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Investigating visual factors affecting visitors' experience with smartphone Augmented Reality in Institutional Informal Learning Places

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Abstract

Augmented Reality (AR) is an emerging technology that blends virtual elements with the real world, creating immersive experiences that have been explored in various fields, including architecture, entertainment, education, the military, transportation, aerospace, logistics, and medicine. Informal Institutional Learning Places (IILPs) such as museums and science centers are also embracing this technology. Among the available AR devices, smartphones stand out as the most accessible and widely used. Despite AR's numerous advantages, it poses several challenges. This thesis addresses one such significant concern: the impact of visual factors, particularly display luminance and ambient luminance, on visitors' experiences with smartphone AR applications in IILPs. Using the Stimulus-Organism-Response (S-O-R) framework, this study investigates how the interaction between device display luminance and ambient luminance, referred to as the luminance ratio, affects perceived visual discomfort and legibility. These visual factors are then analyzed for their influence on visitors' affective states, task performance, intention to revisit, hedonic motivation, and perceived learning outcomes. An experimental field study was conducted in an insectarium, where participants interacted with various AR stimuli under different ambient and display luminance settings and provided psychometric feedback through surveys. The findings underscore the critical importance of optimal luminance conditions, which significantly impact perceived legibility and, consequently, affect visitors' emotional responses and hedonic motivation. These factors are crucial for user experience and engagement in IILPs. This study offers valuable theoretical, methodological and practical insights into the effective design and implementation of AR in educational and informal learning environments.

Keywords : AR, Informal Institutional Learning Places (IILPs), Luminance, Visual Discomfort, Legibility, Affective state, Hedonic Motivation, User Experience, S-O-R Framework

Research methods : Field study, Psychometric Measurements, Experiments, Questionnaires, Self-reported measures

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List of abbreviations

AR: Augmented Reality

CFF: Critical flicker frequency

HCI: Human-Computer Interaction

IILP: Institutional Informal Learning Places

OST: Optical See-through

QoE: Quality of Experience

SOR: Stimuli, Organism, Response

UTAUT: Unified Theory of Acceptance and Use of Technology

UX: User Experience

VR: Virtual Reality

VST: Video See-through

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I sincerely thank everyone who has contributed to this achievement, even in the slightest way. This thesis stands as a reminder that even the most ambitious goals can be realized with hard work, dedication, and the support of a remarkable community.

Preface

This thesis represents the culmination of the student's work as part of the Master's in User Experience program at HEC Montreal. The content has undergone rigorous evaluation and has received approval from the administrative management of the M.Sc. program at HEC Montreal. This evaluation process ensures that the thesis meets the high standards expected by the institution.

In line with the requirements outlined in the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans, every phase of the research included in this thesis underwent an extensive ethical review process before data collection commenced. This process was crucial in ensuring that the research adhered to the highest ethical standards. The Research Ethics Board at HEC Montreal thoroughly reviewed the proposed research methodology and granted approval under certificate number 2023-5269 (Appendix A).

Ethical considerations were paramount throughout the research process. The approval by the Research Ethics Board signifies that the research plan was scrutinized and found to be in full compliance with ethical guidelines. This includes ensuring that all interactions with human participants were conducted with the utmost respect and consideration for their rights and well-being. Informed written consent was obtained from all participants, guaranteeing that they awere fully aware of the nature of the research and their role within it. This step was vital in upholding the ethical integrity of the study, ensuring that participants' autonomy and confidentiality were maintained throughout the research.

Chapter 1
Introduction

1.1. Background

Rapid digitization across industries has necessitated technological adaptation to address emerging challenges and leverage new opportunities (Bresciani et al., 2018; Bunn et al., 2002). Among these innovations, Augmented Reality (AR) stands out as a significant advancement, blending virtual elements with the real world to create immersive experiences (Chang et al., 2015). Unlike Virtual Reality (VR), which fully immerses users in a virtual environment, AR superimposes digital information onto the physical world, facilitating a blended experience (Serravalle et al., 2019).

Though AR may seem like a product of science fiction, its conceptual roots extend back to early 20th-century ideas about electronic displays overlaying real-life data (Tomiuc, 2014). Significant milestones in AR's development include cinema-style implementations in the 1950s, advancements by pioneers like Ivan Sutherland and Myron Krueger in the 1960s, and the first 3D immersive simulator by Morton Heilig (Cipresso et al., 2018). The 1980s and 1990s witnessed the commercialization of AR with applications such as flight simulators and maintenance assistance tools (Carmigniani et al., 2011). Azuma's (1997) seminal definition of AR provided a foundational framework, emphasizing its combination of real and virtual elements, interactivity in real-time, and 3D registration.

Modern AR systems primarily utilize two display technologies: Video See-Through (VST) and Optical See-Through (OST) displays, each with distinct operational dynamics and latency issues (Cipresso et al., 2018). The proliferation of smartphones has revolutionized AR, transforming these devices into powerful VST AR tools accessible to a broad audience (Tomiuc, 2014). This accessibility has propelled AR's integration into various sectors, including education, healthcare, entertainment, and logistics (Chicchi Giglioli et al., 2015).

Informal Institutional Learning Places (IILPs) play a pivotal role in lifelong learning, offering educational experiences outside traditional settings. These environments, from museums to zoos, support cognitive engagement through interactive and self-directed learning opportunities (Deed & Alterator 2017). The shift towards visitor-centric approaches and the incorporation of emerging technologies like AR has enhanced the educational potential of IILPs, fostering engagement and curiosity (Tomiuc,2014).

The widespread adoption of smartphones has significantly influenced the integration of AR into IILPs. As of 2024, there are approximately 4.88 billion smartphone users worldwide (Backlinko, 2024; Oberlo, 2024), facilitating the development of smartphone AR applications that extend beyond traditional museum walls. These applications enhance visitor engagement by offering immersive experiences that blend natural and augmented elements.

For instance, the de Young Museum collaborated with Snap Inc. to create an AR experience allowing visitors to virtually try on historical fashions from designers such as Yves Saint Laurent and Valentino (Charr, 2024). Similarly, the Muséum National d'Histoire Naturelle in Paris developed "REVIVRE," an app enabling visitors to view digital recreations of extinct animals at their actual size (Charr, 2024). The Smithsonian Institute's "Skin & Bones" app (Figure 1) overlays digital skins on animal skeletons, illustrating how these creatures looked and moved (Charr, 2024). Additionally, the Art Gallery of Ontario's "ReBlink" app reimagines classic artworks with contemporary elements using AR (AGO, 2017).

