



# Virtual Experiences, Real Memories? A Study on Information Recall and Recognition in the Metaverse

Nannan Xi<sup>1</sup> · Juan Chen<sup>2</sup> · Filipe Gama<sup>1</sup> · Henry Korkeila<sup>1,3</sup> · Juho Hamari<sup>1</sup>

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## Abstract

There are high expectations towards extended reality (XR), namely the “metaverse”. However, human performance in the metaverse has been called into question when undertaking everyday activities (e.g., working, shopping, and learning etc.), as complex human-technology interaction required may hinder cognitive abilities such as processing of information. Therefore, this study attempts to address whether and how XR impacts abilities to recall and recognize information in daily-life settings. We investigated the effects of VR and AR in a 2 (VR: yes vs. no) × 2 (AR: yes vs. no) between-subjects design experiment related to a shopping task (N = 153) on textual (product names) and pictorial (product pictures) recognition and recall. The results show that textual information recall and pictorial information recognition did not significantly suffer in XR compared to shopping in a brick-and-mortar store. While regarding textual information recognition performance, the results show that fully physical environments offered the highest performance compared to the different XR technologies being used. Overall, the study provides important findings and guidance for the use of extended reality technologies in consumer-facing businesses, as well as the use of XR in everyday life in general.

**Keywords** Virtual Reality · Augmented Reality · Metaverse · Memory · Retail

## 1 Introduction

Today, there are multiple veins of development along which our lives both converge and diverge in terms of “reality” and “virtuality”. Increasingly important areas of our lives are experienced through computer and information

technology-mediated environments, but these environments shape what is important to us and introduce new facets of meaning into our lives. At the helm of these multifaceted developments have been XR (Extended Reality) technologies which most commonly consist of VR (Virtual Reality) and AR (Augmented Reality) (Rauschnabel, 2021; Rauschnabel et al., 2022). Today, VR refers to technologies that attempt to substitute the present reality via multimodal and multisensory stimuli (Bonetti et al., 2018; Xi & Hamari, 2021) and create a sensation of “being there” – i.e., being in another reality (Hardiess et al., 2015). Different from VR, AR refers to technologies that superimpose information on top of the reality, and thus “augment” the reality (Pantano & Servidio, 2012; Rauschnabel, 2021). In addition to physical reality, virtual reality can also be augmented by similarly superimposing other content onto it. Thus, the augmentation of virtual reality has sometimes been separately referred to as augmented virtuality (AV) (Albert et al., 2014; Riar et al., 2023).

As a significant topic in contemporary information systems, there is a general consensus in both industry and academia that the “Metaverse” technologically represented by XR has the potential to disrupt marketing, retailing and business in various ways (Cranmer et al., 2021; Rauschnabel,

✉ Nannan Xi  
nannan.xi@tuni.fi

✉ Juan Chen  
juanchen@aufe.edu.cn

Filipe Gama  
filipe.gama@tuni.fi

Henry Korkeila  
henry.korkeila@tuni.fi

Juho Hamari  
juho.hamari@tuni.fi

<sup>1</sup> Tampere University, Kalevantie 4, Tampere 33100, Finland

<sup>2</sup> School of Business Administration, Anhui University of Finance and Economics, Caoshan Road No. 962, Bengbu 233030, China

<sup>3</sup> University of Turku, Turun Yliopisto 20014, Finland

2021; Steffen et al., 2019). Even though metaverse-related technologies have been developed for more than 30 years, they rocketed to public attention when Facebook renamed itself as Meta in 2022. From the first AR/VR head-mounted display “The Sword of Damocles” created in 1968 to the AR contact lens prototype “Mojo Lens” launched in 2020 (Wang et al., 2021), XR is undergoing transformative development which leans toward being consumer-facing, with high usability, accessibility and customization. In the past few years, the increasing number of consumer-grade AR and VR devices have mushroomed in the market, where they are gradually being used for non-gaming purposes such as shopping (e.g., IKEA’s Place App for AR display and Amazon’s AR View), work (e.g., VR workroom<sup>1</sup>), learning (e.g., Arbibook for AR reading), tourism (e.g., 360-degree virtual tour<sup>2</sup>) and social activities (e.g., VR Chat<sup>3</sup>). The global metaverse market size surpassed USD 68 billion in 2022, and is estimated to be worth over USD 3000 billion by 2032 (Precedence Research, 2023).<sup>4</sup> Especially in the post-COVID-19 world, an increasing trend can be seen in the virtualization and digitalization of business activities, and consumers are anticipated to become more accepting of further technological innovation in the delivery of consumption experiences (Barnes, 2020).

However, it can be witnessed that many metaverse-related practices have rarely been considered and examined in relation to their potential cognitive ramifications, as XR developers and designers instinctively overlook the possible detriments of cognitive processing compared to non-XR-mediated environments. Limitations in current interaction and communication technologies and computing power pose challenges to metaverse to function properly on a global scale (Wang et al., 2023), and many users are not satisfied with their task performance and are skeptical and dubious about the efficiency compared with traditional ways of shopping, learning, working and conducting activities (Xi et al., 2023). Especially in XR-mediated business and marketing environments, one prominent locus of benefit and detriment as well as a trajectory of inquiry is understanding how consumers’ psychological and cognitive facilities are adept at processing information (Barreda-Ángeles et al., 2021; Katona, 2021) and making decisions (Shen et al., 2021) under extended realities. Consequently, this influences how these new realities should be shaped to match them. We should notice that *memory* (i.e., acquisition/encoding, retention, and retrieval) is a fundamental cognitive process in all

information systems, be they mechanical, electronic, or biological, as is the case with humans (Glenberg, 1997). Especially, episodic memory (a kind of memory used for our everyday personal experiences) forms the basis for cognition (Breed & Moore, 2016). High memory functioning is a core component of decision-making processes, and is therefore a vital aspect to consider in any marketing considerations that affect what the consumer senses, remembers, retrieves from memory, and ultimately implements in their decision-making (Flacandji & Krey, 2020). On one hand, hyperbolic expectations towards XR set a premise of virtual technologies being able to provide experiences that are more engrossing compared to our daily reality, and therefore ultimately support memory (see e.g., Repetto et al., 2016) and facilitate knowledge transfer to the real world (see e.g., Wallet et al., 2011). On the other hand, pessimistic stances perceive optimistic expectations as being inflated and highlight the reductions in multimodality and multisensory aspects compared to “real” life which are essential components in cognitive functioning (Makransky et al., 2019). However, there is still a significant but mostly unanswered research question regarding information processing and management in everyday metaverse settings — *How would XR influence consumers’ memory performance?*

In the literature, only a handful of existing studies have ventured to discuss memory-related questions in the context of XR. However, as is the case with any young corpus, there are caveats. Firstly, the majority of the previous literature has studied memory in the education and training field, focusing on learning performance and knowledge retention. There is also a dearth of studies relating to the context of marketing and consumer psychology that could satisfy the needs of firms that are rapidly moving from brick and mortar into pixels and 3D voxels as the base material for their consumer-facing interfaces. Secondly, perhaps due to the difficulty in designing and developing XR systems as research materials, previous studies have mostly assessed memory performance in settings involving a single technology — either VR or AR. It is still unknown to what extent the “augmenting” and “replacing” features inherent in AR and VR might affect consumers’ memory, both separately and interactively. What should be mentioned is that quite a few studies have investigated the effect of XR when comparing with a non-XR setting by adding more interactive content or information, and therefore, mostly inform us about the effects of added information and interactivity in terms of cognitive function and decision-making (see e.g., Yim et al., 2017). Furthermore, beyond studies such as those of Chen et al. (2019), Ruiz-Ariza et al. (2018), and Roettl and Terlutter (2018), the corpus has focused on specific types of memory in XR, and mostly examined memory capacity in memorization tasks. As a consequence, little attention has been paid to the difference between two core memory processes (recall vs. recognition) influenced by different information types, especially in daily-life settings supporting natural information

<sup>1</sup> Horizon Workrooms (beta) is the VR space for teams to connect, collaborate and develop ideas, together.

<sup>2</sup> <https://visitvirtuallapland.fi/>

<sup>3</sup> VRChat offers an endless collection of social VR experiences by giving the power of creation to its community.

<sup>4</sup> <https://www.prnewswire.com/news-releases/metaverse-market-size-to-worth-usd-3-118-67-billion-by-2032--301998071.html>.

processing. Overall, while the current corpus holds some scattered research in this area, the research objective of this present study is to provide a fundamental understanding of memory function based on the empirical evidence regarding how consumers recall and recognize information in daily-life metaverse settings.

In order to achieve the research objective regarding understanding the role of XR in consumers' cognitive function of information processing and management (i.e., memory) in daily life, this study experimentally examines how the two core XR technologies influence memory recall (textual information<sup>5</sup>) and recognition (textual and pictorial information) towards information in a "daily" shopping context. A 2 (VR: yes vs. no) × 2 (AR: yes vs. no) factorial between-subjects controlled experiment was conducted (N = 153). A brick-and-mortar store was built on a university campus. Approximately 600 products were acquired for the store to be resold to participants. Head-mounted display headsets (Microsoft HoloLens and Valve Index) and controllers were used for AR, VR and AV (augmented virtuality combining AR and VR) mediated shopping experiences. In the self-constructed stores, participants were able to freely interact with the products, enabling them to make purchase decisions and take items home, replicating the experience of everyday shopping. Following the 10-min shopping task, participants were required to recall and recognize the products they had browsed and interacted with. This methodology allowed us to assess the extent of information retention within a realistic shopping environment, thus providing insights into participants' memory retention within the context of authentic shopping experiences, rather than merely evaluating their memorization skills and cognitive capabilities. Based on the findings, this study provides research evidence and consequent practical implications stemming from the effects of AR and VR on information recall and recognition in information systems and human–computer interaction, as well as in the context of digital retailing and consumer psychology.

