Exploring the effect of XR modality (VR vs. AR) on memory recall: The mediating role of perceived affordances, attention allocation, Psi, enjoyment and self-regulation

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June 2024

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Abstract

This study explores the differential effects of Virtual Reality (VR) and Augmented Reality (AR) on students' memory recall in the context of science education. By exploring the immersive dynamics and different structural affordances, the study aims to clarify how VR and AR sequentially affect the perceived affordances, attention allocation, plausibility illusion (Psi), enjoyment, self-regulation and memory recall. A between-subjects experiment was conducted with 70 participants who interacted with digital stimuli, using either VR or AR equipment. PLS-SEM was used for the statistical data analysis and testing of the hypotheses. The results indicated that VR induced a feeling of being transported into the virtual environment, which subsequently created a higher amount of attention allocation to virtual stimuli compared to AR. Attention allocation was found to positively affect Psi, where an increased attention allocation resulted in a higher sense of Psi. Additionally, a high sense of Psi was positively associated with the users' feeling of enjoyment. No significant results were found for enjoyment negatively affecting self-regulation, and regarding self-regulation affecting memory recall. The research aims to expand the understanding of immersive technologies in an educational context, by highlighting the distinct effects of VR and AR on complex cognitive processes and memory recall.

Keywords: immersive technologies, virtual reality, augmented reality, perceived affordances, attention allocation, plausibility illusion, enjoyment, self-regulation, memory recall

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Exploring the effect of XR modality (VR vs. AR) on memory recall

Immersive technologies within the Extended Reality (XR) domain, such as Virtual Reality (VR) and Augmented Reality (AR), are rapidly advancing and becoming widespread among many fields of interest. Despite being discussed together frequently, it is important to recognize their different characteristics. VR allows users to be fully immersed into a three-dimensional virtual environment, inducing a sense of being there and making the real world disappear completely (Huang et al., 2019; Steffen et al., 2019). Conversely, AR overlays digital elements on existing environments, "augmenting" the real world (Antonioli et al., 2014; Chen et al., 2023). Both VR and AR hold great potential for learning experiences in healthcare, industry and tourism (Steffen et al., 2019) and have received special attention in science education (Lui et al., 2023). The power to create an immersive experience provides users the opportunity to engage with complex and abstract concepts within the scientific field, of which space is an example (Jdaitawi et al., 2022; Önal & Önal, 2021). As astronomical concepts cannot be experienced in day-to-day life, it may make learning about them more complicated as it requires some level of imagination to process information (Chen et al., 2022; Suh & Prophet, 2018). Using VR or AR to visualize abstract concepts, theoretical concepts are brought to life and learning becomes more dynamic, which can effectively improve the comprehension and memorization of information (Chiang et al., 2019; Önal & Önal, 2021).

Within an XR environment, the level of immersion considerably depends on the perception of realism of the environment and corresponding digital elements. Consequently, the concept of presence is essential to consider when analyzing the effects of VR and AR on learning outcomes. Presence was introduced by previous studies to clarify the cognitive impact of immersive technologies and refers to the subjective feeling of being physically present in the virtual environment and perceiving it as real (Latoschik & Wienrich, 2022). It

is a crucial concept that significantly shapes user experience and engagement (Skarbez et al., 2017a). However, the broadness of this concept makes it a challenging one to measure, due to the different structural affordances of VR and AR (Skarbez, 2016; Westermeier et al., 2023). While VR creates the feeling of being present in the virtual environment, AR provides the illusion that a digital object is present in the user's physical surroundings (Steffen et al., 2019). Slater (2009) addressed this difference by dividing presence into place illusion (i.e., the sense of being present in the virtual environment) and plausibility illusion (i.e., the illusion that the occurring events in the virtual environment are real). Recent studies have begun to exclusively adopt the concept of plausibility illusion (i.e., Psi) to compare the potential effects of VR and AR on user perceptions and behaviors (Latoschik & Wienrich, 2022). Possibly, place illusion (i.e., Pi) may not be fully applicable to an AR setting, as AR lacks the opportunity for the user to be transported into the virtual environment. Therefore, focusing on the illusion of realism (i.e., Psi) within this study may result in a more valid measurement of presence.

To be able to feel any form of presence in general, research suggests that attention allocation is a requirement (Schubert et al., 2001; Skarbez, 2016). It is therefore an essential concept to consider when examining Psi in a virtual environment. Attention allocation represents the cognitive resources that are used to process stimuli, while eliminating irrelevant information (Archibald et al., 2015). When on a high level, it creates a deep engagement between the user and the virtual environment which may influence the sense of Psi (Skarbez, 2016). The deep engagement that Psi creates can be related to enjoyment, which is frequently associated with immersive learning environments. Namely, a believable and coherent virtual environment (Psi) can enhance the enjoyability of the immersive experience (Hartmann et al., 2023). The temptation to get involved in hedonic behavior arises, which prioritizes the enjoyment of the technology's usage (Van der Heijden, 2004).

While this generates more curiosity and pleasure, it may result in shallow learning and less knowledge transfer. The high levels of presence and engagement could overwhelm the learner resulting in a hedonic experience rather than an educational one, even though an immersive experience does not have enjoyment as the main purpose (Makransky & Petersen, 2021). This effect can be further explored by the influence of enjoyment on self-regulation, which is a self-management skill to successfully endure the learning process (Makransky & Petersen, 2021). When induced effectively, self-regulation can enhance the working memory during a learning experience, which is needed for successful memory recall (Jeneson & Squire, 2012). However, it is reasoned that the highly engaging nature and hedonic experience of immersive technologies can negatively affect self-regulated learning, potentially lowering memory recall (Wang et al., 2023).

Despite the possibilities, comparative studies on the effectiveness to use VR and AR in an educational setting are limited (Shen et al., 2017), with previous research failing to include the distinct affordances of the modalities and their impact in a science education context. Additionally, recent literature has presented conflicting results regarding the actual effects on learning outcomes (Buchner et al., 2022; Han et al., 2021), followed by the presented arguments on enjoyment and self-regulation in this study. Therefore, this research aims to explore whether the distinct features of VR and AR will influence memory recall through the sequential mediating roles of perceived affordance, attention allocation, Psi, enjoyment and self-regulation in the context of science education. The current research aims to answer the following research question in particular:

> RQ: "Will Perceived Affordance, Attention Allocation, Plausibility Illusion (Psi), Enjoyment and Self-regulation mediate the effects of XR modality (VR versus AR) on memory recall in the context of science education?"