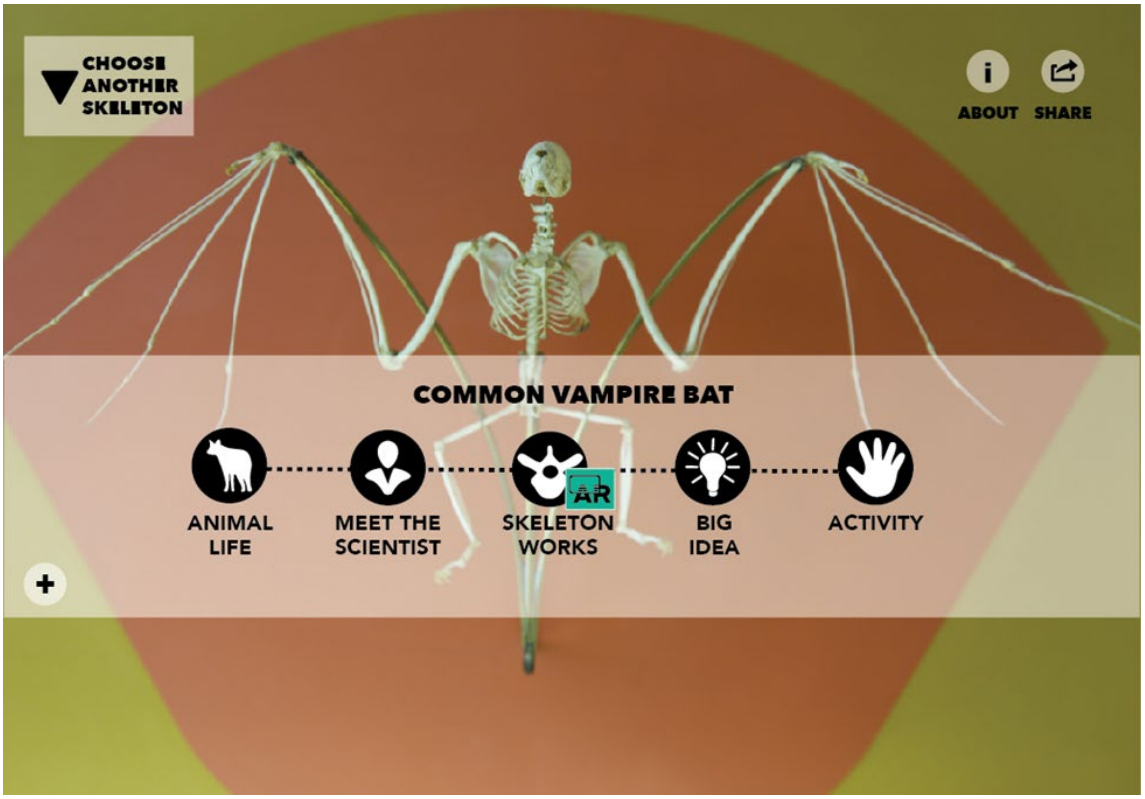

Figure 1: The Skin and Bones app

These modern AR applications leverage the ubiquitous nature of smartphones to enhance visitor engagement and educational value in museums. By offering interactive and immersive experiences, they aim to bridge the gap between physical exhibits and digital content, providing a richer, more engaging learning environment.

The educational benefits of AR in IILPs are multifaceted. AR enhances cognitive engagement by providing visualizations that bring abstract concepts to life, support active participation, and offer personalized learning experiences (Billinghurst & Duenser, 2012; Yoon et al., 2013). AR's interactive nature also fosters motivation and curiosity, transforming learning into an adventure and accommodating diverse learning styles (Chen et al, 2024). Studies have demonstrated that AR applications in heritage museums and science centers improve visitor satisfaction, knowledge retention, and engagement with complex scientific concepts (Hidayat & Wardat, 2024).

1.2. Problem Statement

Despite the potential benefits, AR in IILPs faces several challenges. One fundamental aspect to consider for AR is the Quality of Experience (QoE) it provides to visitors. In the literature, QoE for 3D content—the primary form used in AR—is typically assessed based on perceived visual quality, perceived depth quality, and considerations of visual fatigue and comfort (Urvoy et al., 2013). While technological advancements have significantly improved perceived visual and depth quality, visual discomfort or fatigue from prolonged interaction with AR content remains a concern (Zhdanov et al., 2019). Visual fatigue, or asthenopia, signifies the physiological and psychological demands imposed by the perception of 3D content in AR (Urvoy et al., 2013) and is characterized by symptoms such as eye discomfort, headaches, blurred vision, and difficulty focusing (Solimini et al., 2012).

This problem is significant because it can hinder the adoption and effectiveness of AR technologies in educational settings. Users who experience significant discomfort are less likely to engage with AR applications, reducing the technology's educational benefits. Understanding the impact of visual factors on user experience is crucial for designing AR systems that are both effective and comfortable to use (Sheedy et al., 2003; Wilkins et al., 2021).

Factors contributing to visual discomfort include the vergence-accommodation conflict, where the eyes' focusing and convergence mechanisms are mismatched, leading to strain (Zhdanov et al., 2019). Although this factor is frequently studied, it is less relevant for smartphone AR than head-worn AR, which acts as a stereoscopic display. More relevant for smartphone AR are the lighting conditions where the AR contents are presented in IILPs, particularly the screen luminance of the AR device and the ambient luminance of the location where the AR application is used.

1.3. Research Objectives

Considering the above factors and their relevance, the research conducted in this study aimed to investigate two primary questions:

RQ 1: To what extent do ambient and display luminance affect the visual discomfort/fatigue levels in individuals interacting with smartphone AR in IILPs?

RQ 2: What other factors consequently impact the visitors' interaction with smartphone AR and their overall experience in IILPs?

A review of the relevant literature shows that the effectiveness of AR applications heavily depends on the display and ambient lighting conditions, which can induce visual discomfort and affect the legibility of the presented content. Inadequate lighting can obscure text and graphical overlays, making them difficult to read and interpret (Cipresso et al., 2018). This can hinder the user's ability to access important information and detract from the educational value of the AR experience (Radu et al., 2014). Conversely, optimal luminance settings enhance readability and reduce visual strain (Dobres, 2015).

The affective state of users, referring to their emotions and mood (Russell, 1980), can also be influenced by lighting conditions during AR experiences. Pleasant and well-lit environments can enhance user satisfaction and enjoyment, while poor lighting can contribute to lower legibility and higher visual discomfort, leading to frustration and negative emotions (Benedetto et al., 2014). This emotional response can impact the overall perception of the AR application and the institution hosting it.

Task performance, including the efficiency and accuracy with which users can complete tasks, is closely tied to lighting conditions. Optimal lighting can enhance legibility, thereby improving task performance. Conversely, poor lighting can lead to errors, slower task completion times, and reduced overall effectiveness (Zhou et al., 2021).

Perceived learning outcomes may also be impacted. Adequate lighting enhances the visibility and clarity of educational content, facilitating better understanding and retention of information and significantly improving learning outcomes (Radu, 2014). On the other hand, poor lighting can obscure critical details and hinder the learning process, reducing the perceived educational value of the AR experience (Radu et al., 2014).

Hedonic motivation, or the pleasure of using AR applications, is another critical consideration. Well-designed lighting can create a more enjoyable and engaging experience, increasing the users' affective state and encouraging them to explore and interact with the AR content. In contrast, poor lighting, leading to a lower affective state, can diminish the fun and immersive aspects of AR, reducing user motivation to engage (Yoon et al., 2013).

Finally, the intention to revisit IILPs may be significantly influenced by the quality of AR experiences, which are affected by lighting conditions. Positive experiences facilitated by adequate lighting can lead to higher satisfaction and a greater likelihood of visitors returning to the institution. Conversely, negative experiences due to poor lighting can deter repeat visits, impacting the institution's ability to attract and retain visitors (Urvoy et al., 2013).

The Stimulus-Organism-Response (SOR) framework, developed by Mehrabian and Russell (1974), explains how environmental stimuli (Stimulus) influence an individual's internal state (Organism) and subsequent behavior (Response). In this context, the SOR framework posits that external factors like display and ambient luminance (Stimuli) affect an individual's internal state, including emotional and cognitive responses such as visual discomfort and content legibility (Organism). These internal states, in turn, influence user behaviors and outcomes (Response), such as their affective (emotional) state, learning performance, perceived learning outcome, hedonic motivation, and the intention to revisit IILPs. This study employs the SOR framework to explore how the interaction between device display luminance and ambient lighting conditions impacts users' visual and cognitive experiences, ultimately affecting their overall engagement and educational outcomes.

1.4. Expected Contributions

The study's findings are expected to provide valuable insights into the factors that influence the effectiveness and user experience of AR in IILPs, offering significant theoretical, practical, and methodological contributions. The findings are anticipated to advance our understanding of the role of visual factors in AR user experience, particularly within informal educational settings. Practically, the findings can inform the design of AR applications that minimize visual discomfort, thereby enhancing user engagement and learning outcomes. The research aims to provide insights that will contribute to the development of more user-friendly AR systems, ultimately enhancing the educational experience in IILPs. Methodologically, this study emphasizes the importance of psychometric measures to capture the nuanced aspects of user experience, which objective metrics may overlook.