## 2 Literature Review

### 2.1 Theoretical Foundation

#### 2.1.1 Consumer Memory

Memory is a fundamental part of practically any means of holistic information processing, and it involves encoding

<sup>5</sup> This study focuses on investigating visual information including textual and pictorial information. Regarding pictorial information, during the time when the experiment was conducted, there was no suitable approach for the authors to measure free recall of such information of a large amount of products (54 products for each participant).

(perceiving information and relating it to past knowledge), storing (maintaining information over time), and retrieving information (accessing the information when needed) (McDermott & Roediger, 2020; Squire, 2004). Prior research in the marketing domain has examined the role of memory in product judgment (Ghosh et al., 2021), purchase decision (Karimi et al., 2015), brand preference (Davtyan et al., 2020) and advertising effectiveness (Segijn & Eisend, 2019), and memory process (e.g., recall and recognition) has been more commonly investigated in a few brand-related studies in online contexts (Chaney et al., 2018; Vyvey et al., 2018).

Consumers' perceptions and processing abilities towards marketing information are commonly influenced by different information formats. For example, while image-related stimuli are better recalled (Simola et al., 2013) and provide more vividness and entertainment (Leung et al., 2017), they may also distract consumers from performing relatively high demanding cognitive activity (Adaval & Wyer, 1998). Textual information has been found to cause greater information overload and further lead to negative consumer perception (Lee et al., 2020). In most consumption scenes, consumers have to search and process a large amount of available information from current external cues, including e.g., environment, product and service beyond their prior knowledge. Thus, consumers' capabilities to process and retrieve different types of information that they encounter during consumption influence their decision-making or the formation of specific judgments.

#### 2.1.2 Memory Process

In cognitive psychology, *recall* and *recognition* are regarded as the two main ways of "remembering" (Lynch & Srull, 1982). Whereas recognition consists of recognizing given informational cues that represent aspects of the given situation being remembered (familiarity decision: Courage & Richards, 2020; Haist et al., 1992), recall is based on being able to retrieve information about the given situation without external cues (Contractor et al., 2019). A number of previous studies have investigated the effectiveness of marketing or branding strategies by measuring the numbers of the exposed brand names recalled and recognized (out of a total of given brand names) (see e.g., Davtyan et al., 2016; Thoma & Wechsler, 2021). In the case of the present study, for the recognition task, participants were provided with music products to recognize that had been presented during the shopping activity, whereas in the recall task, the participants had to independently recall and produce the title information of the music products. Therefore, recognition and recall represent two different methods of information retrieval from the cognitive information structure, where recognition relies on matching external stimuli with stored information, and recall is a more explorative cognitive task

of mentally revising and/or exploring the information structures of the given situation, and then recognizing the mentally retrieved cues to match with the given situation (Haist et al., 1992). Recognition provides individuals with learned information along with distractor items, to determine if a previously studied item can be detected (Kent et al., 2018). Thus, recognition can be considered as a less cognitively demanding task (Caruso et al., 2020). As one of the early views on human memory, strength theory states that recognition performance is superior to recall performance since recalling usually requires more information in storage than recognizing an item, which increases cognitive difficulty (Haist et al., 1992).

Approximately 90% of information transmitted to the brain is visual (Bullier, 2001) – thus visual information plays the key role in individuals' cognitive function and decision-making. Regarding different visual information modalities, text comprehension and picture comprehension are considered to be different ways of constructing mental representations (Pérez et al., 2020), including text surface representations and visual perception-proximal representations (Schnotz & Kürschner, 2008). The dual-code theory states that pictures are more likely to be encoded both as images and as verbal traces, and hence can be better memorized (Hodel et al., 2022; Sadoski & Paivio, 2012). To conduct a more granular analysis of the cognitive performance in XR, this study examines the memory performance towards different types of information, which refers to the ability of the mind to encode, retain and retrieve environmental information (McDermott & Roediger, 2020; Squire, 2004). To be more specific, we measure the recognition of both textual and pictorial information, as well as the recall of textual information given there is no existing suitable approach for measuring it in daily-life settings as designed in this present study.

### 2.1.3 Cognitive Load Theory (CLT)

Using and operating technologies such as XR may require more cognitive resources compared to the natural environment without such technological involvement. According to cognitive load theory (CLT), human beings have a limited cognitive capacity in working memory (which refers to a brain system that offers temporary storage and the manipulation of necessary information: Baddeley, 1992), and information to which people allocate more cognitive resources to process would be better remembered than information to which people allocate fewer cognitive resources (Sweller, 2005, 2020). In other words, when the working memory is more highly loaded by non-task-related stimuli, the information may not be processed as well, thus leading to worse understanding and retention (Mestre, 2012). The two main identified resources impacting working memory

load are intrinsic cognitive load and extraneous cognitive load (Anmarkrud et al., 2019). Intrinsic cognitive load is the cognitive resource required for understanding content which directly contributes to the memorization of the content, while the extraneous cognitive load is the cognitive resource required to conduct a number of cognitive activities related to searching and organizing information, which might generate errors in memory recognition (Paas & van Merriënboer, 2020; Plass & Kalyuga, 2019; Sweller, 2020). The intrinsic cognitive load is usually caused by the inherent nature of the content (e.g., the amount and complexity of the content), while the extraneous cognitive load is more related to how the content is presented (Paas & van Merriënboer, 2020), which can be influenced by using the different techniques (Anmarkrud et al., 2019; Sweller, 2020). Based on CLT, we have theoretical reason to postulate that XR technologies might have an influence on memory processes such as recall and recognition. However, referring only to CLT, it is still unknown how and what kind of impact XR may have on memory. Therefore, we conducted a state-of-the-art review of the current literature related to the effect of XR on memory to help us sort out the current research progress, and to identify gaps in the research.

## 2.2 XR and Visual Memory

Prior studies related to consumer memory have examined the impact of different factors such as game-related stimuli (Chaney et al., 2018), media multitasking (Chinchana-chokchai et al., 2020), media richness (Maity et al., 2018), and visual attention (Simmonds et al., 2020). All of these factors are highly related to the information presentation format. The rapid advancements in immersive technologies such as AR and VR provide more opportunities for information display (Xi & Hamari, 2021), which have the potential to influence consumer's memory further. However, there is still a lack of discussion on the relationship between XR and consumer memory. VR has been used as a context tool to create a naturalistic situation for assessing e.g., episodic memory (Penaud et al., 2023; Smith, 2019) and the everyday memory (Ouellet et al., 2018) of elders and patients, while AR has often been associated with spatial memory in education and training (e.g., Hoe et al., 2019; Munoz-Montoya et al., 2019; Yang et al., 2023). To pursue more heuristic thinking and to clarify the research questions, we reviewed the most relevant empirical studies that have examined how memory has been influenced by different XR technologies in various fields (see Table 1).

Firstly, it can be seen that as the core concept in cognitive psychology, memory has rarely been examined in the XR-mediated business and marketing field. The majority of the previous literature has studied memory in education and training (Chen et al., 2019; He & Hong, 2020; Rosello

et al., 2016), with other studies in fields such as psychology and rehabilitation (Cadet et al., 2022; Ijaz et al., 2019; Smith & Mulligan, 2021), and media and communication (Clemenson & Stark, 2015). Studies targeting consumer memory in XR such as those of Roettl and Terlutter (2018) and Lin et al. (2023) mostly assessed memory through basic brand name recall tasks. However, due to the complexity of consumption and marketing management, it is difficult to apply these findings from diverse contexts to understand whether XR would influence information processing and storage for consumers, especially in daily-life business settings. Second, probably due to the difficulty in designing and developing different XR systems, the majority of relevant literature has mainly investigated a single technology (e.g., VR or AR) by comparing different design interfaces, content, interaction and perceptions (see e.g., 2D vs. 3D content, Lin et al., 2023; immersion, Smith & Mulligan, 2021; bodily self-consciousness, Pénard et al., 2023), rather than comparing the different experiences brought by the two XR technologies. Therefore, there is a lack of comprehensive understanding of the extent to which the “augmenting” and “replacing” features, respectively supported by AR and VR, may differentially and interactively influence consumers’ memory. Moreover, in terms of research methodology, a number of confounding factors (e.g., individual prior knowledge and experience, information amount, experiment time, usability of the system) have not been considered and controlled for in the majority of experiment-based studies. Therefore, there has been an inconsistency in results regarding the role of XR in memory function. For example, XR has been examined to be positively related (Hou & Wang, 2013; Krokos et al., 2019; Rosello et al., 2016), negatively related (Roettl & Terlutter, 2018), and unrelated (Chen et al., 2019; Ruiz-Ariza et al., 2018) to memory. Furthermore, from the perspective of memory-related research, there is a research gap in the granular analysis of memory performance based on various information forms. Previous studies have indicated that the differences in mechanisms of processing textual and pictorial information might differentiate memory performance (Childers & Houston, 1984; D’Agostino et al., 1977). However, performances of processing and memorizing textual and pictorial information have rarely been distinguished in XR-mediated environments.

### 2.3 Research Questions

In summary, it is quite difficult for us to posit reasonable research hypotheses related to the different roles of AR and VR in consumer memory process based on previous scattered studies with inconsistent findings, especially regarding different types of memory (e.g., recall and recognition) and different types of visual information (e.g.

text and pictures). Recall and recognition are the core components in memory process, and text comprehension and picture comprehension are the two main ways of constructing mental representations in forming memories. Also, as previously mentioned, there was no suitable approach that could be applied to measure recall of a large amount of pictorial information in daily-life settings as designed in the present study. So instead, we propose the following specific research questions in order to address elemental aspects of the topic and draw a fundamental grounding.

RQ1: Whether and how do AR and VR differentially influence recall, e.g., toward textual information?

RQ2: Whether and how do AR and VR differentially influence recognition toward textual and pictorial information?

