT authorship contribution statement

Anabela Marto: Conceptualization, Data curation, Investigation, Resources, Writing – original draft, Writing – reviewing and editing, Visualization. **Alexandrino Gonçalves:** Writing – reviewing and editing. **Miguel Melo:** Formal analysis, Validation. **Maximino Bessa:** Methodology, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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