Additionally, using smartphone AR in real-world scenarios enhances the ecological validity and generalizability of the findings. The detailed operationalization of luminance ratios and systematic assessment framework will serve as a valuable reference for future research in this field. By addressing the identified research gap, this study also aims to provide actionable recommendations for developers and educators on optimizing AR experiences in IILPs and directions for future research on the topic. The findings of the study may also be generalized and serve as a starting point for other sectors utilizing smartphone AR for various purposes.

1.5. Overview of the structure of the thesis

The thesis is structured as follows:

Chapter 1: Introduction - Provides the context of the study, problem statement, research objectives, and an overview of the thesis structure.

Chapter 2: Literature Review - Reviews existing literature on AR, visual discomfort, and their applications in IILPs, identifying key gaps that this study aims to address.

Chapter 3: Theoretical Framework and Hypothesis Development - Describes the theoretical background, develops the hypotheses, and discusses their rationale.

Chapter 4: Experimental Design and Methods - Details the methods, materials, measures used, and the experimental setup, procedures, and data analysis.

Chapter 5: Results - Presents the study's findings, including statistical analyses and their implications.

Chapter 6: Discussion - Interprets the results within the context of existing literature, discusses contributions, limitations, and future research directions.

Chapter 7: Conclusion - Summarizes key findings and their implications for AR in educational settings and provides final thoughts on the study's contributions and potential impact.

1.6. Contribution and Individual Responsibility

This master's thesis was conducted within the Tech3Lab, a collaborative research environment where multiple contributors are involved at various stages. To clearly outline my personal intellectual contributions, Table 1 below provides a detailed breakdown of my involvement in each aspect of the thesis.

The Tech3Lab operates under the standard that a student should achieve a minimum overall contribution level of 50%. For dimensions where my personal contribution exceeds 50%, it indicates that I took on a leadership role and demonstrated ownership of those specific phases of the thesis.

Table 1: Student Contributions

Steps	**Contribution**
Research Question	Identifying gaps in current literature and defining the research problem and its implications – 60% Identifying the research questions – 60%
Literature Review	Conducting relevant research, reading scientific articles related to the topic – 80%

Conception and Experimental design	Designing and development of the experimental protocol – 60% Developing the operational stimuli – 100% Applying to the CER – 50%
Recruitment of participants	Recruiting the participants for the studies – 30%
Pre-tests and data collection	Pre-testing the experimental design and collecting data – 70%
Data Analysis	Extracting raw data and formatting – 80% Analyzing the data using appropriate statistical methods – 50%
Writing the thesis	Writing the chapters of the thesis – 75%

Chapter 2
Literature Review

2.1. Introduction

This literature review examines the integration of Augmented Reality (AR) in Informal Institutional Learning Places (IILPs), such as museums, zoos, and science centers. AR has the potential to revolutionize visitors' experiences by enhancing engagement, comprehension, and interactivity. However, the effective implementation of AR in these settings faces several challenges and opportunities that this review aims to address. By synthesizing current research findings, this review provides a comprehensive understanding of the benefits, challenges, and impacts of AR on user experiences in IILPs while highlighting areas of concern and identifying where further research is needed.

2.1.1. Scope of the review

The scope of this review includes a broad range of topics related to AR in IILPs. It encompasses the historical development of AR technology, its current applications in various sectors, and its specific use in informal educational contexts. The review will also address technical aspects of AR implementation, such as hardware and software considerations, as well as environmental factors like lighting conditions that can affect AR experiences. Next, it will discuss issues related to visual discomfort and legibility, which are directly affected by the lighting conditions, and how they, in turn, affect other aspects of the visitors' experience in IILPs, such as their affective state, learning task performance and Intention to Revisit.

2.1.2. Methodology

This narrative-style literature review (Green, Johnson, & Adams, 2006; Paré, Trudel, Mirou & Kitsiou, 2015) focuses on understanding the current literature by bringing together interdisciplinary literature. The review takes knowledge from Computer science, Media and Information Technology to understand the development and working of AR and related technological advancements, Health, medicine and ophthalmology to understand the working and anatomical features of the human eye, from psychology and sociology to understand the impact of AR, from tourism, architecture and engineering to understand the inclusion and application of AR in IILPs, from Optics to understand the characteristics of lighting conditions, and from psychology, HCI and UX to identify the potential ways in which the use of AR affects the user experience of visitors in IILPs.

The search for the literature started in February 2023 and ended in April 2024. Regarding the databases, preliminary searches were done on Google Scholar to identify relevant keywords and synonyms, narrow down specific research fields, and identify journals and publishers. Once identified, the search was moved to other relevant databases, including Bibliotheque HEC Montreal, ScienceDirect, ACM Digital Library, Web of Science, IEEE Xplore, SpringerLink, and Google Scholar. Due to the specificity of the research objective, backward and forward searches were a valuable method to identify important literature in the field. From there, the research question was formulated, and the evaluation criteria were determined. While no restrictions were made based on publication date, the articles were identified and evaluated based on their title, number of citations, and relevance, as determined from their abstract.

2.2. History and Characteristics of AR

Digitization has left no industry untouched, and companies have had to adapt to keep up with the pace and come up with ways to address the main challenges in implementing the use of these technologies (Klein & Knight, 2005; Klein & Sorra, 1996). Augmented Reality (AR) is one of these emerging technologies that has been gaining much traction recently and has been adapted to various sectors (Chang et al., 2015).

Considered by some to be the evolution of virtual reality (VR), AR implies a mix of the real world and virtual experience (Tomiuc, 2014). AR is primarily a visualization technology that overlays digital information and virtual objects onto the real world, unlike VR, which completely replaces it (Serravalle et al., 2019). While usually considered to be primarily visual, this technology can include a variety of multi-modal interactions by superimposing visual, auditory, tactile, or even olfactory materials in real-time on physical objects (Bressler & Bodzin, 2013; Feiner et al., 1997), presented via AR-enabling devices like smartphones and Head-Mount Displays (HMDs).

Although it sounds straight out of a sci-fi movie, its roots can be traced back to the early 1900s, when it was mentioned as an idea of electronic display/spectacles that overlay data onto real life. Since then, it has been the goal of numerous researchers and inventors to try and create a workable implementation of the idea by using the newest technology available to them at the time. (Tomiuc, 2014)

Consequently, AR evolved significantly over the years following a long development process: through cinema-style implementations in the '50s, followed by significant developments through inventors like Ivan Sutherland, Myron Krueger and Howard Rheingold in the '60s (Tomiuc, 2014). Also during this decade, the first 3D immersive simulator was developed by Morton Heilig (Cipresso et al., 2018, p. 3), and the first HMD that was able to update virtual images by tracking the user's head position and orientation was developed by Philco (Sutherland, 1965). The '80s saw the beginning of commercial AR devices, with the US Air Force creating the first flight simulator (Visually Coupled Airborne System Simulator (VCASS). During the early '90s, multiple AR systems started emerging from various sources, beginning with the first prototype for an AR system by Boeing to show employees how to set up a wiring tool (Carmigniani et al., 2011). A few more applications of the time include

- An AR fixture for maintenance assistance by Rosenberg and Feiner which showed that the operator performance was enhanced by adding virtual information on the fixture to repair (Rosenberg, 1993);

- An AR GPS-based system by Loomis and colleagues to help blind people in assisted navigation through adding spatial audio information (Loomis et al., 1998); and

- An AR theatre developed by Julie Martin in which actors interacted with virtual objects in real-time (Cathy, 2011).

Even though all these developments were in progress, AR got its first formal definition only in 1997, when Azuma (1997) described it as a variation of Virtual Environments (VE) or Virtual Reality as it is more commonly called. VE technologies completely immerse a user inside a generated synthetic environment. While immersed, the user cannot see the real world around him. In contrast, AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality rather than completely replacing it. Ideally, it would appear to the user that the virtual and real objects coexisted in the same space. Augmented reality is a live direct or indirect view of a physical, real-world environment whose elements are augmented (or supplemented) by computer-generated sensory input such as sound, video, graphics or GPS data. As a result, the technology functions by enhancing one's current perception of reality.'