## 3 Experiment and Results

### 3.1 Design

A 2 (VR: yes vs. no)  $\times$  2 (AR: yes vs. no) factorial between-subjects controlled experiment was conducted to examine how AR and VR affect memory performance (e.g., recall and recognition) towards textual and pictorial product information in the “daily” shopping context. A brick-and-mortar music record store was built on a university campus. The store was scanned using LiDAR and photography into pointcloud and photorealistic textures, from which it was modeled into a 3D model in Unity in 1-to-1 scale. Approximately 600 music products were acquired for the store to be resold to participants, and half of them were modeled into 3D model products and displayed in the virtual stores. Head-mounted display headsets (Microsoft HoloLens 1 and Valve Index) and controllers were used for the other three XR-enabled shopping experiences. Table 2 illustrates the operationalization of the two independent variables, AR and VR as well as the used XR devices. All participants were recruited from online and offline ad responses based on convenience sampling, and randomly assigned to one of the four groups (AR<sub>0</sub>VR<sub>0</sub> Group, AR<sub>1</sub>VR<sub>0</sub> Group, AR<sub>0</sub>VR<sub>1</sub> Group, AR<sub>1</sub>VR<sub>1</sub> Group). After a 10-min shopping task, one memory recall test and two memory recognition tests were separately conducted (See 3.3.4. Measurement). The study design and procedure adhered to the Finnish National Board on Research Integrity TENK Guidelines (2019). Figure 1 presents the flowchart of this experimental study, including the recruitment stage (step 0), experiment book and pre-survey stages (steps 1 and 2), randomization and experiment stages (steps 3 and 4), and memory tasks stages (steps 5, 6, and 7).

**Table 1** Review of empirical studies on how XR influences (visual) memory

Sources	Objectives	Methods	XR technologies/ devices	Information types	Memory-related variables	Measures	Results
Cadet et al. (2022)	To explore, in both children and adults, the respective roles of the specific factors of VR, such as immersion, sense of presence and emotion, on memory performance	Experiment	HTC Vive VR HMD	Fifty-eight 3D assets displayed in virtual environments	Free recall	Correct recall of the stimuli (positive vs. negative vs. neutral) that they had seen in the six places in two virtual environments	Memory performance was better for emotional than for neutral stimuli regardless of age group
Chen et al. (2019)	The use of AR to improve memory recall and learning experiences in human anatomy and physiology	Experiment	Head-based AR (Microsoft HoloLens) for HoloAnatomy demonstration	Visual display and pre-recorded voice	Memory recall (five-minute, three-subject anatomy identification, and brain physiology memory test)	Content recall scores	The results of the exam demonstrate that, for this study, the use of the HLNS did not have a positive effect on test scores (memory recall) versus the more traditional PPT method
Clemenson and Stark (2015)	Whether virtual environments within video games have positive effects on enhancing human cognition (or mitigate cognitive decline)	Experiment with a longitudinal design	Desktop VR	3D video games	Spatial navigation memory (Enumeration task, MST recognition memory task)	<ul style="list-style-type: none"> <li>- Basic visual accuracy (error rate)</li> <li>- Basic visual processing speed (reaction time)</li> <li>- Lure discrimination index (the probability of correctly calling a lure object similar minus the probability of incorrectly calling a foil object as similar)</li> <li>- Recognition memory score (hits—false alarms)</li> </ul>	3D video gamers performed better on a demanding recognition memory task than 2D video gamers
Clemenson et al. (2020)	Spatial relationships between real and virtual environments to better understand how well the virtual experiences parallel the same experiences in the real-world	Experiment	Desktop VR	3D environment	Spatial memory (object location, environment layout & navigation strategy)	<ul style="list-style-type: none"> <li>- Average number of place errors</li> <li>- Average number of response errors</li> </ul>	While general spatial information did transfer between real and virtual environments, there were several limitations of the virtual experience

Table 1 (continued)

Sources	Objectives	Methods	XR technologies/ devices	Information types	Memory-related variables	Measures	Results
Gabana et al. (2017)	How working memory performance is affected when playing a VR game, and the effects of valence and arousal	Experiment	VR HMD	VR games: memory break	Working memory (Automated OSpan test, heart activity)	Different Heart Rate features: - Average of normal to-normal intervals (AVNN) - Root mean square of successive differences (rMSSD) - Low-high frequency ratio (LFHF)	An improvement in working memory performance when playing in VR compared to Desktop. High arousal and positive valence can lead to a flow state that may have a positive impact on the working memory performance
Hejzmanek et al. (2020)	The effects of learning modality (real-world vs. immersive VR vs. desk-top computer) on spatial knowledge acquisition	Experiment	HTC Vive VR HMD and treadmill	3D environment	Memory recognition (spatial)	- Walking distance - Time spent on each task - Number of visitation errors	Participants learning in immersive VR and transferring to real-world demonstrated worse walking performance than those transferring to immersive VR from the real-world
He and Hong (2020)	Whether and how AR affects students' learning and memory effects in history and humanities education	Experiment	Hand-based AR (iPad) for ancient poems	3D models and audio	Mechanical memorization Meaningful memorization	- Fill in the blank (background information about the poem, 50 scores) - Dictation (recall the poem. 20 scores) - Short answer Questions (30 scores)	AR has an impact on both mechanical and meaningful memorization: AR helps to improve students' meaningful memory ability while the impact of AR on mechanical memorization is not always positive
Hou and Wang (2013)	Gender's impact on AR's effectiveness on the learning curve of assembling tasks	Experiment	ARToolkit and paper-based markers	Animated AR visualization of LEGO model	Working memory (A set of LEGO model to be assembled)	- Number of assembly trials until assembly was completed without an error - Time consumed to complete a trial - Number of errors committed during a trial	AR helps both male and female trainees learn the assembly routine faster, and AR training is more effective for both male and female assemblers than the 3D manual

Table 1 (continued)

Sources	Objectives	Methods	XR technologies/ devices	Information types	Memory-related variables	Measures	Results
Ijaz et al. (2019)	The feasibility of an immersive VR platform to assess spatial navigation memory in older adults	Prototype development and pilot study (experiment)	Oculus Rift VR HMD	360-degree panoramas (Google Street View)	Spatial navigation memory (a landmark recall test)	<ul style="list-style-type: none"> <li>- Number of correct landmark recalls</li> <li>- Specific landmarks identified—Number of time navigational mistakes were made</li> </ul>	Participants in VR were significantly more engaged, achieved higher landmark recall scores, made less navigational mistakes than those in standard PC SPC setup
Krokos et al. (2019)	Whether modality (HMD VR vs. desktop VR) affects memory recall performance	Experiment	VR HMD (Oculus DK2) for a virtual memory palace	3D environment and model	Memory recall (spatial)	<ul style="list-style-type: none"> <li>- Total number of answers</li> <li>- Number of correct answers</li> <li>- Number of errors</li> <li>- User confidence with recall accuracy</li> </ul>	Virtual memory palaces in HMD condition provide a superior memory recall ability compared to the desktop condition
Lin et al. (2023)	How do brand placements and TV show characteristics influence the effect of AR title sponsorships and product placements in entertainment television? And how do these effects differ across countries	Experiment	Smartphones	3D dynamic ads (vs. 2D ads) when watching video clips	Memory recall (brand recall, free recall and aided recall)	<ul style="list-style-type: none"> <li>- Correct recall of brand names</li> <li>- Correct response rates for free recall of title sponsorship brands</li> <li>- Correct response rates for aided recall (with the help of cues)</li> </ul>	Dynamic AR advertisements increase free recall of brands

Table 1 (continued)

Sources	Objectives	Methods	XR technologies/ devices	Information types	Memory-related variables	Measures	Results
Penaud et al. (2023)	Investigates the relationship between bodily self-consciousness (BSC) and episodic memory (EM) in virtual reality	Experiment	HTC Vive Pro headset equipped with headphones	Close-to-daily-life urban landscape with rich ambient sounds, animations, and scenes	Unattended free recall and recognition events in all three navigations	<ul style="list-style-type: none"> <li>- Recall event including contextual egocentric spatial and temporal information and specific details</li> <li>- Recognition task (a total of 54 trials)</li> <li>- For the scoring: 1 point was attributed for every correctly recognized or recalled event (what), spatial egocentric (where), and temporal information (when)</li> </ul>	Synchronous visuo-motor stimulation positively enhances both objective and subjective components of EM compared to the asynchronous condition and, to a lesser extent, the no-body condition
Roettl and Terlutter (2018)	How an identical video game that is either played in a 2D, stereoscopic 3D or (HMD) VR version is experienced by the players, and how the placed brands are affected	Experiment	VR HMD (Oculus DK2) for action video games	Brand appeared three times during gameplay	Memory recall (placed brand) Memory recognition (placed brand)	<ul style="list-style-type: none"> <li>- Number of correct answers participants named the placed brand</li> <li>- Number of correct answers participants ticked the placed brand</li> </ul>	Memory for the placed brands was lower in the HMD VR than in the stereoscopic 3D than in the 2D video game
Rosello et al. (2016)	The effectiveness of the memory tool combining AR and the memory palace method	Prototype development and pilot study (experiment)	Mobile app and an Epson Moverio BT-200 AR headset	AR memory palace for remembering images	Recall the content memorized in the tasks (after 2 min, after 24 h and after 7 days)	Content recall rate	Content memorized with AR remains longer in memory compared to general memorization techniques
Ruiz-Ariza et al. (2018)	The effect of durable mobile AR use on cognitive performance (including memory) and emotional intelligence in adolescents	Experiment with a longtitude design	Hand-based AR (mobile) game	Pokémon GO	Memory recall (remembering 15 playing cards in 1 min)	Number of correct answers	Adolescents who have systematically practiced Pokémon GO for 8 weeks have not increased memory with regard to their peers