Theoretical Framework

VR versus AR in Science Education: Structural Differences in their Affordances

VR and AR have gained popularity in the educational field, serving as tools to make learning experiences more effective and engaging (Ardiny & Khanmirza, 2018; Steffen et al., 2019; Tang, 2024). Particularly in the domain of science education, VR and AR have captured the attention of educators (Lui et al., 2023). Traditional tools that explain spatial subjects like biology, geography and astronomy, often lack effectiveness and students may struggle to understand such complex ideas (Lelliott & Rollnick, 2009; Parong & Mayer, 2018). When looking at astronomy in particular, a certain level of imagination is needed to process information about corresponding concepts, as experiencing them is not possible in real life (Chen et al., 2022; Suh & Prophet, 2018). Immersive technologies can create the opportunity to support this imagination by letting learners engage with the complex astronomical concepts and visualizing them in a virtual 3D-environment. This makes the concepts more tangible and serves to improve comprehension and knowledge retention in an effective way (Jdaitawi et al., 2022; Önal & Önal, 2021). Both VR and AR have been studied individually in the context of enhancing educational experiences (Makransky et al., 2019; Zhang et al., 2017). However, comparative research that explores which technology is the most suitable for implementation in the educational field is lacking (Suh & Prophet, 2018; Tang, 2024). The growing use of immersive technologies in education makes it essential to address this knowledge gap.

Although VR and AR are both highly immersive technologies and frequently discussed together in research (Latoschik & Wienrich, 2022), it is essential to distinguish their unique characteristics and structural differences in terms of modality perception, level of immersion and learning experience. For instance, VR can be characterized by the fully

immersive simulation it provides, where the user is isolated from the physical world and therefore transported into the virtual environment (Chang et al., 2018; Steffen et al., 2019). The user is typically able to interact with the synthetic 3D environment through a headset and goggles, to limit the consciousness of the physical world and creating a feeling of immersion and control. The occlusion that VR creates possibly deepens presence and engagement (Jensen & Konradsen, 2017). On the other hand, AR enhances the physical world with digital content rather than replacing it (Westermeier et al., 2023). It creates a blended environment, mostly through AR glasses or a smartphone, by projecting digital objects onto the physical world. The semi-immersive nature of AR allows users to perceive and engage with the digital elements within their own physical surroundings (Steffen et al., 2019).

The structural differences between the two immersive technologies highlight the relevance of understanding how user perceptions and experiences are affected by the different modality affordances. Given these differences, it can be predicted that the fully immersive character of VR will cause users to feel disconnected from their physical surroundings and deeply engaged with the virtual space. On the contrary, AR's semi-immersive nature will create a more blended experience, enabling users to remain conscious of their physical surrounding while incorporating digital elements to interact with. Therefore, the following hypothesis is proposed:

> H1: Participants in the VR condition will experience the feeling of being transported into the virtual environment, while participants in the AR condition will experience the feeling of the virtual environment being transported into their own.

Perceived Affordance and Attention Allocation

In the context of VR and AR, attention allocation represents the cognitive resource used to process and focus on the virtual stimuli, while eliminating information that is irrelevant to the task (Archibald et al., 2015). It is a limited cognitive resource and must be

deployed carefully, to ensure effective task performance and efficient information processing (Harvey et al., 2022). Understanding the concept of attention allocation is crucial in VR and AR research due to its effect on user perception and effectiveness of immersive technologies, which several studies have highlighted before (Chen et al., 2023; Huang et al., 2019; Ogawa et al., 2022; Skarbez, 2016).

For instance, Huang et al. (2019) compared the effects of VR and AR on knowledge retention and found that attention allocation was recorded to be the highest in a VR environment. Participants were found to allocate more visual attention to the virtual environment and have more cognitive responses related to attention in the VR condition. This could be explained by the fully immersive experience VR creates. During the immersive experience, the user is transported into the virtual environment with limited consciousness of the physical world (Skarbez, 2016) which enhances immersion, presence and engagement (Jensen & Konradsen, 2017). The state of sensory and cognitive immersion is induced by allocating the user's perceptual and cognitive attention from the physical world to the virtual environment. Simultaneously, when immersed into a sensory-rich virtual space, the user's attention is directed towards the virtual environment (Byström et al., 1999). This asserts a feedback loop, in which heightened attention to the virtual space leads to increased immersion, presence and engagement, while high levels of the same concepts enhance the allocation of attentional resources (Byström et al., 1999). Therefore, the user's attention is likely to be allocated towards the virtual stimuli when feeling transported into an immersive virtual environment.

Considering the structural differences between VR and AR, it is reasonable that an augmented environment may allocate attention differently than a fully immersive virtual environment. This is supported by the previously mentioned study by Huang et al. (2019), who recorded a lower amount of attention allocation to the AR environment due to the high

dissimilarity between the physical environment and the augmented digital objects. The continuous pairing of the augmented and physical environment may cause a reduced amount of immersion and attention, as the transportation of digital objects into the user's physical surroundings can be perceived as inconsistent and disturb the allocation of attention to the augmented environment (Önal & Önal, 2021). The previous findings indicate that users who feel transported into a virtual environment are likely to allocate more attention to the virtual stimuli. Due to the high level of immersion that is experienced, attention is successfully allocated to the virtual environment. Therefore, it is hypothesized:

> H2: Participants who feel transported into a virtual environment will allocate more attention to stimuli compared to those who feel the virtual environment is transported into their own physical surroundings.

Attention Allocation and Plausibility illusion

The level of immersion in VR and AR environments is frequently assessed using the specific concept of 'presence' (Latoschik & Wienrich, 2022). The concept significantly impacts the user's experience and engagement within the virtual environment, which makes it crucial to address when examining the effects of VR and AR on a learning outcome (Skarbez et al., 2017a). In the context of immersive technologies, presence is defined as the subjective feeling of physically 'being there' and the perception that the virtual or augmented environment is real (Latoschik & Wienrich, 2022; Slater, 2009). It is a rather broad concept, which poses challenges when trying to measure it directly in a VR and AR context (Skarbez et al., 2021). Solely the sense of 'being there' can be challenging to interpret for both VR and AR, as these environments transcend the simple perception of space and have distinct structural affordances (Skarbez et al., 2021; Westermeier et al., 2023). One of the problems in the AR setting, for example, can be the maintenance of a cohesive design that integrates the digital elements smoothly into the physical environment of the user (Latoschik & Wienrich,

2022). Furthermore, in VR, it can be difficult to simulate sensory experiences or create a realistic virtual environment. The mismatch between the virtual and physical surroundings could therefore result in a less authentic experience (Simeone et al., 2015).