It was also in 1997 that the first Mobile AR System (MARS) was developed that could add virtual information about tourist buildings (Feiner et al., 1997). Several AR-based mobile applications have been developed since then. (Arth et al., 2015)

Until this time, many researchers described AR in a way that, by definition, required the use of HMDs. Hence, to avoid being limited to specific technologies, Azuma (1997) described three fundamental characteristics of AR: 1) It combines the real and virtual, 2) It is interactive in real-time, and 3) It is registered in 3-D. This allowed for multiple technologies to be considered AR as long as they fulfilled all three criteria.

On a similar note, Carmigniani et al. (2011) stated that any AR system must have three essential components: 1) a geospatial datum for the virtual object, like a visual marker, 2) a surface to project virtual elements to the user, and 3) an adequate processing power for graphics, animation, and merging of images, like a pc and a monitor (Carmigniani et al., 2011). To function, an AR system must also include a camera that tracks the user's movement for merging the virtual objects and a visual display through which the user can see the virtual objects overlaying the physical world. (Cipresso et al., 2018) The QR code is the most widely utilized form of visual marker for AR, primarily due to its automatic compatibility with the latest smartphone models (Lalicic & Weismayer, 2016).

To date, there are two display technologies used in AR.: a video see-through (VST) display and an optical see-through (OST) display (Botella et al., 2005; Juan et al., 2005). A VST Display presents virtual objects to the user by capturing the real objects/scenes with a camera and overlaying virtual objects, projecting them on a video or a live feed via a screen. On the other hand, the OST display merges the virtual object on a transparent surface, like glasses, through which the user sees the added elements. The main difference between the two systems is the latency: an OST system could require more time to display the virtual objects than a VST system, generating a time lag between the user's action and performance and the detection by the system. (Cipresso et al., 2018, p. 4)

With the introduction of the Smartphone, AR has witnessed a massive surge in interest. These devices pack very high computational power coupled with powerful cameras and vivid, responsive displays in a relatively small form factor, making them powerful video see-through (VST) AR devices that people can fit in their pockets. Add to it the wide-scale penetration of Smartphones, and it has proved to be the perfect new base for creating augmented realities that are more realistic, generate more interest in various fields, and can be accessed by a much more significant percentage of the population. (Tomiuc, 2014., p. 11).

Hence, AR has since been investigated and used in several research areas such as architecture (Russo, 2021), maintenance (Schwald & De Laval, 2003; Webel et al., 2013), entertainment (Ozbek et al., 2004), education (Nincarean et al., 2013; Bacca et al., 2014; Akçayır & Akçayır, 2017), military (Livingston et al., 2011), transportation and aerospace (Regenbrecht et al., 2005), logistics (Schwerdtferger et al., 2009) and medicine (De Buck et al., 2005) to name a few. (Chicchi Giglioli et al., 2015)

In architecture, AR is being utilized for real-time interactive visualization of construction sites, allowing for enhanced planning and error detection (Russo, 2021). Maintenance processes have seen significant improvements with AR applications, such as the development of smart maintenance systems that integrate wearable technology to reduce unscheduled downtime (Aransyah, Rosa, & Colombo, 2020), and the implementation of AR for machine maintenance to simplify operations and lower costs (Sabarinathan & Kanagasabapathy, 2018). Additionally, user-centred tools have been developed to support AR maintenance system design (Del Amo, Galeotti, Palmarini, & Dini, 2018).

The entertainment industry has also benefited from AR through innovative applications that enhance user experience and engagement (Ozbek et al, 2004). In education, AR has been recognized for its potential to provide immersive and interactive learning experiences, addressing various challenges and enhancing educational outcomes (Akçayır & Akçayır, 2017; Nincarean, Alia, Halim, & Rahman, 2013; Bacca, Baldiris, Fabregat, Graf, & Kinshuk, 2014). Military applications of AR include training simulations and real-time data overlays to improve situational awareness and decision-making (Livingston et al., 2011). The transportation and aerospace industries utilize AR for vehicle assembly and maintenance tasks, contributing to increased efficiency and safety (Regenbrecht, Baratoff, & Wilke, 2005).

In logistics, AR aids in optimizing warehouse operations by simulating potential benefits and improving the accuracy and speed of picking tasks (Schwerdtferger, Klinker, & Reif, 2009). The medical field has adopted AR for skill transfer in minimally invasive surgery, enhancing training and operational precision (De Buck et al., 2005). These examples underscore the broad applicability and transformative potential of AR across diverse sectors.

Even if the AR experiences are different from VRs, the quality of the AR experience could be considered similar. Just like in VR, the feeling of presence, level of realism, and degree of reality represent the main features that can be regarded as indicators of the quality of AR experiences. The higher the experience is perceived as realistic, and the more congruence between the user's expectation and the interaction inside the AR environments, the higher the perception of "being there" physically and at cognitive and emotional levels. The feeling of presence, both in AR and VR environments, is important in making the users behave naturally as they would in the real world (Botella et al., 2005; Juan et al., 2005; Bretón-López et al., 2010; Wrzesien et al., 2013)

A well-implemented, good-quality AR can significantly improve users' experience and enable new interaction methods. It has been shown to aid learners' comprehension and perception of dynamic models in education (Rosenbaum et al., 2008) while increasing learners' motivation and interests and supporting a diversity of teacher-student interaction scenarios (Shelton et al., 2002; Dunleavy et al., 2014; Kotranza et al., 2009), Similarly, in healthcare, it has been used to train healthcare students in subjects like anatomical education. By providing access to features like 3D anatomical models, it has been proven that AR enhances spatial understanding of the interrelationships between different body structures (Huang et al., 2012).

2.3. AR in IILPs

Informal Institutional Learning Places (IILPs) are environments where learning occurs outside of formal educational structures such as schools and universities. These places include museums, zoos, and insectariums, which offer self-directed and experiential learning opportunities that complement formal education. IILPs are crucial because they support lifelong learning and cater to a diverse range of learners, promoting access to knowledge and cultural experiences in a relaxed and interactive setting. They play a significant role in the community by fostering an appreciation for science, history, and the arts and encouraging curiosity and critical thinking skills.

The significance of IILPs lies in their ability to create new narratives of participation and engagement in learning. They are designed based on principles that prioritize a student-centric and meaningful experience, which is foundational to maximizing the learning potential of individuals (Deed & Alterator, 2017). Moreover, IILPs offer a unique ecological model that accommodates intersecting concepts relevant to informal learning, such as pedagogical coherence and lived experiences (Deed & Alterator, 2017). These spaces allow for cognitive engagement and spark conceptual learning without the confines of a formal curriculum, aiding in the development of content knowledge (Hussim et al., 2024). Furthermore, informal learning environments enable formal spaces to evolve and respond to new learning needs, fostering connection, invention, and discovery.

IILPs have gradually shifted focus from objects and collections to individuals and communities, emphasizing dialogues, interpretations, and experiences due to a fundamental change in cultural experiences arising from rapid expansions in media technology. Consequently, they have adopted various emerging media technologies, including augmented reality (AR) (Tomiuc, 2014).

The driving force behind this massive adoption of AR is the widespread reach of smartphones. In 2024, the number of smartphone users worldwide was estimated to be a whooping 4.88 billion (Backlinko, 2024; Oberlo, 2024). Meanwhile, the advent of mobile apps has provided IILPs with innovative communication channels that extend into the personal spaces of visitors, transcending the confines of museum walls. In the 1990s, the emergence of digital mobile guides, exemplified by initiatives like the audio tours at the Minneapolis Institute of Art in 1994 and the HIPS/HIPPIE project in Europe in 1997, marked significant developments. These guides facilitated a more interactive museum experience, enabling visitors to independently explore galleries while receiving pertinent information and engaging with the specific context and surroundings at their own pace (Russou 2018).