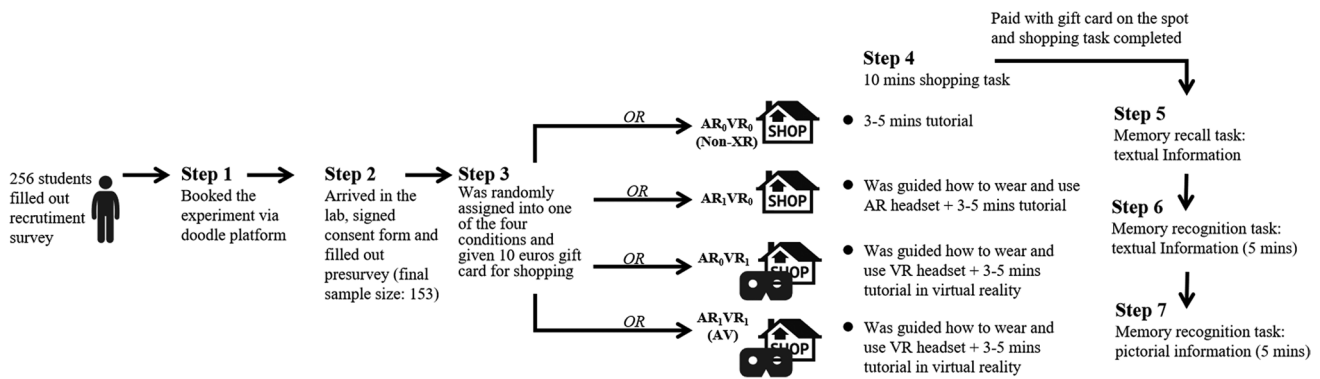
Table 1 (continued)

Sources	Objectives	Methods	XR technologies/ devices	Information types	Memory-related variables	Measures	Results
Schöne et al. (2019)	The immersive qualities of VR in memorizing virtual experiences	Experiment with a longtude design	HTC Vive VR head-mounted display	360° video (motorcycle ride in the region of Osnabrück)	Autobiographical memory (during the ride & 48 h after)	- Retrieval success - Reaction time	Immersive VR experiences become part of an extensive autobiographical associative network, whereas the conventional video experience remains an isolated episodic event
Smith and Mulligan (2021)	How properties of VR environments affect episodic memory. Specifically, how presence and memory were affected by three manipulations of immersion	Three experiments	VR HMD	3D objects in virtual rooms	Free call (item memory) and recognition of all 80 items (40 old, 40 new; source memory)	- Recall items names (3D objects in virtual rooms) - Source memory was calculated using identification-of-origin (IO) score	Immersion effects on presence and memory are variable and appear to be dependent (in part) on the particular characteristic of immersion under investigation
Yang et al. (2023)	How AR could help industrial training from a human perspective	Experiment	Microsoft HoloLens 2	Text information and 3D models in a physical console assembly task	Week and month-term memory in perception	Three questions regarding to the assembly process; using the percentage of questions answered correctly as accuracy in phase 1 (after the task) and phase 2 (a week and a month after phase 1)	Training with the AR system was more effective than ordinary training in increasing the knowledge retention of participants without increasing their overall workload, especially for the month-term memory

**Table 2** The 2 (VR: yes vs. no) × 2 (AR: yes vs. no) between-subjects experiment design in this study

Group	Variable		Shop	Extra product information	Visual environment engine	Device (headset)
	AR	VR				
AR <sub>0</sub> VR <sub>0</sub>	No	No	Physical	Paper sheet	Reality	N/A
AR <sub>1</sub> VR <sub>0</sub>	Yes	No	Physical	Augmented	Reality and Vuforia Engine in Unity	Microsoft HoloLens 1
AR <sub>0</sub> VR <sub>1</sub>	No	Yes	Virtual	Paper sheet (Digital)	Unity	Valve Index
AR <sub>1</sub> VR <sub>1</sub>	Yes	Yes	Virtual	Augmented	Unity	Valve Index

See the open-access video link <https://cutt.ly/XR-shopping>



**Fig. 1** Flow chart of the study

### 3.2 Participants

The same advertising content was used in both online and offline student participant recruitment. From September to November 2019, a total of 265 students from a university in Northern Europe successfully entered our online recruitment system, and 162 student participants completed the laboratory experiments. A total of 153 valid samples<sup>6</sup> were used for memory analysis (AR<sub>0</sub>VR<sub>0</sub> = 41, AR<sub>1</sub>VR<sub>0</sub> = 42, AR<sub>0</sub>VR<sub>1</sub> = 34, AR<sub>1</sub>VR<sub>1</sub> = 36). 54.9% were male and 77.2% were between the ages of 20–29. 57.8% of participants were bachelor students, 36.6% were master students, and 60.1% were from the study area of engineering and technology. Participants originally stemmed from 33 countries (including Finland, 31.4%; China, 9.8%; Vietnam, 8.5%; Germany, 8.5%). In addition, among the 153 participants, 58.1% used

<sup>6</sup> All participants were asked to complete three memory tasks, including one recall task and two recognition tasks. Out of 162 participants, 155 completed the two recognition tests within the specified time frame (10 minutes). However, two participants were excluded during the data analysis because they did not provide any answers related to the titles in the recall task. The total sample size was 153, and the effect size was 0.23.

English quite frequently, with 37.3% considering music important and 28.8% considering it extremely important (See Appendix A for more details of the demographic and personal information of participants). The F test results indicated that there were no statistically significant differences in the samples divided among all groups (all *p*-values > 0.05). Each participant was asked to complete a 10-min daily shopping task in a second-hand shop. As compensation for participating, the participants would receive the products they chose to keep. This also helped to increase the external validity of the experiment, and the number of products purchased during the experiment ranged from 0 to 3<sup>7</sup>.

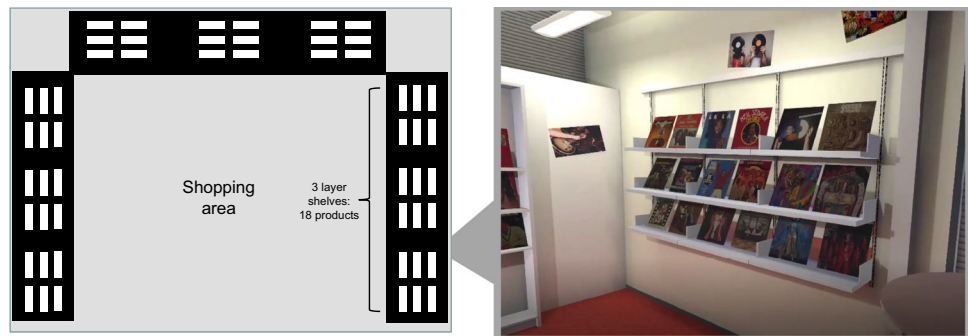
### 3.3 Material

#### 3.3.1 Shop

A physical shop (4.24 × 5.09 m<sup>2</sup>) was built on the university campus, and functioned as the experimental setup for each

<sup>7</sup> Two participants did not purchase any products during 10 min of shopping. Therefore, the minimum amount of purchased items was 0 and maximum amount of purchased items was 3.

**Fig. 2** Floor plan (left) and VR interface (right) of the shop. In order to provide a daily-life shopping experience, after completing the experiment, the participant was actually given the record products they had “bought”. Any records “bought” by previous participants were restocked with new records in the same price category in the shop



condition. In the  $AR_0VR_0$  (non-XR) Group, the shop functioned as a common brick-and-mortar shop. In the  $AR_1VR_0$  Group, the shop functioned similarly but with the exception of product information being displayed through an AR headset display. In the  $AR_0VR_1$  Group, the same room was used; however, the “control” condition was fully replicated by employing laser scanning (LiDAR) to acquire a point-cloud map of the space-based on which a 1-on-1 scale 3D model of the shop was built in Unity. After geometric modeling, realistic and photorealistic textures and lighting conditions were applied. For the  $AR_1VR_1$  (AV) Group, it combined the treatment in  $AR_0VR_1$  Group and the overlaid product information as featured in the treatment of  $AR_1VR_0$  Group.

### 3.3.2 Product

To control the external influence of prior product knowledge and preference on memory, the product category was considered carefully during the research design. Second-hand English music products (LP records) were selected as the ideal product stimulus. From the perspective of a daily general shopping task, LP records have a certain amount of information on which to base consumer shopping decision-making. All records in the shop were acquired second-hand and produced before the 1990s. We measured previous product knowledge through seven items based on a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree), including items such as “I knew pretty much about these products” and “I felt familiar with these products”, which were adapted from Awasthy et al. (2012). The results indicate that participants were not familiar with the products they browsed in the shop (Mean = 2.67, Standard Deviation = 1.19). Therefore, the external influence of prior knowledge on memory performance was controlled.

To maximize the realistic shopping experience, approximately 600 products were used in the experiments. The products in each condition were evenly and randomly distributed to record pools per treatment group, so as to fill the store shelves. In each treatment group, 141 records formed the product pool. In  $AR_0VR_1$  and  $AR_1VR_1$  groups, the front and back covers of the music products were

scanned in high quality and added as textures on the sides of plain 3D objects. Participants used a Valve Index headset and its controllers that enable a haptic 5-finger interface for grabbing the virtual records (3D objects) as the records were not physically in the space. Each product was priced at €3, €6, or €9. For each participant, 54 products were displayed in the shop (see Fig. 2).

### 3.3.3 Extra Information

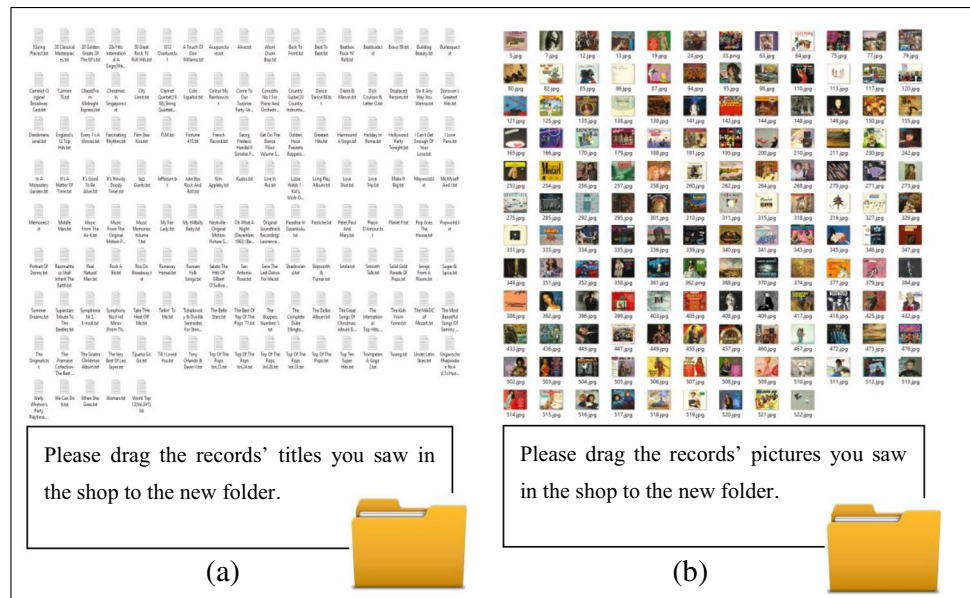
In addition to the products on the shelves of the shop, a product information sheet was placed next to each product in conditions not involving AR (i.e.,  $AR_0VR_0$  and  $AR_0VR_1$ ). In conditions involving AR, the product information was displayed as a superimposed floating information box appearing next to the product the participant was looking at (head tracking). The product information (containing e.g., label, format, country, release year, genre and style, tracklist, statistics, companies, and credit information) was gathered from one of the primary record databases international Discogs.