To address the complexity of measuring presence in immersive environments, Slater (2009) divided presence into place illusion (i.e., the sense of being present in the virtual environment) and plausibility illusion (i.e., the illusion that the occurring events in the virtual environment are real). Recent studies have begun to exclusively adopt the concept of plausibility illusion (Psi) to compare the potential effects of VR and AR on user perceptions and behaviors (Latoschik & Wienrich, 2022). Possibly, place illusion (Pi) may not be fully applicable to an AR setting, as the digital elements are transported into the physical surrounding rather than the user being transported into a virtual environment (i.e., the sense of being present in the virtual environment). Focusing on Psi may result in a more valid measurement of presence when comparing the effects of VR and AR in science education, as the illusion of realism can be interpreted beyond the perception of space in the immersive environment. Additionally, earlier research has demonstrated that Psi has a major impact on how users perceive and experience virtual environments (Berthiaume et al., 2018; Latoschik & Wienrich, 2022; Skarbez, 2016; Skarbez et al., 2021). Understanding the ways in which VR and AR evoke Psi can therefore provide valuable insights on how to effectively engage students in a immersive learning environment and assist them in knowledge retention (Huang et al., 2019; Makransky et al., 2019).

Plausibility illusion (Psi) refers to the subjectively perceived illusion of reality experienced by the user (i.e., the perceptual illusion that the events in the virtual environment are really happening) and involves the believability and authenticity of a virtual environment (Berthiaume et al., 2018; Skarbez et al., 2017a; Slater, 2009). In essence, the sense of plausibility concerns the subjective state that emerges during an XR experience when the

cognitive, perceptual and sensory levels confirm the information to be coherent (Latoschik & Wienrich, 2022). Therefore, "coherence" is a closely related concept that is used in previous research to describe the authenticity and realism of a virtual environment. Namely, the level of coherence contributes to the illusion that events in the virtual environment are taking place for real (i.e., Psi; Skarbez, 2016; Skarbez et al., 2017a). It is argued that a virtual environment can be considered as coherent if it aligns with the expectations and prior experiences of the user, contains internal logic and operates consistently (Skarbez et al., 2017). Ultimately, rational and predicable behavior determine the degree of realism and the coherence between the digital components in the virtual environment, which is needed to effectively induce Psi (Latoschik & Wienrich, 2022; Slater et al., 2022).

Another contributor to the successful inducement of Psi is attention allocation. The sense of plausibility is a complex cognitive activity, which demands a certain amount of effort and attention to be induced (Hofer et al., 2020). Skarbez (2016) argued that a strong sense of Psi requires the user's capability of allocating attention to the virtual environment. The plausibility of an immersive experience will increase when more attention is allocated to the coherent stimuli, which creates a feedback-loop. The amount of attention that is allocated towards the virtual environment is based on its plausibility, which in turn increases the perceived plausibility again (Byström et al., 1999; Skarbez, 2016). Hence, successful attention allocation increases the chance that users will believe the virtual occurrences are real. It can therefore be reasoned that a high amount of attention allocation creates a deep engagement with a virtual environment, possibly increasing the illusion that the occurring events in the virtual environment are real (i.e., Psi; Skarbez, 2016). Subsequently, the following hypothesis is proposed:

H3: Attention allocation will be positively associated with Psi.

The Influence of Plausibility Illusion on Enjoyment

When evaluating the use of XR technologies in an educational setting, enjoyment is an important factor to be considered. Enjoyment is interpreted as the degree to which an individual considers the virtual experience to me amusing and pleasant (Tokel & İsler, 2013). A variety of studies have associated a high amount of presence with higher feelings of enjoyment (Khenak et al., 2020; Makransky & Lilleholt, 2018; Tussyadiah et al., 2018). The presence-inducing affordances of an immersive technology can enhance hedonic satisfaction, which may lead to a higher feeling of enjoyment (Tamborini & Bowman, 2010; Tussyadiah et al., 2018). An example by Lui et al. (2023) showed that using immersive VR in a classroom setting can improve students' enjoyment during a learning experience, as the immersive virtual experience provides a greater feeling of presence as opposed to a non-immersive one. As previously mentioned, Psi is linked to presence and gives virtual environments more credibility by enhancing their perceived realness and coherence (Skarbez, 2016; Skarbez et al., 2017a; Slater et al., 2022). Consequently, a virtual environment that is believable and coherent stimulates the immersiveness and enjoyability (Hartmann et al., 2023). It can therefore be reasoned that a strong sense of plausibility illusion in a virtual environment will stimulate a more enjoyable experience. The following hypothesis is proposed to test this reasoning:

H4: Plausibility illusion will be positively associated with the feeling of enjoyment

Enjoyment and self-regulation

Self-regulation is defined as a learner's skill to self-manage behavior to successfully endure a learning process. Effective self-regulation leads to the creation of ideas, emotions and behaviors in favor of a learning goal and encourages the transfer of factual, conceptual and procedural information (Sitzmann & Ely, 2011; Zimmerman, 2013). It is therefore a

relevant concept to consider when looking at the knowledge transfer capabilities of immersive experiences.

Enjoyment, in terms of a students' joy within a certain learning experience or task, has been frequently related to self-regulated learning (e.g., Ahmed et al., 2013; Chatzistamatiou et al., 2013). However, it is a feeling that can restrict self-regulation, as learners may be intrigued to engage in hedonic behavior during a serious task (Van der Heijden, 2004). Hedonic behavior is awakened by the fun aspects of immersive technologies and leads to more interest and enjoyment while using the system. While immersive experiences may enhance positive responses like enjoyment, they do not always result in improved learning outcomes. This can possibly be related to the complex balance that is essential for the cognitive resources needed for self-regulation (Makransky et al., 2019).

Although an immersive experience may not be designed for fun in the first place, the engaging nature and high levels of presence are still risking the overwhelmed learner to behave hedonically (Makransky & Petersen, 2021). Additionally, the temptation for a learner to engage in hedonic activities and focus on an enjoyable experience rather than an educational one, can potentially fade the productive use of immersive technologies and lowers the level of learning and knowledge transfer (Makransky et al., 2020). Therefore, virtual environments that evoke a strong sense of enjoyment can be reasoned to negatively affect the user's self-regulation. To test this, the following hypothesis is proposed:

H5: The feeling of enjoyment will be negatively associated with self-regulation.

The Influence of Self-regulation on Memory Recall

Memory recall in an immersive context can be defined as the ability to retrieve knowledge that is previously acquired within the virtual learning environment. The engaging and multidimensional experience that is provided by VR and AR, activates cognitive functions and has been demonstrated to improve memory recall (Tang, 2024). Especially in

an educational setting, immersive technologies can provide an opportunity to improve memory recall and overall learning experience. They can help learners to explore and engage with virtual or augmented environments, which can improve academic success and the comprehension of challenging topics in for example science education (Badilla-Quintana et al., 2020; Klippel et al., 2019).