The improved accessibility of mobile applications for IILPs, attributed to both additional multimedia content (Tussyadiah et al., 2018) and the growing number of smartphone owners, allows for greater personalization and enhanced visit experiences for tourists, tailoring museum interactions to the specific needs of each individual (Chang et al., 2015; Guttentag et al., 2018). Visual content and videos have started replacing traditional explanatory panels, allowing visitors to experiment with smartphones, tablets, or other mobile devices of their choice during their visit.

Some of the newest smartphone applications used by IILPs are based on AR to provide immersive experiences for their visitors. Examples include The British Museum App “A Gift for Athena” (Figure 2) (Museums and the Web, 2015) and the Tate Modern “Pocket Art Gallery”. Among the first museums to implement this technology were the Stedelijk Museum in Amsterdam, which used AR to install artworks in a local park (ARTours), and the San Francisco Exploratorium, which turned an evening event into a surreal AR playground (Get Surreal) (Tomiuc, 2014). More recently, The Smithsonian Institution's “Apollo's Moon Shot AR” app (Figure 3) lets users view artifacts such as the Apollo 11 Command Module in 3D and place them within their own environments (Smithsonian Institution, 2023). Similarly, the Cleveland Museum of Art's “ArtLens” app enhances gallery tours by allowing visitors to scan artworks to access multimedia content such as artist interviews and process videos (Cleveland Museum of Art, 2023).

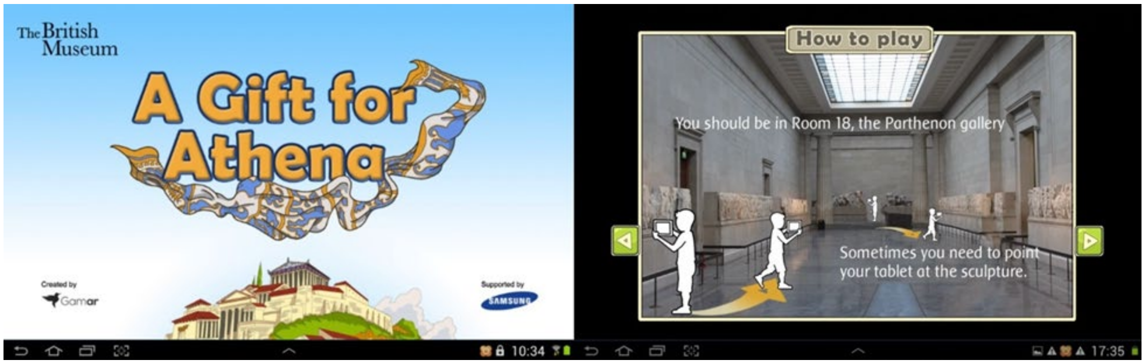

Figure 2: The British Museum app "A gift for Athena"

Figure 3: The Apollo's Moon Shot AR app

With such implementations, IILPs have aimed to enhance user interaction by seamlessly blending actual reality with augmented elements, offering natural feedback through simulated cues (Milgram et al., 1994; Tussyadiah et al., 2018). These supplementary images enrich the consumer experience, delivering compelling information that is more memorable and enhances attention (Lambie, 2015). Smartphone AR is reshaping the IILPs, offering an interactive and immersive educational experience that traditional methods cannot match. By superimposing digital information onto the physical world, AR engages learners in a multisensory journey, enhancing their cognitive engagement through visualizations that bring abstract concepts to life. This technology captures attention and fosters a deeper level of cognitive involvement, leading to improved understanding and retention of information. For instance, AR can convert complex scientific processes into 3D simulations, allowing learners to manipulate variables and observe real-time outcomes, thereby supporting active participation and inquiry-based learning (Billinghurst & Duenser, 2012).

The interactivity of AR applications increases visitor engagement and motivation, often integrating game-like elements that transform learning into an adventure and encourage exploration. This is particularly effective in informal learning environments that aim to spark curiosity and self-directed learning. Moreover, AR provides a personalized learning experience, offering multilingual support and catering to different learning styles, which is crucial in today's diverse society. It also offers scaffolding of learning experiences, providing hints and explanations that guide learners through exhibits or concepts, making even the most complex topics accessible and engaging (Yoon, Elinich, Wang, Steinmeier, & Tucker, 2013).

Smartphone AR is especially beneficial for special needs education, offering customizable experiences that can be adapted to individual learning requirements. Visual and auditory information can be adjusted to suit the needs of learners with sensory impairments, ensuring that learning is inclusive and accessible to all. Additionally, AR promotes lifelong learning by engaging users in a way that is both educational and enjoyable, encouraging them to continue exploring and learning beyond the confines of formal education settings (Charr et al., 2024).

Integrating AR with social media further extends the reach of informal learning environments, creating opportunities for broader community engagement and discussion. Users can share their AR experiences on social media platforms, promoting a learning culture and community involvement.

A study on the British Museum by Mannion (2014) identified four interaction categories for the potential use of AR: outdoor guides and explorers, interpretive mediation, new media art and sculpture, and virtual exhibitions. Utilizing animated 3D models to depict the appearance of extinct animals or plants is another excellent application of AR. They can also enhance the user's experience when travelling in IILPs by providing real-time information about the location and its features, including comments made by previous site visitors, catering to a social experience (Anamaria et al., 2014). According to Tomiuc (2014), constructing such applications has become progressively more accessible and cost-effective.

AR technology has significantly impacted how visitors engage with exhibits in IILPs, such as museums, science centers, and zoos. The immersive nature of AR allows for more profound interaction with the content, providing a multisensory learning experience that can enhance cognitive and affective outcomes. According to Charr (2024), the integration of AR in heritage museums has positively influenced visitor satisfaction and intention to revisit, with technical novelty, individual technology trust, and situational aesthetics being key factors. He notes that AR adds a dynamic layer to museum displays, making them more engaging and accessible to a broader audience.

Furthermore, the application of AR in science centers has been found to facilitate the understanding of complex scientific concepts through visualization and interaction. A systematic review by Hidayat and Wardat (2024) revealed that AR is particularly beneficial in Science, Technology, Engineering, and Mathematics (STEM) education, enhancing spatial ability, practical skills, and conceptual understanding (Hidayat & Wardat, 2024).

The potential of AR to transform educational approaches in IILPs is further highlighted by its ability to bring historical figures to life, turn artifacts into storytellers, and convert museum visits into interactive quests, thereby revolutionizing the educational landscape (Xsite, 2023). Moreover, the learner control design in AR-based exhibits has been shown to increase the quality of learner control, providing visitors with contextual feedback and enhancing their overall experience (PLOS, 2022). As AR technology continues to evolve, it promises to yield even more innovative applications that will further transform the learning landscape. The scientific literature provides extensive research and analysis on the application and impact of smartphone AR in informal educational settings, underscoring its potential to revolutionize the way we learn and interact with the world around us (Squire & Jan, 2007, Zhou et al., 2022).

While head-mounted displays (HMDs) can be more immersive than smartphones, they are less suited for AR in IILPs due to concerns about simulator sickness, including headache, disorientation, and nausea (Portales et al., 2009). Although immersion is sacrificed to some extent, the widespread availability of smartphones, the lack of a need for specialized devices, and the lower risk of simulator sickness make smartphone AR a more practical choice in this context.

Overall, AR, specifically smartphone AR, is an emerging and trending technology with excellent potential to improve visitors' experiences in IILPs. It can significantly contribute to the invaluable preservation of cultural heritage (Unal et al., 2021). Along with providing additional information through physical interaction and enabling unique new ways of engagement, AR allows visitors to appreciate the interwoven nature of the natural world and simulations (El Sayed et al., 2021).

2.4. Potential concerns with smartphone AR

Although AR offers numerous advantages, implementing smartphone AR is not without challenges. It is essential to consider the potential problems and flaws associated with any technology that might negatively affect the visitors' experience in the IILPs. Issues such as ensuring equitable access to technology, addressing privacy concerns, and providing pedagogically sound content must be addressed to fully realize this technology's potential. (Wu et al., 2013). In IILPs, emotions are strongly correlated with satisfaction, which is based on the consumer's participation and experiences (De Rojas & Camarero, 2008).