### 3.3.4 Measurement

After the shopping task, participants were asked to recall (album titles) and recognize (album titles and cover pictures) as many products they had seen in the shop (out of 54 that had been displayed in the shop) from among 141 possible products. Thus, three memory tasks were separately conducted, with the memory (free) recall task arranged before the recognition task<sup>8</sup>. The recall and recognition performance tasks were both scored by negative marking (NM) or “right-minus-wrong” (see e.g., Moran et al., 1960; Levin & Levin, 1990; Minear et al., 2016; Fandakova et al., 2018), thus allowing scores to range from

<sup>8</sup> In the task of recognizing products, the participant could have the opportunity to review all of the product information again. Thus, the memory recall test was conducted before memory recognition tests.

**Fig. 3** Memory recognition task for a) textual and b) pictorial information



a theoretical maximum score of 54 (i.e., selecting all 54 products correctly) down to a minimum score of -54 (i.e., selecting only incorrect products).

**Memory Recall Task:** A recall test usually requires participants to produce items from their memory that formed part of the target event (Richardson-Klavehn & Bjork, 1988). Given that participants might have been familiar with or have known specific products in the shop, in this study, we asked each participant to list the product names (see e.g., Vashisht & Royne, 2016; Herrewijn & Poels, 2015) that they had never seen (in real life) before the shopping task, without the aid of external cues (Richardson-Klavehn & Bjork, 1988). Two researchers counted the number of titles recalled and evaluated the correct answers. Since an album title usually contains 3–5 words, the following scoring method was used: if a participant listed an album title approximately correctly, it was coded as 1. If partially correct, the answer was coded as 0.5 (see Appendix B for more details of the scoring method). The score of correct answers was achieved by adding up the total number of items correctly recalled (Bainbridge et al., 2019; Bouffard et al., 2018; Neri et al., 2021), while the score of incorrect answers was achieved by balancing the number of answers the participant provided minus the score of correct answers<sup>9</sup>. The instruction was as follows:

**Instruction:** please recall your shopping experience and write down as many album names/titles as you can remember that you have **never seen** before (including the records you just bought).

<sup>9</sup> For example, if a participant provides 5 answers, the total expected score should be 5 if all are correct. While if only two answers are approximately correct and one is partially correct, the score of correct answers would be 2.5 and the score of the incorrect answers would be 2.5. Accordingly, the final score of this participant would be 0 (2.5–2.5).

**Memory Recognition Task:** The memory recognition tasks were designed and adapted from the studies of Herrewijn and Poels (2015) and Gillespie et al. (2012). In a recognition test, a participant needs to distinguish items/stimuli that were present during the target event from non-present items/stimuli (Richardson-Klavehn & Bjork, 1988). In this study, for measuring the different memory recognition performances towards textual information and pictorial information, each participant was asked to try to find and select a maximum of 54 correct album titles and 54 correct album pictures from two selection pools (141 in both), respectively. The amount of album titles and pictures reported by participants in this study ranged from 1 to 54. We evaluated the recognition performance by calculating the score of the correct items recognized (true-positives) minus the score of incorrect items recognized (false-positives). Figure 3a) and Fig. 3b) present the two memory recognition tasks. The instruction was as follows:

**Instruction:** Please try to find all the 54 records from the folder you saw in the shop. You can just drag the files to the new folder. Remember you only have 5 minutes for each task.

### 3.4 Procedure

#### 3.4.1 Tutorial

Once the pre-survey task (including consent form and basic information) was completed, experimenters guided the participant to the shop room and introduced the experiment procedure step by step, according to a prepared instruction manual.

**Table 3** Descriptive statistics of information recall (text) in four conditions

Group	AR	VR	N	Total answers		Correct answers		Final score (correct – incorrect)	
				M	SD	M	SD	M	SD
AR <sub>0</sub> VR <sub>0</sub>	No	No	41	1.80	1.62	0.78	0.85	-0.10	0.63
AR <sub>1</sub> VR <sub>0</sub>	Yes	No	42	1.62	1.55	0.68	0.70	0.00	0.56
AR <sub>0</sub> VR <sub>1</sub>	No	Yes	34	1.68	2.01	0.82	1.27	-0.25	0.94
AR <sub>1</sub> VR <sub>1</sub>	Yes	Yes	36	1.67	1.41	0.99	0.96	-0.16	0.56

Total answers = number of answers (album titles) the participant provided; Correct answers = the total number of items correctly recalled (partial = 0.5, correct = 1); Incorrect answers = Total answers – Correct answers; Final score = score of correct answers – score of incorrect answers; M = Mean, SD = Standard Deviation

Participants in all conditions also got to briefly practice in the tutorial session before starting to shop. Each participant was also told that if they needed any help or felt uncomfortable during shopping, a short break during the experiment could be offered and they were welcome to request additional breaks.

### 3.4.2 Experiment

All participants were randomized to join one of the four groups. Participants were asked to completely spend 10 min in the shop and make the purchase decision independently, without knowing about the memory tasks. After the 10 min, participants were asked to pay with the given gift card (€10 value). When the shopping was completed, after making sure the participants were not suffering any physical problems, they were guided to take the memory tests after completing a series of questions in the postsurvey. The researchers gave the records that the participants bought in the shopping experiment once the whole experiment task was completed. The purchased records would be replaced with the same price records after each participant's shopping experiment.

### 3.4.3 Pilot Study

Before the actual experiment, a pilot study of 20 participants was conducted for all conditions, in order to test the measurement, experimental procedure, instruction, apparatus, and methods. Especially in the conditions involving VR, the use and guidance of the head-mounted display headset and corresponding program were key aspects of the pilot studies. In addition, in this study, all shopping environments were designed as experimental conditions that provided the same daily shopping functions, similar to the field experiment.

## 3.5 Results

The study was conducted to see whether and how AR and VR may have significant effects on memory recall (RQ1)

and memory recognition (RQ2). The randomization was successful given there were no significant differences in all of the demographic variables among all four conditions (see Appendix A). To address the research questions, a series of between-subjects two-way analyses of variance (ANOVA) were used to test recall of textual information, and the recognition of textual and pictorial information. Prior to conducting the ANOVAs, the normality distribution assumption was tested. For dependent variables of test-based memory recognition and picture-based memory recognition, almost all of the Shapiro–Wilk's statistics in AR, non-AR, VR, and non-VR groups were insignificant ( $p$ -values > 0.05), indicating normality distribution assumption achieved (See Appendix C). For these two dependent variables, the homogeneity of variance assumption was tested, and a series of *Levene's F* tests were statistically insignificant (all  $p$ -values > 0.05: See Appendix D).

### 3.5.1 Memory Recall

As the dependent variable of test-based memory recall failed the Shapiro–Wilk's test of normality distribution (all  $p$ -values < 0.05), we chose the Kruskal–Wallis H analysis (a type of non-parametric test) to examine if the distribution among different groups had significant differences.

Table 3 presents the descriptive information of the memory recall of the items (namely the album titles) in each group. The mean score of memory recall (correct – incorrect) was -0.10 (AR<sub>0</sub>VR<sub>0</sub> Group), 0.00 (AR<sub>1</sub>VR<sub>0</sub> Group), -0.25 (AR<sub>0</sub>VR<sub>1</sub> Group) and -0.16 (AR<sub>1</sub>VR<sub>1</sub> Group), respectively. The result of the Kruskal–Wallis H analysis shows that the distribution differences of text-based memory recall among different groups were insignificant ( $p = 0.426$ ), indicating that participants' memory recall performances were similar across the groups.

Total answers = number of answers (album titles) the participant provided; Correct answers = the total number of items correctly recalled (partial = 0.5, correct = 1); Incorrect answers = Total answers – Correct answers;

**Table 4** Descriptive statistics of information recognition (text & pictures) in four groups

Group	N	Total selections				Correct selections				Final score (correct – incorrect)			
		Text		Picture		Text		Picture		Text		Picture	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
AR <sub>0</sub> VR <sub>0</sub>	41	13.00	5.86	27.76	9.93	9.46	4.56	23.39	7.95	<u>5.93</u>	4.77	<u>19.02</u>	8.24
AR <sub>1</sub> VR <sub>0</sub>	42	17.52	9.53	28.57	9.70	9.48	4.31	23.67	8.01	1.43	5.55	18.76	8.66
AR <sub>0</sub> VR <sub>1</sub>	34	19.03	14.78	26.91	11.78	9.71	6.50	21.00	7.20	0.38	6.13	15.08	8.68
AR <sub>1</sub> VR <sub>1</sub>	36	12.64	9.46	26.31	11.87	7.14	4.41	22.56	9.00	1.64	4.31	18.81	8.55

Total selections = number of answers (album titles & pictures) the participant reported; Correct selections = the total number of album titles/pictures correctly recognized; Incorrect selections = Total selections – Correct selections; Final score = score of correct selections – score of incorrect selections; M = Mean, SD = Standard Deviation

Final score = score of correct answers – score of incorrect answers; M = Mean, SD = Standard Deviation.