A learning experience concept that can be related to memory recall is self-regulation. Generally, self-regulation positively influences the transfer of factual, conceptual, procedural knowledge (Sitzmann & Ely, 2011). Self-regulation, more specifically defined as self-regulated learning, concerns the active control of cognitive processes and behavior by the learner, mostly to meet a certain goal. It also highlights the active role that learners play during a learning experience (Wirth et al., 2020). In a study that focused on immersive AR content, students with high levels of self-regulation were found to independently endure a learning process while simultaneously mastering the augmented environment (Albelbisi & Yusop, 2019; Muali et al., 2020). This suggests that effective self-regulation during a learning experience can enhance the working memory, which is needed to successfully recall short-term information (Jeneson & Squire, 2012).

However, previous research on self-regulated learning has emphasized the importance of incorporating strategies to enhance self-regulation in an immersive context, to create an effective learning performance (Wu et al., 2021). This indicates that self-regulation during an immersive experience may not always come naturally and can be explained by the cognitive load that immersive technologies create, which can influence the learning experience due to the limited capacity of the working memory (Jeneson & Squire, 2012). The high cognitive load can cause learners to exceed this capacity, disengage from self-regulation and therefore negatively affect task performance in for example, a VR environment (Wang et al., 2023). In this study, it is therefore expected that the low levels of self-regulation will result in a lower

score on memory recall, due to the cognitively demanding nature of immersive technologies. This is tested by proposing the following hypothesis:

H5: Self-regulation will be positively associated with memory recall.

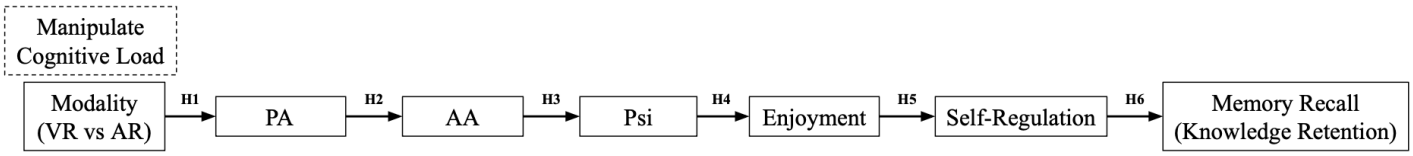
Methods

Experimental design

The research employed a between-subjects design experiment to compare the effects of VR and AR on memory recall and the sequential mediating role of space transportation, attention allocation, plausibility illusion, enjoyment and self-regulation. The research model is presented in Figure 1.

Figure 1

Research model



Note 1. PA = Perceived Affordances, AA = Attention Allocation, Psi = Plausibility Illusion.
Note 2. To test if VR or AR might require more cognitive capacity than the other, manipulative cognitive load is imposed before the experiment.

Participants

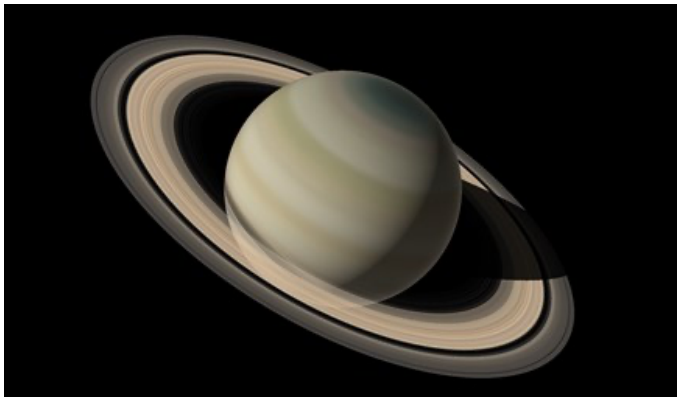
For this study, participants were recruited through the SONA human-subject pool, the Tilburg University recruiting system for experiments. The sample (N = 70) consisted of 45 females (64.4%) and 25 males (35.7%) and their age ranged from 18 to 34 years, with an average of 22 years. Other demographic features included participants' level of English (M = 6.10, SD = 1.07) and need for cognition (M = 3.69, SD = 0.68), which were both relatively high. Participants' prior knowledge about cosmology was limited (M = 2.87, SD = 1.52). Additionally, participants' familiarity with the technology they interacted with was assessed. Participants were more familiar with the technology in the VR condition (M = 4.49, SD = 1.77) than in the AR condition (M = 3.63, SD = 1.70).

Stimuli

The application Galaxy Explorer by Microsoft was selected to serve as stimuli for this study[1]. Galaxy Explorer is a three-dimensional audiovisual experience which lets the user travel through space, while discovering scientific information about the Milky Way galaxy as they go. This research focuses on the Solar System sub-construct of the application, which the user can have a closer look at when traveling there. The Solar System consists of the sun, eight planets and one dwarf planet. Each planet is identified audibly with its name, appearance, orbital period and a couple of characterizing phrases. By focusing on a planet, the user can magnify it to receive the auditory information. When selecting the planet Saturn for instance, the application will move closer to display the planet (see Figure 2) as the following auditory information is provided: "Saturn is best known for its beautiful ring system, which is mostly composed of particles of ice as well as rocks and dust. The planet's pale yellow color is due to ammonia crystals in its upper atmosphere." The user can go back to the Solar System afterwards, to be able to select a new planet.

Figure 2

Galaxy Explorer close-up of Saturn



[1] *Galaxy Explorer - Microsoft Apps* https://apps.microsoft.com/detail/9nblggh4q4jg?hl=nl-sr&gl=SR

Equipment

To conduct the experiment in the two different modalities, both VR and AR equipment was needed. The HP Reverb G2 VR-headset was used for the VR condition, holding a 2160 x 2160 screen resolution and a 90Hz refresh rate. This system enables participants to interact with the virtual environment and have a completely immersive experience, during which they are surrounded by the stimuli and the physical world is not visible. Two connected controllers were given in addition to the head mount, to facilitate interaction with the stimuli.

Figure 3

Equipment for the VR condition

The Microsoft Hololens 2 was used for the AR condition, with a 2k screen resolution and a 120Hz refresh rate. This device projects digital stimuli onto the physical world, which enables participants to only see the presented elements and interact with them directly with their own voice and hands.