Visitors' satisfaction, thus, is influenced by both the technical and tangible aspects of the museum product and by emotional factors, social values and cognitive aspects of the whole visit experience (Martín-Ruiz et al., 2010).

One of the fundamental characteristics to consider for AR is the Quality of Experience it provides to the visitors. In the literature, the Quality of Experience (QoE) for 3D content, the primary form of content used in AR, is typically assessed based on perceived visual quality, perceived depth quality, and considerations of visual fatigue and comfort. (Urvoy et al., 2013). Firstly, visual quality refers to image quality irrespective of the depth effect. Secondly, depth quality is associated with the 3D effect and is evaluated based on various features such as realism, power, and presence (Ijsselsteijn., 2004). Alternatively, naturalness is suggested as a dual feature that captures aspects of both visual and depth qualities (Seuntiens et al., 2005). Finally, visual fatigue and discomfort signify the physiological and psychological demands imposed by the perception of 3D content. (Urvoy et al., 2013, p. 2).

Achieving adequate naturalness in augmented reality (AR) necessitates addressing the registration task of the virtual elements. Precision requirements are demanding, given that AR applications must seamlessly blend virtual and real information in six degrees of freedom (6DOF) and in real-time. Even minor inaccuracies in registration can lead to intolerable distortions in the combined view (Arth & Schmalstieg, 2011). While technological progress has allowed significant improvements in the 3D registration task due to enhanced AR optics, realistic representations of the virtual world, high-resolution LCDs, robust processing power and powerful sensors, these fulfill only the necessary conditions for the natural perception of the virtual world. For sufficient natural perception, it is essential to avoid discomfort in visual perception arising from issues such as the vergence-accommodation conflict or incorrect illumination of virtual objects (Zhdanov et al., 2019, p. 1). It has been found that observers tend to favour a 2D version of the content over a 3D version when fatigue or discomfort arises while using the latter. Consequently, ensuring a comfortable experience becomes essential for observers to recognize the depth effect as a meaningful visual enhancement (Urvoy et al., 2013, p. 2).

2.5. Visual discomfort & fatigue: Definitions, characteristics & measurements

Depending on the specific field of investigation, the adverse effects in vision have been referred to as visual fatigue (Lambooji et al., 2009), asthenopia (Sheedy et al., 2003), eyestrain (Kuze & Ukai, 2008) or visually induced motion sickness (VIMS) (Kennedy et al., 2010). The World Health Organization classifies visual fatigue as a subjective visual disturbance (ICD-10, H53.1), manifested by a high degree of visual discomfort typically occurring after prolonged visual activity and characterized by fatigue, pain around the eyes, blurred vision or headache. However, a further distinction has been made between its objective and subjective conditions by Lambooji et al. (2009). He defined visual fatigue as the decrease in the performance of the human vision system in the form of physiological strain or stress resulting from excessive exertion of the visual system and visual discomfort as its subjective counterpart.

As extensively reviewed (Ukai & Howarth, 2008), visual fatigue is characterized by various symptoms, such as eye discomfort, tiredness, pain around the eyes, dry or watery eyes, headaches, visual distortions such as blurred and double visions, as well as difficulties in focusing (Solimini et al., 2012). A multitude of both objective and subjective indicators contribute to identifying visual fatigue (Cail & Salsi, 1992), including observable signs like dried mucus of the eyes, tears around the eyelid, alterations in blinking rate (Jaschinski et al., 1996), and a reduction in the speed of eye movements [Saito, 1992; Chi & Lin, 1998]. Researchers have particularly emphasized the near vision triad (accommodation, vergence, and pupillary response) (Urvoy et al., 2013).

To objectively quantify visual fatigue, physiological measures, such as monitoring changes in accommodation response, pupillary diameter, and eye movement characteristics, may be used (Yano et al., 2002). Critical flicker frequency (CFF), defined as the frequency at which flickering light is perceived as continuous, also holds a prominent role in assessing visual temporal processing, as reported by (Eisen-Enosh et al., 2017). CFF serves as a robust measure of visual performance, reflecting the fundamental temporal function of the visual system. Simonson (Simonson et al., 1941) pioneered using CFF to measure fatigue in the 1940s. In a related context, Murata's study (Murata et al., 1991) further endorsed CFF as a suitable parameter for evaluating chronic visual fatigue (Yu & Akita, 2020).

Moreover, visual fatigue not only manifests in ocular disorders but also induces cerebral and psychological disturbances such as headaches (Ando et al., 2002). Consequently, a growing focus on brain activity measurements, such as EEG, MEG, and fMRI, offers a promising avenue for investigating the fundamental nature of asthenopia (Lambooij et al., 2009).

On the other hand, visual discomfort, being inherently subjective, is typically evaluated through questionnaires in almost all studies [Kennedy et al., 1993; Howarth & Costello, 1997; Ohno & Ukai, 2000; Schiffman et al., 2000; Sheedy et al., 2003; Ogata et al., 2005; Yang et al., 2011; Ranasinghe et al., 2016]. These questionnaires aim to gauge the presence of specific visual discomfort-related symptoms, with most studies requiring observers to rate the level of discomfort on a scale (Urvoy et al., 2013; Chawla et al., 2021).

Kennedy (Kennedy et al., 1993) introduced a questionnaire to assess simulator sickness (SS), which was later adapted by Howarth and Costello for more general purposes due to the shared symptoms with visual fatigue and discomfort (Howarth & Costello, 1997). Subsequent studies proposed additional questionnaires (Ohno & Ukai, 2000), some explicitly targeting ocular disorders and others (Schiffman et al., 2000) employing the Suzumura questionnaire with 37 items and five stages, assessing various visual symptoms (Suzumura, 1981). Recent studies often combine items from the SS questionnaire (Kennedy et al., 1993) with broader Quality of Experience (QoE) questions (Yang et al., 2011). Discomfort, particularly, is often assessed using subjective scales (Yano et al., 2002), such as the Single Stimulus Continuous Quality Evaluation (ITU-R-BT.500-11, 2004) or subjective symptom questionnaires for fatigue, such as the one proposed by Sakai (2002) and the six-item Visual Fatigue Scale (VFS) introduced by Heuer et al. (1989

The relationship between perceived visual discomfort and objectively measurable visual fatigue is well-documented. Studies have shown that subjective reports of discomfort often correlate with objective measures, such as changes in accommodation response, pupillary diameter, and eye movement characteristics (Lambooij et al., 2009).

Subjective assessments of visual discomfort are critical because they capture the nuanced and individualized experiences of discomfort that might not be fully evident through objective measures alone. Symptoms such as dry eyes, headaches, and blurred vision can significantly affect a person's daily functioning and quality of life, even if objective measures do not show severe anomalies. Moreover, the subjective experience of discomfort can often precede detectable objective signs of visual fatigue, making early intervention possible.

Integrating subjective evaluations with objective physiological measures provides a comprehensive understanding of visual fatigue. This dual approach enhances the accuracy of diagnosing visual fatigue and aids in developing targeted interventions to mitigate its effects. Subjective assessments become particularly valuable in situations where objective evaluations are not feasible. Given their strong correlation with visual fatigue, subjective reports of visual discomfort can reliably indicate objectively experienced visual fatigue. Understanding these subjective experiences allows researchers and clinicians to address a broader spectrum of symptoms associated with visual fatigue, ultimately improving visual health and overall well-being and experience.

2.6. Vergence-Accomodation conflict and its limited relevance for smartphone AR

Our ability to perceive a third dimension is rooted in the characteristics of the human visual system. With eyes positioned horizontally, our optical system receives two views of the scene – one from each eye. Although these views largely overlap, there are slight differences due to the distinct perspectives. The visual system processes information from both eyes to create stereoscopic depth (Wheatstone et al., 1838; Howard et al., 2002; Patterson and Martin., 1992). Despite constant eye movement, even during fixation (Raynar, 1998), the binocular visual system adeptly coordinates both the eyes' movements

(Liversedge et al., 2009). Accommodation, vergence, and pupillary dynamics, i.e., the ocular near triad, continuously interact to control this functioning of the eyes. (Lambooji et al.)