**3.5.2 Memory recognition: Main and Interaction Effects**

Table 4 presents the descriptive information of the recognition of textual and pictorial information. It can be seen that the highest scores of textual information recognition and pictorial information recognition were both in the AR<sub>0</sub>VR<sub>0</sub> Group,  $M_{textual\ information\ recognition} = 5.93$  and  $M_{pictorial\ information\ recognition} = 19.02$ , respectively. Table 5 presents the results of between-subjects effects.

**Main Effect:** In terms of memory recognition (see Table 5), the results of the ANOVA analyses for text-based memory recognition reveal that the VR groups ( $M = 1.03$ ,  $SD = 5.27$ ) had worse text-based memory recognition compared to the non-VR groups ( $M = 3.65$ ,  $SD = 5.62$ ),  $F(1, 149) = 9.91$ ,  $p = 0.002$  and VR explained 6.2% of the variance in the dependent variable. AR groups ( $M = 1.53$ ,  $SD = 4.98$ ) had no significant difference from the non-AR groups ( $M = 3.41$ ,  $SD = 6.06$ ),  $F(1, 149) = 3.66$ ,  $p = 0.058$ . In addition, AR ( $F(1, 149) = 1.56$ ,  $p = 0.214$ ) and VR ( $F(1, 149) = 1.98$ ,  $p = 0.162$ ) had insignificant main effects on pictorial information recognition.

**Interaction Effect:** The results also show that there was no significant interaction between AR and VR on pictorial information recognition ( $F(1, 149) = 2.07$ ,  $p = 0.153$ ), while there was a significant interaction between AR and VR on textual information recognition ( $F(1, 149) = 11.53$ ,  $p = 0.001$ ). The interaction explains 7.2% of the variance for textual information recognition. To interpret the interaction effect, pairwise comparisons on textual information recognition (see Table 6 and Fig. 4) were conducted (Bonferroni) using the EMMEANS syntax command within SPSS (Bréchet et al., 2019; Herrewijn & Poels, 2015). The results show that only when participants were in the conditions not involving VR, did AR ( $M = 1.43$ ,  $SD = 0.81$ ) significantly lead to a lower level of textual information

**Table 5** Tests of between-subjects effects

Factor			Information recognition	
			Text	Picture
VR	Yes (n=70)	M	1.03	17.00
		SD	5.27	8.75
	No (n=83)	M	3.65	18.89
		SD	5.62	8.41
F(1, 149)			9.91	1.98
p			0.002	0.162
Partial $\eta^2$			0.062	0.013
AR	Yes (n=78)	M	1.53	18.78
		SD	4.98	8.55
	No (n=75)	M	3.41	17.24
		SD	6.06	8.61
F(1, 149)			3.66	1.56
p			0.058	0.214
Partial $\eta^2$			0.024	0.010
VR × AR				
F(1, 149)			11.53	2.07
p			0.001	0.153
Partial $\eta^2$			0.072	0.014

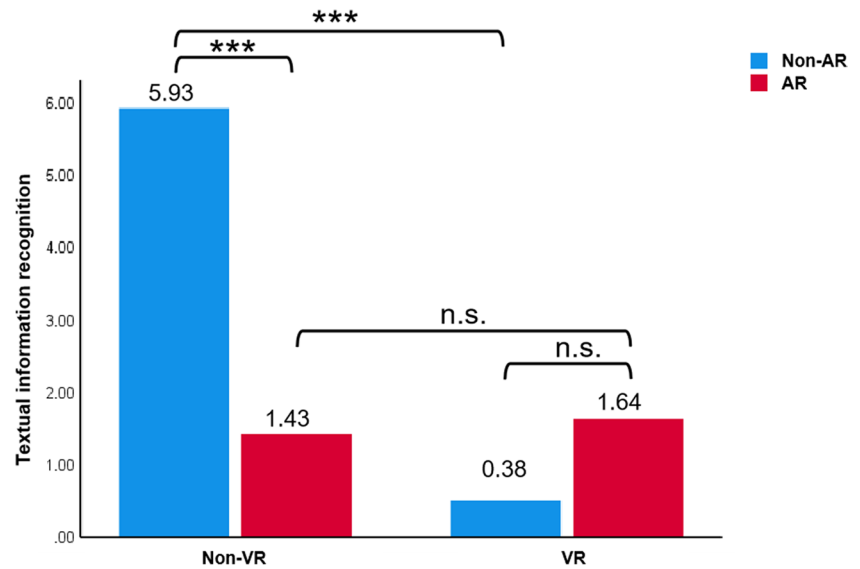
M = Mean; SD = Standard Deviation; The F value is the statistical value used in the F-test, a significance test checking the effect of the focal independent variable(s) on the change of the dependent variable's deviation by examining if the statistical values follow an F-distribution under the null hypothesis (the effect is insignificant). The p-value (corresponding to the statistic value, in this case the F value) represents the probability of sample occurrence under the null hypothesis; if the p-value is less than the significance threshold .05 (the probability of small event happening), the null hypothesis is rejected, meaning the opposite hypothesis (the effect is significant) is acceptable

recognition than non-AR ( $M = 5.93$ ,  $SD = 0.82$ ),  $p < 0.001$ ). However, when participants were in the conditions involving VR, no significant difference was detected between AR and non-AR ( $p = 0.316$ ). When participants were in the

**Table 6** Pairwise comparisons on recognition of textual information

	(I)	(J)	Comparison between conditions	MD (I-J)	SE	p	95% CI	
							Lower	Upper
Non-AR	Non-VR	VR	AR <sub>0</sub> VR <sub>0</sub> vs. AR <sub>0</sub> VR <sub>1</sub>	5.55	1.21	<0.001	3.15	7.94
AR	Non-VR	VR	AR <sub>1</sub> VR <sub>0</sub> vs. AR <sub>1</sub> VR <sub>1</sub>	-0.21	1.19	0.859	-2.55	2.13
Non-VR	Non-AR	AR	AR <sub>0</sub> VR <sub>0</sub> vs. AR <sub>1</sub> VR <sub>0</sub>	4.50	1.15	<0.001	2.23	6.76
VR	Non-AR	AR	AR <sub>0</sub> VR <sub>1</sub> vs. AR <sub>1</sub> VR <sub>1</sub>	-1.26	1.25	0.316	-3.72	1.21

MD = Mean Difference; SE = Standard Error; CI = Confidence Interval

**Fig. 4** The interaction effect of VR and AR on the recognition of textual information

conditions not involving AR, VR ( $M = 0.38$ ,  $SD = 0.90$ ) led to a significantly higher level of pictorial information recognition than non-VR ( $M = 5.93$ ,  $SD = 0.82$ ,  $p < 0.001$ ).

## 4 Discussion

Overall, the results based on ANOVAs and pairwise comparisons provide important findings on the use of XR in cognitive psychology in relation to information technology-mediated activities such as shopping, and especially how consumers' memory recall and recognition might perform in different realities mediated by virtual technologies, compared to the physical world. However, the empirical results of this study neither fully confirm the positive effect nor strongly support such concerns of XR on memory recall and recognition, which is consistent with the findings of a few studies. For example, in the

studies of Ruiz-Ariza et al. (2018) and Chen et al. (2019), AR did not significantly influence memory recall. To better address the research questions proposed in subsection 2.3, we deepen the discussion and synthesize the key results of this presented study.

*Key finding 1. Compared with physical reality, using single XR technology could lead to a worse recognition of textual information.* The results indicate that fully non-XR mediated (e.g., physical) environments offer better textual information recognition performance, especially when compared only to a single technology being used (either VR or AR). According to the results presented in Table 5 and Table 6, we can argue that the use of VR would lead to a worse memory regarding recognizing textual information. One possible explanation for this might be related to the readability of textual information provided by current VR technologies. Prior studies have also shown that paper-based reading is more preferable compared with e-book

reading (Gregory, 2008; Woody et al., 2010). In the study of Baceviciute et al. (2021), reading in VR demands more cognitive engagement, and is less time efficient. Thus, users might have less motivation and desire to discover, search, read, process and memorize textual information in the VR-mediated environment (the digital replica of the physical reality) compared with the non-VR environment due to the high amount of required resources for acquiring textual information (Grout et al., 2015; Ryan, 1999). For example, during shopping activities, consumers may spend e.g., more mental and cognitive resources to process text-related information in virtual reality. What should be mentioned is that even though the main effect of AR on textual information recognition was statistically insignificant, we can still see the probability that AR had a tendency to have a negative impact ( $p = 0.058$  indicates there was a 5.8% probability that the observed differences were the result of sampling error). Additionally, the interaction effects also indicate that using AR alone might lead to worse memory performance compared to a non-XR environment. Such a worse memory recognition level led by AR might be explained by cognitive load theory which raises a concern that the use of AR might increase the extraneous cognitive load (where users need to mentally integrate multiple sources of physically or temporally disparate information, resulting in a split-attention effect (See e.g., Sweller, 2005), and which is intuitively negatively associated with memory function. For example, in the study of Xi et al. (2023), AR was significantly associated with overall workload, especially mental demand and effort. Therefore, when processing text information in augmented reality and other information in physical reality, users might encounter a high cognitive load since the visual cues coming from multiple resources have to be combined.

*Key finding 2. The combination of AR and VR would not significantly increase the difficulty of recognizing textual information compared to single XR.* According to the results of the interaction effects, in the conditions with either AR or VR, the addition of another technology did not lead to a significant difference in the recognition of textual information. In other words, when employing AR in virtual reality, the challenge of processing and recognizing information might not be so high given that the augmented information can be seamlessly embedded into the virtual environment (e.g., as with the AR<sub>1</sub>VR<sub>1</sub> Group in this study). From the user's perspective, all textual information is digitally displayed in the same technological media. Therefore, there is a possibility that the split-attention effect caused by processing information from multiple sources might become weak. In addition, a suspension of disbelief (the intentional avoidance of critical thinking) might also occur in virtual reality (de Gelder et al., 2018). Therefore, the "augmented" information in virtual reality might be considered as part of "reality" rather than being easily and intentionally distinguished as would be the case in physical reality.