Figure 4

Equipment for the AR condition

Procedure

The experimental study was conducted in the Tilburg University New Media Design lab. Firstly, participants were asked to carefully read and sign a form of consent before being randomly assigned to one of the two modality conditions: VR or AR. Verbal instructions were given on the use of the equipment, the Milky Way Galaxy application and the completion of the task. To test if VR or AR might require more cognitive capacity, cognitive load was imposed beforehand by having participants remember six digits of numbers during the experiment and report them after the experiment. Once the participants had gotten used to the equipment and the features of the application, they were instructed to locate and choose the Solar System in the Milky Way Galaxy. They were then given the task to choose and listen to an explanation of the Sun and five planets (Mars, Mercury, Venus, Pluto and Saturn) each lasting roughly ten to thirty seconds. When finished, participants were instructed to take off the equipment and report the 6-digit code. Then they were asked to fill in the cued recall test, after which they answered the survey questions about their attention allocation, plausibility illusion, enjoyment and self-regulation. The survey concluded with questions related to need for cognition, perceived affordances, demographics, level of English, prior knowledge of cosmology and familiarity with the immersive technology they interacted with. Finally, the participants received a debrief and were thanked for participating in the experiment.

Measures

The measures used in this study are based on previous studies and adapted if necessary to fit the current research model[2]. All measure items can be found in Appendix A.

[2] There might be some content that shares similarities with prior studies conducted under the supervision of Dr. Mincheol Shin.

Attention allocation was assessed using four items adapted from Sundar et al. (2017) using a 7-point Likert Scale, e.g., “I devoted my whole attention to the Virtual Environment.” The internal consistency reliability was acceptable (α = .85).

Plausibility illusion was measured using five 7-point Likert Scale items based on a questionnaire from Mal et al. (2022). These items examine the participants' believability of the experience in the VR or AR environment, e.g., “The appearance of the virtual objects and the background environment where I belonged to matched well.” Again, the internal consistency reliability was acceptable (α = .85).

Enjoyment was measured with seven items adapted from Tamborini et al. (2010) and Tamborini et al. (2011). Participants had to rate their feeling of enjoyment during the experiment using a 7-point Likert Scale, e.g., “While I was doing this activity, I was thinking about how much I enjoyed it.” Two reverse-coded items were used to control for a balanced response, e.g., “I thought this was a boring activity.” The internal consistency reliability was acceptable (α = .92).

For *self-regulation*, a modified version of the Motivated Strategies for Learning Questionnaire - Chinese Version by Lee et al. (2010) was used and adapted to make the statements align with the current study. Three statements of the MSLQ-CV were eliminated, as they were focused on studying for a course and therefore not relevant when measuring self-regulation during a specific task. In addition, the wording of the remaining statements was adjusted to the experiment-specific context rather than study behavior in general. E.g., “I ask myself questions to make sure I know the material I have been studying.” was changed to “I asked myself questions during the task to make sure I remembered the information I had been given.” The internal consistency of the items experienced a minor issue and was not acceptable (α = .664).

To measure *memory recall*, a cued recall test addressing the stimuli content has been administered (see Appendix B). Participants were asked to answer eight multiple choice questions and two true or false questions, adapted from the study design by Ahn et al. (2022).

Finally, some control variables were assessed to gain insight in participants demographic information (age and gender), level of English (7-point Likert Scale; "I consider my understanding of the English language to be good."), prior knowledge about both cosmology (7-point Likert Scale; "I have a lot of knowledge on cosmology."), experience with VR or AR (7-point Likert Scale; "I am familiar with the technology I interacted with.") and need for cognition. Need for cognition was assessed with six statements adopted from the Need for Cognition Scale developed by De Holanda Coelho et al. (2018), that were rated on a 5-point Likert Scale. E.g., "I really enjoy a task that involves coming up with new solutions to problems." Additionally, cognitive load was imposed before the experiment to test if VR or AR might require more cognitive capacity than the other. Participants were asked to remember a six-digit number (492075) during the VR or AR task and report it directly after, before starting the cued recall test.

Manipulation Check

A manipulation check was employed to guarantee that each modality operated in line with its affordances. This measure was also used to assess the perceived affordances variable in the research model. A 7-point semantic differential scale (1 = I felt the space was transported into my space, 7 = I felt I was transported into the space) was used to measure the participants' experience with the XR modalities. An independent *t*-test showed a significant result: $M_{diff} = -2.03$, $t(68) = -5.05$, $p < .001$. This indicates that each modality was perceived according to its affordances.

Data analysis

After the completion of the data collection, partial least squares structural equation modeling (PLS-SEM) was used for the statistical data analysis. PLS-SEM makes it possible to analyze complex research models and structural correlations between variables with small sample sizes. The descriptive statistics and an independent samples t-test for the manipulation check were conducted in Jamovi.

Results

Measurement Validity

Prior to testing the hypotheses, the validity of the measurement model was assessed using PLS-SEM. According to Kock (2020), item loadings for reflective indices must require a p-value lower than .001 to guarantee that the PLS-SEM measurement model is sufficiently reliable. Additionally, the item loadings ought to have values equal or greater than .50 to ensure the validity of the measurement. Two items from the self-regulation measure had an item loading below .50. To ensure the reliability of the model, those items were not included in the analysis.

To determine the internal consistency and reliability of measurements, the additional composite reliability and Cronbach's alpha values were assessed. Except for the self-regulation measure ($\alpha = .664$), all reviewed constructs had a composite reliability and Cronbach's alpha value higher than 0.7, which is in line with the standard recommended for assessing the internal consistency reliability of measures (Hair Jr et al., 2014). As a means of verifying the measurement model's convergent validity. the values of the average extracted variance (AVE) were evaluated. The convergent validity was confirmed as the AVE for each construct exceeded 0.5.

To ensure the discriminant validity, the Heterotrait-Monotrait ratio (HTMT) was evaluated. The constructs of the measurement model all showed HTMT ratios lower than 0.9,

which is suggested to be a good criterion for the discriminant validity. The results of the reliability and validity analyses can be found in Tables 1 and 2.