When we fixate on a point in space with both eyes, the images of that point fall on the fovea of both eyes, which is the area of the retina with the highest acuity. This allows the object to be perceived as a single entity. The fixation point falls on the horopter (Helmholtz et al., 1909; Schreiber et al., 2008), a curved line or surface containing all points at the same geometrical or perceived distance from the fixation point. Objects located on the horopter are fused into a single percept. However, objects in front of or behind the horopter produce disparate images on the left and right retinas, resulting in horizontal retinal disparities. Points in front of the horopter have a crossed (negative) disparity, and object points behind have an uncrossed (positive) disparity. The retinal disparity's magnitude increases with the object's distance from the horopter. The human visual system uses these disparities to perceive the relative depth of objects in the visual scene. (Tam et al., 2011)

Objects within a small region in front of and behind the fixation plane can still be fused into a single percept, known as Panum's fusional area. Objects outside this area may result in double vision but might still be perceived in depth (Ogle, 1950; Ogle, 1953). The size of Panum's area depends on various factors, such as exposure duration, spatial resolution and temporal frequency of disparity variation (Schor et al., 1984). When the point of fixation changes to a new object at a different distance, the eyes move simultaneously and in opposite directions to bring the new object into the center of each fovea. This process, called vergence, is closely related to accommodation, which refers to the eye adjusting the shape of the pupil to match the optical power needed for the object of interest (gaze point), ensuring a clear image. Accommodation is measured in diopters (δ), which is the reciprocal of the accommodation distance (focus point) (Urvoy et al., 2013, p. 4). Under normal conditions, changes in accommodation and vergence occur together. However, conflicts can arise when viewing stereoscopic targets (Tam et al., 2011), which we will discuss shortly after.

Points located closer or farther than the accommodated point are not imaged adequately on the retina and, thus, become subject to an increasing degree of blur. However, the visual system is tolerant of a small amount of blur, and objects within a small region around the accommodated point are perceived to be in focus. This region is known as the depth of field, which varies inversely with pupil diameter and is measured in meters. There is a corresponding conjugate region on the retinal plane that is the projection of this range. It is called the depth of focus and is measured in diopters (δ). (Tam et al., 2011). Depth-of-field is a crucial element in 3D content, and hence in AR as well. In 3D stereoscopic imaging systems, depth-of-focus refers to the range in front and behind the screen where displayed objects are sharply focused (Urvoy et al., 2013, p. 7).

The focus and vergence points align when viewing a real object with normal binocular vision. The oculomotor system is specifically tuned for this, featuring a reciprocal relationship between accommodation and vergence: accommodation feedback can trigger vergence responses (convergence accommodation - CA-) and vice versa (accommodative convergence -AC-)(Hung, 2001). This interaction, assessed through ratios like CA/C and AC/A, represents the accommodation-vergence balance, also called oculomotor balance and is affected by visual fatigue (Urvoy et al., 2013).

With stereoscopic displays, however, the point where the eyes converge and where they focus no longer stay in sync. The eyes adjust to the screen's distance when viewing, requiring accommodation on that plane. Simultaneously, if an object has crossed disparity (views shifted in opposite directions) or uncrossed disparity (views shifted in the same direction), the eyes must converge at a point either in front of or behind the display. (Urvoy et al., 2013). As the disparity between the display screen and the perceived depth of the displayed object increases, so does the vergence response. This change in vergence triggers an accommodation response, potentially causing the focus to shift away from the screen toward the point of convergence (Hung, 2001). However, if accommodation moves excessively away from the screen, the object depicted on the screen becomes blurred. To prevent this blurring, corrective adjustments in accommodation become necessary. Therefore, during stereoscopic viewing, accommodation faces conflicting demands, the severity of which depends on the associated vergence response (Tam et al., 2011). Hence, in 3D stereoscopic systems, excessive disparities may place objects outside the depth of focus, potentially causing discomfort (Urvoy et al., 2013).

This conflict between accommodation and convergence processes in the eyes, where the eyes try to accommodate the screen plane but converge at a different depth, is called the accommodation-vergence conflict. It arises due to the artificial de-coupling of an otherwise reflexively coupled mechanism and has often been theorized as a significant factor underlying the occurrence of visual discomfort [Emoto et al., 2005; Hoffman et al., 2008; Wann et al., 1995; Okada et al., 2006; Lambooij et al., 2009]. While this effect is most prominent in 3D stereoscopic displays, numerous studies reviewed by Blehm et al. (2005) showed that even in 2D displays, visual fatigue transiently induces accommodation and vergence disorders. (Urvoy et al., 2013)

The interplay between accommodation and vergence also involves corresponding changes in pupil diameter. The pupil constricts during near vergence/accommodation to compensate for a narrow depth of field and increased spherical aberration. Conversely, it dilates during far vergence/accommodation to reduce diffraction and enhance retinal illumination. These pupillary dynamics, regulated by the autonomic nervous system, reflect mental activity and can indicate visual discomfort. As part of the ocular near triad, alterations in pupil diameter may also impact accommodation and vergence (Lambooij et al., 2009).

Coming back to AR in IILPs, while the Accommodation-Vergence conflict has been a frequently studied factor in the past couple of decades [Ukai & Howarth, 2008; Yano et al., 2002; Yano et al., 2004; Emoto et al., 2004; Hoffman et al., 2008; Miyashi & Uchida, 1990; Hiruma & Fukuda., 1993; Wann et al., 1995; Inoue & Ohzu., 1997; Takeda et al., 1999; Mizushina et al., 2009, Tam et al., 2011] contributing to visual discomfort and fatigue in 3D stereoscopic images and AR. However, it is crucial to note that smartphones are the predominant AR devices in contemporary IILPs these days, and they typically do not align with the conventional definition of stereoscopic displays. According to Woods (2012), stereoscopic displays present a 3D image to an observer by sending a slightly different perspective view to each of the observer's two eyes. The visual system of most observers then processes the two perspective images to interpret an image containing a perception of depth by invoking a process called binocular stereopsis, allowing them to see it in 3D.

While smartphones act as Video See-Through (VST) AR devices that display the live camera feed with overlayed virtual elements, the result is still a 2D representation on the single display screen of the device. Since this prevents smartphones from being classified as stereoscopic, Zhadanov et al. (2019) have argued that the issues of discomfort for smartphone AR mainly arise from the ergonomics of representing the virtual data.

While studies reviewed by Blehm et al. (Blehm et al., 2005) indicate that visual fatigue can induce accommodation and vergence disorders even in 2D displays, Yano et al.'s analysis suggests that depth of field can be used to define a comfortable viewing zone. It is generally assumed that, to minimize the accommodation-vergence conflict, the disparities in a stereoscopic image should be small enough so that the perceived depths of objects fall within this "comfort zone." This comfort zone is influenced by the distance from the display screen, which, in turn, depends on the screen size (International Telecommunication Union, 2010).

For instance, under typical television broadcast conditions, researchers assume a depth of field between 0.2D and 0.3D [Yano et al., 2022; Hiruma & Fukuda, 1993; Nojiri et al., 2003]. For a viewer focusing on a TV screen 3 meters away, a 0.2D depth of field yields a focus range from 1.87m to 7.5m; for a 0.3D depth of field, the range is 1.57m to 30m. Distance variation affects this range—for a 0.2D depth of field, decreasing the viewing distance to 1.5m results in a range of 1.15m to 2.14m, while increasing it to 4.5m extends the range to 2.36m to 45m (Tam et al., 2011).

Considering the handheld nature of smartphones and users' flexibility in adjusting the distance between the device and their eyes—unlike fixed-distance 3DTVs or stereoscopic HMDs—it can be assumed that users would usually position the smartphone within their comfort zone instinctively, thus mitigating any accommodation-vergence conflict that could have arose.