Another explanation is that users might have a higher perception toward vividness and interactivity when information is displayed in an augmented way (Yim et al., 2017), which leads to a psychological compensation response to the high cognitive load. Thus, for most users, the AV environment (where AR and VR are combined) might eliminate the high cognitive load brought by AR, and bring similar experiences as the VR environment. Certainly, such assumptions should be further investigated in future studies based on empirical evidence.

*Key finding 3. There is not sufficient statistical evidence to suggest that XR technologies significantly affect the recall of textual information.* Surprisingly, one important inference from the results of this study is that neither AR nor VR had significant negative or positive effects on the recall of textual information. In other words, the two main XR technologies and the combination of the two could create a similar performance level of information recall as seen in purely physical reality. Previous literature has shown that free recall performance is lower than recognition (Roettl & Terlutter, 2018). Therefore, one potential explanation for this might be that the memory recall activity itself is difficult for most consumers in a daily-life setting. For example, in this study, participants were asked to free recall product names (album titles), and according to the results, the free recall performance was unsatisfactory in all four shopping conditions given that the mean value of total answers was 1.68 (near to only two product names). Due to the low answer base per participant, we can reasonably assume that it is hard to identify a statistical difference between different groups through the data test, which further led to the insignificant effect of XR observed on text recall. Thus, such results can still indicate that XR did not have a significant effect on the recall of textual information, and neither did it improve or diminish information recall. It is not difficult to find that most VR and AR-related studies focused on investigating spatial memory recall (e.g., Krokos et al., 2019; Munoz-Montoya et al., 2021). This may be because XR has a greater impact on spatial information processing than other information types such as textual information.

*Key finding 4. All three XRs would lead to a similar recognition performance of pictorial information as physical reality.* Since there was no significant difference in the performance of pictorial information recognition between all three XRs and physical reality, we can reasonably postulate that XR users could actually have similar performance when recognizing pictorial information as they do in physical reality, which is a new and relatively positive finding (compared to key finding 1). The negative impacts of AR and VR stemming from cognitive load and low readability were less evident in the situation of recognizing pictures. Due to current technological limitations as well as reading habits, browsing pictures might be much easier than reading digital text on the screen or with a lens. In addition, and different from text, memorizing pictures usually requires

a more elaborate encoding because pictures automatically engage various representations and associations with other knowledge about the world (Grady et al., 1998). As an innovative information display method, XR might be more likely to provide an opportunity for participants to conduct free imagination and make rich associations (Huang & Liu, 2014), and even disentangle the information from the reality they come from (Riecke, 2003). Therefore, one reasonable explanation for the insignificant impact of AR and VR on pictorial information recognition might be that there is an offset effect between the negative and positive effects of XR on such memory performance.

Another possible reason might be that participants may store and process picture information through other psychomotor activities that have not been detected and examined in this current study, and which fully mediate or moderate the effect of XR on the recognition of pictorial information. The in-depth mechanism and boundary conditions of how XR might influence the recognition of pictures, therefore, require more empirical research in the future.

## 5 Contribution and Implications

### 5.1 Research Contribution

Even though metaverse-related research is a natural extension of current IS research (Walsh & Pawlowski, 2002), it still lacks sufficient academic attention and valuable research insights. In the majority of XR-related studies, a lot of attention related to cognitive function and activity has been directed towards motivation and the resources used for overcoming challenges when searching for and acquiring information (e.g., information need, Wu, 2015; workload, Xi et al., 2023). It is noticed that these studies were mostly used for clinical, healthcare and cognitive training purposes (Baker et al., 2020; Park et al., 2019; Tuena et al., 2020). Such trends can also be observed through the empirical studies presented in Table 1. However, it is still unknown how XR would influence the actual performance of processing daily-life information. To answer such a fundamental question, this current study empirically investigated the two core aspects of recall and recognition in the information process in extended realities based on a series of memory tests following natural shopping activities, which contributes to the interdisciplinary research of contemporary information systems, human–computer interaction, cognitive psychology, and digital marketing.

As presented in the literature review of Merino et al. (2020) and Smith (2019) that the few existing studies in the area mainly focused on spatial memory and episodic memory, different types of visual information (textual vs. pictorial) have rarely been discussed, and especially in

business and marketing contexts. Therefore, the current study enriches the current metaverse literature by investigating and comparing the recall and recognition of different visual information types, and provides new insights into the development of cognitive load theory in the metaverse. The results reveal that XR technologies have different impacts on recall and recognition performance. Textual information recall and pictorial information recognition would seem not to suffer significantly in XR compared to shopping in a brick-and-mortar store. For textual information recognition, both AR and VR led to a significantly worse performance compared to a non-XR mediated reality, while the combination of AR and VR led to the same recognition performance as seen when using a single technology. These findings not only strengthen our understanding of how cognitive function changes towards different information types in extended realities and contribute to the development of cognitive load theory, but also provide implications and inspiration for other research fields such as education and cognitive training, journalism, and communication.

More importantly, due to the lack of in-depth and comprehensive understanding of the concept and nature of AR and VR in the extant literature, many studies have failed to distinguish and compare different XR technologies (either AR or VR, see Table 1). Moreover, among most extant studies, either using single AR/VR applications provided by the market or self-developing simple XR platforms without considering other design and interaction-related factors may not provide the conditions for effective and scientific research design for comparing different XRs. In the current study, we designed and conducted a rigorous laboratory experiment with all possible external variables being controlled (e.g., amount of information, prior product knowledge, task time, textures and lighting conditions, size of the shop, interactivity, and demographic factors of participants) for comparing the core essence of different XR technologies, which we believe can provide valuable hands-on guidance for future researchers.

### 5.2 Practical Implications

The results of this study provide guidance for XR developers and designers to develop and use different XR systems in accordance with specific goals in different areas. For example, XR systems have been used for cognitive training in elders and patients (Curran & Hollett, 2024). Regarding recall-oriented training, developers and decision-makers could choose the most suitable XR technologies while considering other factors such as time resources, economic cost, and development difficulty. However, in regard to recognition-oriented training, the use of XR may not lead to a significant improvement in memory performance. In current practice, another area where XR has been widely discussed is education, and the cognitive activities in learning are

relatively more complex and have higher requirements for memory-related functions. Thus, when developing XR systems and programs for learning environments, educators could consider how to use AR and VR to design different teaching materials for recall- and recognition-related learning tasks.

As a further consideration, business practitioners (especially retailers and marketers) can directly benefit from this study. XR technologies can be used to create a similar cognitive experience of recalling textual information and recognizing pictorial information as experienced in physical environments such as a brick-and-mortar store. However, when VR or AR technology is used alone, the recognition of textual information may be sub-optimal compared to a physical store. Therefore, retailers should be more cautious and adopt a carefully planned design strategy when considering using only VR or AR for creating retailing and marketing environments. Interestingly, if the textual information can be presented in an environment consisting of multiple technologies such as AR and VR, then the recognition performance would not seem to diminish. Therefore, we encourage designers and retailers to attempt to embed augmenting information including product information, advertisements and other marketing content in virtual reality, since such virtual environments might create a more innovative, unique and enjoyable shopping experience for consumers (Xi & Hamari, 2021).

## 6 Conclusions and Future Work

This study conducted a granular analysis of cognitive function—information processing in different extended realities in daily life. More specifically, the study investigated whether and how VR and AR impact consumers' cognitive abilities to recall and recognize product information after a daily shopping task, based on a 2 (VR: yes vs. no)  $\times$  2 (AR: yes vs. no) between-subjects laboratory experiment (N = 153). Four discussed key findings combined with rigorous experiment design provide a considerable research contribution across different disciplines and research fields. Overall, the study provides important findings and guidance for the use of extended reality technologies in consumer-facing business, and also the use of XR in everyday life in general.

In order to ensure the external validity of the results, music products were selected as the suitable product category for use in this study since they contain specific visual information (both textual and pictorial) suitable for a general shopping task. One limitation of this study is that the results of recall and recognition performance may not be applicable to all metaverse contexts. Consumers usually actively search for and process product-related information to make their shopping decisions, which may be different from the information

processing behavior that takes place in other business situations such as advertising, marketing campaigns, and consumer learning. For example, in various XR-mediated advertising environments (e.g., 360-degree VR video, Song et al., 2020; location-based AR, Kim & Kim, 2014), the affective experience might be more important than cognitive processing for consumers. In addition, advertisements usually contain a large amount of relevant and also irrelevant sensory information and clues, and as a result, the memory process and formation are relatively more complex. Thus, in non-shopping contexts, the effect of XR on recall and recognition may change, which requires more investigation and discussion in future studies. It is also worth mentioning that the experimental settings in this study only provided a single consumer shopping function. Therefore, future studies are encouraged to assess memory performance in metaverse enabling multisensory social interactions (Hennig-Thurau et al., 2023).

In this study, recall and recognition tests (text vs. picture) were conducted to evaluate the performance of information processing and management in different extended realities. Future research can consider designing different memory tasks related to various memory types (e.g., sensory memory, working memory, episodic memory, long-term vs. short-term memory, and spatial memory). Regarding the measurement methods, hit/miss rate, response bias and recognition discrimination rate (ROC curve) are also aspects that can be considered in future studies. In addition, technologies such as eye trackers (e.g., Pupil core and Tobii), EEG (electroencephalogram), EDA (Electrodermal activity) devices, and other tracking wearables can be used to collect and measure biological and psychophysiological data related to memory performance such as gaze, attention, brain activity and skin state during the experiments.

Other sensory cues such as auditory, tactile, olfactory and gustatory senses can also effectively change the level and quality of memory (Fong et al., 2023; Serravalle et al., 2022). Thus, future studies could investigate the influences of multisensory experiences brought by XR technologies on cognitive and memory performance. One limitation of this study is that the investigation of memory performance is mainly based on visual experience. In the future, the effect of sound on memory performance should be considered in XR-mediated environments by using earphones and speakers. In addition, given that the current XR technology industry is dominated by virtual vision, it is understandable that researchers will face challenges in carrying out multisensory XR research based on the existing technological conditions in domains such as business, education, and health. However, we still encourage researchers to come up with, e.g., alternative methods for creating virtual touch, movement, smell, and taste (see e.g., Mishra et al., 2021; Allman-Farinelli et al., 2019), and to combine XR with other innovative technologies such as artificial intelligence and big data in the future.