Table 1

Reliability Analysis of Constructs and Convergent Validity

Construct	Item	Loading	Composite reliability	Cronbach's α	AVE
Perceived affordances	PA	1.00	1.00	1.00	1.00
Attention allocation	AA1	.905	.898	.846	.830
	AA2	.734			
	AA3	.769			
	AA4	.898			
Plausibility illusion	Psi1	.617	.891	.846	.790
	Psi2	.736			
	Psi3	.832			
	Psi4	.870			
	Psi5	.867			
Enjoyment	E1	.924	.934	.916	.821
	E2	.908			
	E3	.709			
	E4	.649			
	E5	.809			

	E6	.914			
	E7	.789			
Self-regulation	SR1	.540	.778	.664	.656
	SR3	.693			
	SR4	.645			
	SR6	.657			
	SR7	.579			

Note. PA = Perceived Affordances, AA = Attention allocation, Psi = Plausibility illusion, E = Enjoyment, SR = Self-regulation

Table 2

Discriminant Validity (HTMT Ratio)

Construct	Attention allocation	Plausibility illusion	Enjoyment	Self-regulation	Space transportation
Attention allocation					
Plausibility illusion	.455				
Enjoyment	.652	.544			
Self-regulation	.531	.231	.317		

Perceived

affordances

Hypotheses Testing

H1 predicted that participants in the VR condition will experience the feeling of being transported into the virtual environment, versus participants in the AR condition who will experience the feeling of the virtual environment being transported into their own. The results showed that the feeling of being transported into the virtual environment in the VR condition (M = 5.23, SD = 1.63) was significantly higher than in the AR condition (M = 3.20, SD = 1.73), $\beta = 0.52$, $p < .01$. Therefore, H1 was supported.

H2 proposed that the feeling of being transported into the virtual environment will result in a higher amount of attention allocation. The results revealed a significant positive relationship between perceived affordance and attention allocation ($\beta = 0.34$, $p < .01$, $R^2 = .11$). In other words, participants that felt transported into the virtual environment experienced a greater allocation of their attention to the stimuli, which was in support of H2.

H3 and H4 predicted a positive relationship between attention allocation and plausibility illusion, and between plausibility illusion and enjoyment. The results revealed that attention allocation is positively associated with plausibility illusion ($\beta = 0.35$, $p < .01$, $R^2 = .14$) and plausibility illusion is positively related to enjoyment ($\beta = 0.45$, $p < .01$, $R^2 = .24$). This means that both H3 and H4 were supported.

H5 proposed a negative association, with higher feelings of enjoyment resulting in a smaller sense of self-regulation. Unexpectedly, the results showed a positive association between enjoyment and self-regulation but with no significant effect ($\beta = 0.06$, $p = 0.30$, $R^2 = .08$). Therefore, H5 was not supported.

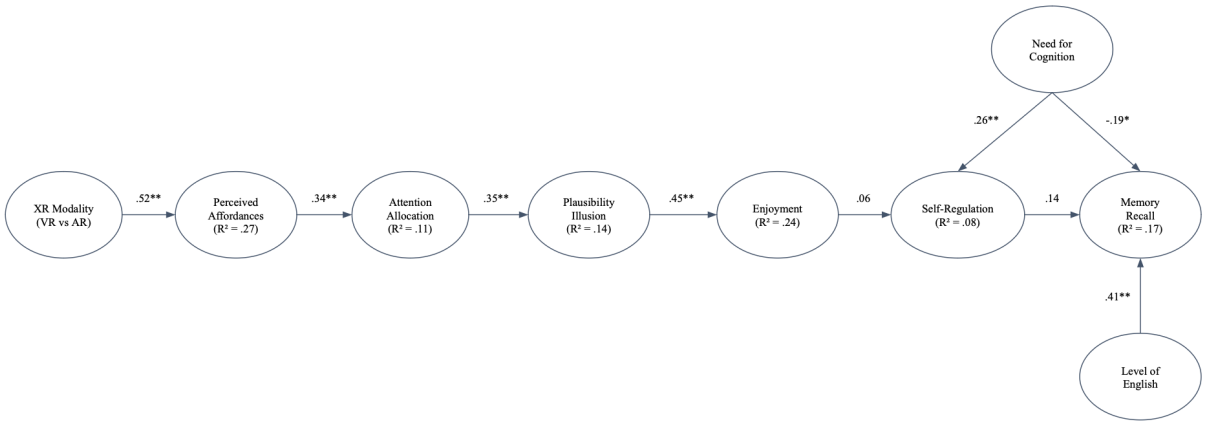
H6 predicted that self-regulation will positively relate to memory recall, with low levels of self-regulation resulting in low scores on memory recall. The results did not show a significant effect of self-regulation on memory recall (β = 0.14, p =.12, R^2 = .17). Therefore, H6 was not supported.

Control variables

In this study, five control variables were used: need for cognition, familiarity with XR, knowledge of cosmology, level of English and cognitive load. The six-digit number that was presented beforehand to impose cognitive load, was reported correctly by 26 out of 35 participants (37.1% of total) in the AR condition and 33 out of 35 participants (47.1% of total) in the VR condition. However, cognitive load as a control variable did not show any significant result on memory recall (β = 0.08, p = .25). Some variables did show significant outcomes. Need for cognition displayed a significant influence on self-regulation (β = 0.26, p 0-< .01) and on memory recall (β = -0.19, p = .05). Furthermore, the level of English (β = 0.41, p < .01) showed a significant effect on memory recall. All the results of the PLS-SEM analysis are presented in Figure 5.

Figure 5

PLS-SEM Results



*Note 1. *p < .05, **p <*. 01

Note 2. Insignificant outcomes of the control variables are not presented in the figure.

Model Fit

Four criteria were applied to evaluate the model fit (Kock, 2020). The average path coefficient (APC) and the average R-squared (ARS) should both have a p-value equal or lower than .05. The research model's good fit was validated by the PLS-SEM results: APC = 0.203 (p = .018), which indicates a positive relationship between variables and ARS = 0.169 (p = .035) indicated that the model has sufficient explanatory power. The average variance inflation factor (AVIF) and the average full collinearity VIF (AFVIV) ought to have values ideally equal or lower than 3.3. In this study, the AVIF = 1.107 and AFVIF = 1.631 provide more support for this model's suitability.

Discussion

The aim of this research was to investigate the effect of VR and AR on memory recall in the context of science education, focusing on perceived affordances, attention allocation, plausibility illusion, enjoyment and self-regulation as mediating variables. The first hypothesis predicted that participants in the VR condition would experience the feeling of being transported into the virtual environment, while participants in the AR condition would experience the feeling of the virtual environment being transported into their own physical surroundings. The results revealed that the feeling being transported into the virtual environment was significantly higher in the VR condition than in the AR condition, supporting the proposed hypothesis. This finding aligns with the perceived affordances of both XR modalities, which indicate that VR fully immerses users into the virtual space by occluding them from their physical surroundings (Huang et al., 2019; Jensen & Konradsen, 2017; Steffen et al., 2019). On the other hand, AR creates a blended environment which enhances the own physical surroundings with digital objects (Steffen et al., 2019; Westermeier et al., 2023). This explains the lower feeling of transportation to the virtual

environment, as the virtual environment is rather transported to the user's own physical surroundings by augmenting it with digital objects.