## Appendix A

### Demographic Information (Numbers of participants, Frequency)

Measure	AR <sub>0</sub> VR <sub>0</sub> Group (n = 41)	AR <sub>1</sub> VR <sub>0</sub> Group (n = 42)	AR <sub>0</sub> VR <sub>1</sub> Group (n = 34)	AR <sub>1</sub> VR <sub>1</sub> Group (n = 36)	<i>F</i>	<i>p</i>
Biological sex					1.214	0.307
Male	27 (65.9%)	19 (45.2%)	19 (55.9%)	19 (52.8%)		
Female	14 (34.1%)	23 (54.8%)	15 (44.1%)	17 (47.2%)		
Age					1.256	0.292
Less than 19	5 (12.2%)	5 (11.9%)	5 (14.7%)	6 (16.7%)		
20–29	30 (73.2%)	34 (81%)	25 (73.6%)	29 (80.6%)		
30–39	5 (12.2%)	3 (7.2%)	4 (11.8%)	1 (2.8%)		
40–49	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)		
50–59	1 (2.4%)	0 (0.0%)	0 (0.0%)	0 (0.0%)		
Education					0.851	0.468
Bachelor student	20 (48.8%)	26 (61.9%)	20 (58.8%)	22 (61.1%)		
Master student	17 (41.5%)	14 (33.3%)	12 (35.3%)	13 (36.1%)		
PhD student	4 (9.8%)	2 (4.8%)	2 (5.9%)	1 (2.8%)		
Monthly income (pre-tax, euro)					1.522	0.212
less than 499	24 (58.5%)	24 (57.1%)	15 (44.1%)	22 (61.1%)		
500–999	6 (14.6%)	11 (26.2%)	10 (29.4%)	6 (16.7%)		
1000–1499	4 (9.8%)	3 (7.1%)	4 (11.8%)	1 (2.8%)		
1500–1999	1 (2.4%)	2 (4.8%)	1 (2.9%)	0 (0.0%)		
2000–2499	4 (9.8%)	1 (2.4%)	0 (0.0%)	1 (2.8%)		
2500–2999	0 (0.0%)	0 (0.0%)	1 (2.9%)	0 (0.0%)		
3000–3499	0 (0.0%)	0 (0.0%)	1 (2.9%)	0 (0.0%)		
Confidential	2 (4.9%)	1 (2.4%)	2 (5.9%)	6 (16.7%)		
Use of English					0.648	0.586
1 Native language all the time	0 (0.0%)	0 (0.0%)	1 (2.9%)	0 (0.0%)		
2	2 (4.9%)	1 (2.4%)	2 (5.9%)	4 (11.1%)		
3	5 (12.2%)	6 (14.3%)	3 (8.8%)	6 (16.7%)		
4	7 (17.1%)	10 (23.8%)	10 (29.4%)	7 (19.4%)		
5	11 (26.8%)	9 (21.4%)	8 (23.5%)	9 (25.0%)		
6	8 (19.5%)	11 (26.2%)	5 (14.7%)	3 (8.3%)		
7 English all the time	8 (19.5%)	5 (11.9%)	5 (14.7%)	7 (19.4%)		
Importance of music					0.702	0.552
1 Extremely unimportant	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)		
2 Unimportant	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)		
3 Slightly unimportant	4 (9.8%)	2 (4.8%)	1 (2.9%)	1 (2.8%)		
4 Neutral	2 (4.9%)	3 (7.1%)	3 (8.8%)	4 (11.1%)		
5 Slightly important	12 (29.3%)	5 (11.9%)	7 (20.6%)	8 (22.2%)		
6 Important	13 (31.7%)	19 (45.2%)	14 (41.2%)	11 (30.6%)		
7 Extremely important	10 (24.4%)	13 (31.0%)	9 (26.5%)	12 (33.3%)		
VR experience					1.942	0.125
1 Never	15 (36.6%)	14 (33.3%)	9 (26.5%)	21 (58.3%)		
2 Rarely	18 (43.9%)	20 (47.6%)	20 (58.8%)	12 (33.3%)		
3 Occasionally	4 (9.8%)	4 (9.5%)	0 (0.0%)	1 (2.8%)		
4 Sometimes	3 (7.3%)	1 (2.4%)	4 (11.8%)	2 (5.6%)		
5 Frequently	0 (0.0%)	2 (4.8%)	1 (2.9%)	21 (58.3%)		
6 Usually	1 (2.4%)	1 (2.4%)	0 (0.0%)	12 (33.3%)		
7 Every day	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (2.8%)		

## Appendix B

### Memory recall scoring method

The first and second authors mutually checked and coded the answers for all 162 participants who completed the experiments (7 were marked as 'excluded' as they didn't complete the following recognition tasks within requested time frame). The first author checked responses from ID 1–90, and the second author checked responses from ID 80–162.

*Step 1:* They used commas, semicolons, and uppercase letters to segment the participant's responses into answers (total answers).

*Step 2:* They compared every single word in each answer with the album titles displayed in that participant's shopping scenario to verify the scores (of correct answers). Coding rules include: (a) Only content words (vs. function words) echoing part of the album title are scored. (b) Words describing the singer, the album cover, the song genre, or the song's name, although they may be correct, are not scored. (c) If the words closely reflected one of the album titles, they added a 1 score to that participant's score of correct answers. (d) If the words echoed some words in the album title yet did not totally match the whole title, they added 0.5 to that participant's score of correct answers. (e) Otherwise, the participant got 0 in his/her score of correct answers.

*Step 3:* Responses of ID 80–90 were duplicated coded and these responses were employed to examine coding reliability. Kappa's test was conducted. The results indicated the two researchers had fair consistency (*kappa's*  $\alpha=0.846$ ,  $p<0.001$ ) in coding.

## Appendix C

### Results of Normality Tests

Dependent variable	Conditions	Shapiro–Wilk's statistic	df	p-value
Textual information recognition	AR	0.986	78	0.524
	Non-AR	0.988	75	0.719
	VR	0.983	70	0.463
	Non-VR	0.987	83	0.592
Pictorial information recognition	AR	0.968	78	0.044
	Non-AR	0.977	75	0.179
	VR	0.975	70	0.168
	Non-VR	0.982	83	0.286
Textual information recall	AR	0.910	78	0.000
	Non-AR	0.735	75	0.000
	VR	0.698	70	0.000
	Non-VR	0.892	83	0.000

(a) Shapiro–Wilk test's alternative hypothesis is data does not obey a normality distribution ( $p < .050$ ), so that data obeys a normality distribution when  $p \geq .050$ ; (b) For the independent variable of pictorial information recognition, despite the AR mediated conditions marginally fails the Shapiro–Wilk test, the hypothesis of a normality distribution could still be accepted under the estimation through a normality Q-Q plot

## Appendix D

### Results of Variance Homogeneity Tests

Dependent variable	Levene's F statistics	df1	df2	p-value
Textual information recognition	0.968	3	149	0.410
Pictorial information recognition	0.121	3	149	0.948

The alternative hypothesis of Levene's test is that the compared groups have heterogeneous variances ( $p < .050$ ), so variance homogeneity assumption cannot be refused when  $p \geq .050$

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**Author Contribution** Nannan Xi: Conceptualization, Methodology, Validation, Investigation, Writing—Original Draft & Review & Editing, Project Administration, Funding Acquisition.

Juan Chen: Investigation, Methodology, Data Curation, Formal Analysis, Writing—Original Draft & Review & Editing.

Filipe Gama: Software, Resources, Investigation, Writing—Original Draft, Visualization.

Henry Korkeila: Software, Investigation.

Juho Hamari: Conceptualization, Methodology, Resources, Writing—Original Draft & Review & Editing, Supervision, Funding Acquisition.

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**Data Availability** The data that support the findings of this study are not publicly available to preserve individuals' privacy under the European General Data Protection Regulation. The data are, however, available from the authors upon reasonable request and with the permission of Tampere University and the Finnish National Board on Research Integrity (TENK).

### Declarations

**Conflicts of Interest** The authors do not have any conflicts of interest to declare.

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**Nannan Xi** is an associate professor at the Faculty of Management and Business, Tampere University. Her research is mainly focused on game-based approaches (e.g., gamification, XR/AR/VR, multimodality, and wearable technology) in information systems, management, consumer psychology and organization studies towards responsible consumption, sustainable decision-making, harmonious organizations and digital business transformation.

**Juan Chen** is a Ph.D., associate professor, currently working at School of Business Administration, Anhui University of Finance and Economics, China. She obtained her doctor's degree (majoring in marketing management) from Zhongnan University of Economics and Law. Aiming at exploring the influences of emerging technologies on economy and marketing strategies, she focuses on researching the effects of extended reality technologies on retailing and tourism.

**Filipe Gama** is currently pursuing the Ph.D. degree in computing and electrical engineering at the Faculty of Information Technology and Communication Sciences, Tampere University, Finland. He was one of the early stage researchers of the Marie Sklodowska-Curie Innovative Training Network programme on Full-Parallax Imaging. His research interests include 3D imaging, light-field imaging, virtual and augmented reality—computer vision and computer graphics.

**Henry Korkeila** is postdoctoral researcher whose recent work has focused on the avatarization of our analog cultures as they inevitably turn into digital cultures. Special focus has been on avatars themselves, usage of avatars in their different contexts including online video game genres. He has approached avatars through the types of capital, or resources, they have. His recent work in progress looks at game accessibility and inclusivity at large.

**Juho Hamari** is a Professor of Gamification and the Head of the Gamification Group at Tampere University. He leads gamification research under Academy of Finland's Strategic Profiling, Flagship and Centre of Excellence programmes. His research is focused on the science and practice of employing gameful approaches in tackling grand global challenges, be they related to the planet, people, prosperity or peace.