The study also demonstrated a significant result in support of the second hypothesis, which posited that the feeling of being transported into the virtual environment will result in a higher amount of attention allocation. Consistent with this prediction, participants who felt transported into the virtual environment experienced a greater allocation of their attention to the stimuli. This aligns with previous research, which suggested that the feeling of being transported into the virtual environment can lead to an increased allocation of attention to stimuli in the virtual environment (Huang et al., 2019; Skarbez, 2016). This highlights the importance of understanding the distinct affordances of the XR modalities and their effect on not only user perception, but also allocation of attention to stimuli within the virtual environment.

The third hypothesis proposed that a higher sense of attention allocation will result in a greater sense of Psi. The results indicated a significant positive relationship, indicating that participants who allocated sufficient attention to the stimuli in the virtual environment experienced a higher sense of Psi. This is supported by previous findings, which stated that a strong sense of Psi requires effort and attention to be allocated to the virtual environment (Hofer et al., 2020). Additionally, when the allocation of attention to the digital stimuli is successful it enhances the likelihood that the virtual environment is perceived as real (Skarbez, 2016).

The fourth hypothesis was supported by a significant positive association between Psi and enjoyment, which indicates that participants with a higher sense of Psi induced a greater feeling of enjoyment during the experiment. This is consistent with previous research, which proposed that enjoyment can be induced by high levels of presence (Van der Heijden, 2004). and the immersive nature of XR technologies can awaken hedonic behavior leading to an

enjoyable experience (Makransky & Petersen, 2021). In addition, when a virtual experience is believed to be authentic (i.e., Psi), a learning experience can become more enjoyable for the learner (Hartmann et al., 2023). This finding emphasizes the value of enjoyable XR content, which can be induced by effective engagement and Psi (Skarbez et al., 2017a).

The fifth hypothesis proposed a negative association between enjoyment and self-regulation, in which participants with higher feelings of enjoyment were expected to have a smaller sense of self-regulation. No significant results were found during the analysis, which means that the fifth hypothesis was not supported. A possible explanation for the non-significant findings could be the contradictory results from previous research about enjoyment and self-regulation. Alongside the negative association between enjoyment and self-regulation that was employed for this study (Makransky et al., 2020; e.g. Van der Heijden, 2004), others have suggested a positive effect as well (Ahmed et al., 2013; Pekrun & Stephens, 2012; Yin, 2021). This highlights the importance for future studies to consider both positive and negative effects of enjoyment in an immersive context, specifically when related to self-regulated learning.

Another possible explanation for the insignificant effect could be the presence of negative emotions that are induced alongside enjoyment during the immersive experience. Boredom or hopelessness, for example, are found to negatively affect self-regulated learning and overlap the effects of enjoyment (Igarzábal et al., 2021; Mega et al., 2014). This shows that when negative feelings coexist with enjoyment, the overall impact of enjoyment on self-regulation may be weakened (Duan, 2022). It is therefore important for future research to consider the interplay between different emotions when assessing self-regulation in an immersive educational context.

The sixth hypothesis proposed that self-regulation would be positively associated with memory recall, but the results showed no significant effect. The absence of statistical

significance could possibly be explained by the potential non-linear relationship between self-regulation and memory recall, due to the cognitive complexity of both variables. Supported by prior research, the complicated interactions between cognitive processes and memory recall could be represented inaccurately by a linear model like the one used for the current study (Amin & Malik, 2013). Additionally, the high cognitive load that immersive experiences impose can cause learners to exceed their limited cognitive capacity and disengage from self-regulation during a task (Jeneson & Squire, 2012; Wang et al., 2023). This highlights the importance of further research on the complexity of cognitive processes related to immersive learning environments, for educators to create effective learning experiences.

Implications

The results of this study contribute to the existing body of literature on the impact of VR and AR on science education. The research demonstrates the differences between VR and AR affordances, contributing to an improved comprehension of how these immersive technologies affect cognitive learning processes. This enhances the understanding of how learners interact with immersive environments, by examining cognitive processes such as attention allocation, Psi and enjoyment. Previous studies, including Önal and Önal's (2021), have emphasized the importance of cognitive processes in immersive educational contexts. The current study specifically contributes to the notion that a strong feeling of being transported into a virtual environment can improve the allocation of attention to the virtual stimuli, subsequently increasing the sense of Psi. This is in alignment with the findings of, for instance, Huang et al. (2019) and Steffen et al. (2019).

The findings provide educators, students and designers with practical suggestions to improve the learning process while using VR or AR as an educational tool. The study implies that VR, for example, can successfully improve engagement and the allocation of attention,

both of which are important for processing complex science topics like astronomy (Jdaitawi et al., 2022; Önal & Önal, 2021). Furthermore, the value of enjoyable XR content is also emphasized by the findings, which be induced by a high illusion of realism (Psi) and is supported by Skarbez et al. (2017a). By inducing a high sense or Psi, educators can develop enjoyable learning experiences, which is argued to be of important value in educational settings (Hartmann et al., 2023; Skarbez et al., 2017a). By considering the cognitive processes and distinctive affordances of immersive technologies, effective learning experiences can be created which enhance the growing understanding of XR technologies in science education.

Limitations and future research

There are certain limitations acknowledged in this study that need to be considered for future research. First, the generalizability can be questioned because of the findings' dependence on a limited sample of student participants from Tilburg University. To improve the study's external validity and create a more nuanced understanding, future studies should aim for a larger and more diverse research sample. Another possible limitation is the internal consistency and reliability of the self-regulation measure, which raised some concerns. To improve the overall model's reliability, two item loadings were removed from the analysis. This means that only five out of seven measurement items were used in the final analysis of the data. Additionally, the internal consistency of the measure could be questioned as its reliability was not accepted ($\alpha = .664$). Future research should look at the individual measurement items more carefully, to create a more reliable measurement for self-regulation in an immersive context. Furthermore, the assessment of self-regulation using a self-reported measure could potentially lead to misleading results. While self-reported measures can offer insightful data on users' subjective experiences, potential bias might depict the fundamental characteristics of self-regulation inaccurately (Makransky et al., 2019). It is important for

future studies to assess self-regulation with a variety of constructs and if feasible, consider the use of more observational measures (Eberhart et al., 2022). In this way, researchers can acquire a deeper understanding of self-regulation in immersive learning environments. Other future directions include the study's focus on short-term memory recall, which can be improved by investigating the long-term effects of VR and AR in science education. The deeper and longitudinal understanding XR modalities and cognitive processes affecting memory recall can provide the educational sector with valuable insights about its sustainable influence (Cai et al., 2014; Hartmann et al., 2023). Given the potential non-linear relationship between self-regulation and memory recall, future studies could consider alternative research models to explore the complexity of the interaction more accurately (Amin & Malik, 2013).

Conclusion

In the context of science education, this study explored the comparative effects of VR and AR on memory recall, particularly emphasizing the mediating roles of perceived affordances, attention allocation, Psi, enjoyment and self-regulation. Key findings implicate that the feeling of being transported into a virtual environment enhances the allocation of attention to the virtual stimuli. Consequently, a heightened attention allocation increases the sense of Psi, which in turn, increases the feeling enjoyment during an immersive learning experience. The study contributes to the growing field of literature on the cognitive processes that affect the learning experience in a VR and AR environment. With this knowledge, educators can use immersive technologies to develop new learning experiences that are engaging, enjoyable and effective.

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Appendices

Appendix A | Questionnaire - Full Measures

1) Attention allocation

Please choose the most appropriate answer that best describes your experience:

(7-point Likert Scale: 1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = neither agree or disagree, 5 = slightly agree, 6 = agree, 7 = strongly agree)

1. I devoted my whole attention to the virtual environment.

2. I concentrated on the virtual environment.

3. The virtual environment captured my senses.

4. I dedicated myself completely to the virtual environment.

Adapted from Sundar et al. (2017).

2) Plausibility illusion

Please choose the most appropriate answer that best describes your experience:

(7-point Likert Scale: 1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = neither agree or disagree, 5 = slightly agree, 6 = agree, 7 = strongly agree)

1. The appearance of the virtual environment seemed plausible to be.

2. The appearance of the virtual environment matched well with its original properties.

3. The virtual object fits into the background environment where I belonged to.

4. The virtual object was a plausible part of the environment where I belonged to.

5. The appearance of the virtual objects and the background environment where I belonged to matched well.

Adapted from Mal et al. (2022).

3) Enjoyment

Please choose the most appropriate answer that best describes your experience:

(7-point Likert Scale: 1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = neither agree or disagree, 5 = slightly agree, 6 = agree, 7 = strongly agree)

1. I enjoyed doing this activity very much.

2. This activity was fun to do.

3. I thought this was a boring activity. (REVERSED)

4. This activity did not hold my attention at all. (REVERSED)

5. I would describe this activity as very interesting.

6. I thought this activity was quite enjoyable.

7. While I was doing this activity, I was thinking about how much I enjoyed it.

Adapted from Tamborini et al. (2010) and Tamborini et al. (2011).

4) Self-regulation

Please choose the most appropriate answer that best describes your experience:

(7-point Likert Scale: 1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = neither agree or disagree, 5 = slightly agree, 6 = agree, 7 = strongly agree)

1. I asked myself questions during the task to make sure I remembered the information I had been given.

2. During the task, it was not difficult for me to decide what the main ideas were.

3. Although the task was hard, I neither gave up nor studied only the easy part.

4. Even when I thought the information was dull and uninteresting, I kept going until I finished the task.

5. When the voice-over was talking, I paid attention to what was being said rather than thinking of other things.

6. During the task, I stopped once in a while and went over what I had read or heard.

7. I worked hard to get a good result even when I did not like the task.

Adapted from Lee et al. (2010)

5) **Need for cognition**

Please choose the most appropriate answer that best describes your experience:

(5-point Likert Scale: 1 = extremely uncharacteristic, 2 = somewhat uncharacteristic, 3 = uncertain, 4 = somewhat characteristic, 5 = extremely characteristic).

1. I would prefer complex to simple problems.

2. I like to have the responsibility of handling a situation that requires a lot of thinking.

3. Thinking is not my idea of fun.

4. I would rather do something that requires little thought than something that is sure to challenge my abilities.

5. I really enjoy a task that involves coming up with new solutions to problems

Adapted from De Holanda Coelho et al. (2018)

6) **Manipulation Check**

Please choose the most appropriate answer that best describes your experience:

(7-point Likert Scale: 1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = neither agree or disagree, 5 = slightly agree, 6 = agree, 7 = strongly agree)

1. I felt I was transported into the space.

2. I felt the space was transported into my space.

7) **Prior knowledge, previous experience and level of English**

Please choose the most appropriate answer that best describes your experience:

(7-point Likert Scale: 1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = neither agree or disagree, 5 = slightly agree, 6 = agree, 7 = strongly agree)

1. I have a lot of knowledge on cosmology.

2. I consider my understanding of the English language to be good.

3. I am familiar with Virtual Reality.

OR

3. I am familiar with Augmented Reality.

8) Demographics

1. What is your age in years?

2. What gender do you identify with? Female / Male / Other / Prefer not to say

Appendix B | Cued Recall Test

1) How old is the sun?

a) 10 million years

b) 2.4 million years

c) <u>4.6 billion years</u>

d) 10 billion years

2) What is the size of Mars compared to Earth?

a) Larger than Earth

b) About the same size as Earth

c) <u>About half the size of Earth</u>

d) About ⅔ the size of Earth

3) What is found at the poles of Mars?

a) Liquid water

b) <u>Dry ice caps</u>

c) Oceans

d) Frozen nitrogen gas

4) Which of the following Statements about Mercury is <u>NOT</u> true?

a) Mercury is the smallest planet in our solar system

b) <u>Mercury has an orbital period of 201 days</u>

c) Mercury is about ⅓ the size of Earth

d) Mercury is located closest to the sun in our solar system

5) What is the primary component of Venus' atmosphere?

a) Water vapor

b) <u>Carbon dioxide</u>

c) Oxygen

d) Methane

6) What makes Venus a less than ideal vacation spot?

a) High temperatures

b) Heavy rainfall

c) Sulfuric acid rain

d) Cold weather

7) What is NOT true about Pluto based on the following text?

a) Pluto is made of ice and rock

b) Pluto was discovered in 1930

c) Pluto was originally considered the 9th planet in the solar system

d) Pluto is larger than our moon

8) Why was Pluto reclassified as a dwarf planet in 2006?

a) Due to having a short orbital period

b) Presence of a large red spot

c) Discovery of other similar objects

d) Changes in its orbit

9) What is NOT true about Saturn?

a) Saturn has a ring system

b) The ring system is mostly composed of ice, rocks and dust

c) Saturn's orbital period is 10,759 days

d) The planet's pale yellow color is due to carbon dioxide in its upper atmosphere

True or False questions

10) The sun will transform into a red giant and engulf all planets in the solar system about 5 billion years from now. (FALSE)

11) Venus shows geological features suggesting it once had large bodies of water, despite having no liquid water on its surface today. (FALSE)