The rapidly increasing popularity of smartphone AR, their deviation from traditional stereoscopic setups – the primary focus of studies on visual fatigue in AR and stereoscopic displays, and the flexibility to adjust viewing distance and hence minimizing the vergence and accommodation disorders in smartphone AR calls for considerations of other sources of visual discomfort and fatigue in the context of smartphone-based AR experiences.

2.7. Luminance and illuminance conditions

Luminance refers to the brightness or intensity of light emitted or reflected from a surface, measured in candelas per square meter (cd/m^2) or nits. It quantifies the amount of light emitted or reflected per unit area in a specific direction (Schanda, 2007). For smartphone augmented reality (AR) applications, phone luminance pertains to the screen's brightness, which is adjustable through smartphone settings (Rukzio et al., 2012).

When an AR application is active, the smartphone operates in a see-through mode, capturing the environment with its camera and displaying it on the screen with virtual elements superimposed. The screen's brightness adapts based on the camera's input, varying with the ambient luminance—the light coming from the surface the camera is pointing at, either by reflection or direct light source. Thus, the phone's luminance is influenced by both the screen settings and the ambient luminance.

Illuminance, on the other hand, is the amount of light falling on a surface per unit area, measured in lux (lx), where 1 lux equals 1 lumen per square meter (1 $lumen/m^2$) (Boyce, 2003). Ambient illuminance encompasses the total illumination in an area from natural and artificial light sources, affecting visibility, comfort, and productivity (Cuttle, 2015).

2.7.1. Relationship Between Luminance and Illuminance

A critical aspect to note is the relationship between luminance and illuminance. Mathematically, luminance (cd/m^2) can be derived from illuminance (lx) divided by π (approximately 3.14159), based on the Lambertian reflection model, which assumes that light is evenly diffused across a surface. This relationship is given by:

$$Luminance\ \left(\frac{cd}{m^2}\right) = \frac{Illuminance\ (lx)}{\pi}$$

This formula arises from the definition of luminance for a perfectly diffusing (Lambertian) surface, where the reflected light is uniformly distributed over all angles. The division by π accounts for the hemispherical distribution of light. (Friedman, 2024)

Although this calculation is precisely accurate for a perfect Lambertian surface, it provides a valuable approximation for general surfaces in typical environments. (DisplayCAL, 2023) The relationship between illuminance and luminance remains valuable for understanding the light dynamics in various settings, including those encountered in AR applications. While illuminance measures the incoming light, luminance measures the reflected light, which is more relevant to understanding the visual experience in AR settings. Ambient luminance becomes a key factor since AR content can be displayed in various environments, including IILPs like museums with integrated light sources. However, since it can be calculated from ambient illuminance, both terms fit the requirements and can be explored freely in the literature.

2.8. Impact of lighting conditions on AR user experience in IILPs

Visual discomfort and fatigue are significant concerns in AR applications. High ambient luminance levels can cause glare and make it difficult for users to distinguish between virtual and real-world elements, leading to visual strain (Kalra & Karar, 2020). Conversely, low ambient luminance can make virtual elements less visible, requiring users to strain their eyes to see them clearly. Hence, the balance of luminance between the display and the environment is crucial for reducing visual discomfort (Hakkinen et al., 2006).

The pupil, particularly its diameter, is the primary determinant of the depth of field of the human eye, and it can vary with ambient lighting conditions. Consequently, the zone of comfortable viewing, determined by the depth of field, can exhibit significant variations based on lighting conditions as well (Mizushina et al., 2009). Zhdanov et al. (2019) reported that another equally significant factor contributing to visual discomfort in virtual and mixed reality systems is the disparity in illumination conditions between objects in the virtual and real worlds. Incorrectly illuminated virtual objects may disorient observers, notably when the absence of naturally oriented shadows deviates from their expected visual experience under current illumination conditions. This mismatch can lead to discomfort as observers perceive something divergent from their brain's anticipated visual cues.

Studies have also shown that prolonged exposure to screens with high luminance can lead to digital eye strain, characterized by symptoms such as dry eyes, blurred vision, and headaches (Sheppard & Wolffsohn, 2018). Managing these factors becomes even more critical in the context of smartphone AR, where the screen brightness and ambient lighting conditions constantly interact.

Therefore, exploring the impact of lighting conditions of both ambient and display luminance conditions on visual discomfort and fatigue within the context of smartphone AR could be advantageous, especially considering the absence of prior studies addressing this specific aspect.

2.9. Influence of lighting conditions on visual fatigue

While not explicitly explored in the literature for smartphone AR, Computer Vision Syndrome (CVS), or digital eye strain, is a widely studied phenomenon, which encompasses a spectrum of eye and vision-related issues—including visual discomfort, fatigue, blurred vision, eye strain, dry and irritated eyes, double vision, vertigo, headaches, neck pain, and difficulty refocusing the eyes—arising from prolonged use of electronic display devices such as computers, tablets, e-readers, and smartphones [Blehm et al.,2005; Rosenfield, 2011; Sheppard & Wolffsohn, 2018; Coles-Brennan et al., 2019]. Notably, visual discomfort and fatigue are the core symptoms. The reported prevalence of CVS among computer users varies widely, ranging from 25% to 93%, depending on the instrument used, sample examined, and methodology applied (Sheppard & Wolffsohn, 2018) (Zhou et al., 2021).

Multiple factors contribute to the severity of CVS, which can roughly be classified into three clusters: eye-related, environment-related and device-related (Coles-Brennan et al., 2019). Among all the influential factors, ambient illuminance (an environment-related factor) and screen luminance (a screen-related factor) seem to be the most influential [Blehm et al.,2005; Rosenfield, 2011] and have attracted much attention in previous studies.

Despite the extensive research on this topic, previous findings have been diverse, and it is not easy to obtain a consensus (Zhou et al., 2021). While some studies suggest that medium illuminance (e.g., 500 or 600 lx) is most beneficial for enhancing visual performance [Lin, 2014; Liu et al., 2017], contrasting research indicates no significant improvement with ambient illuminance [Chen et al., 2016; Huang et al., 2017] and even a preference for low illuminance (200 lx) over high (700 lx) in terms of visual recognition performance (Chen & Lin, 2004).

Regarding subjective visual discomfort, one study observed higher levels under 200 lx compared to 500 lx; however, objective evaluations using critical flicker frequency (CFF) did not show as severe fatigue under 200 lx as compared to the 500 lx condition (Liu et al., 2010). Additionally, it has been noted that visual comfort remains stable at a comfortable illuminance threshold (Chinazzo et al., 2019), with high illuminance (e.g., 1000 lx) potentially causing dissatisfaction, discomfort, and increased visual fatigue [Zhang et al., 2020; Wolska & Switula, 1999]. These collective findings strongly indicate that maintaining relatively low to medium ambient illuminance levels could enhance visual comfort and minimize visual fatigue (Zhou et al., 2021).

Screen luminance is identified as another crucial factor influencing visual discomfort and fatigue. Studies have shown that higher screen luminance is associated with improved visual display quality and task performance by reducing image distortion and improving image quality [Lin & Huang, 2006; Buchner & Baumgartner, 2007]. However, a review of several studies has shown that prolonged exposure to high screen luminance may lead to increased visual fatigue (Rosenfield, 2011).

Examining the nuanced relationship between ambient illuminance and screen luminance, Benedetto et al. (2014) delved into the combined effects of these factors on visual fatigue and performance. The study discovered that subjective visual fatigue remained unaffected by either screen luminance or ambient illuminance through manipulations of ambient illuminance (5 and 85 lx) and screen luminance (20 and 140 cd/m²). However, objective visual fatigue, assessed by blink frequency, exhibited an increase under high luminance conditions (140 cd/m²)

Hong-Ting et al. (2013) investigated the optimum screen luminance of mobile phones under varying ambient illuminance. Their results revealed that optimal screen luminance levels, corresponding to ambient illuminance levels of 0, 100, and 500 lx, were 11, 68, and 257 cd/m², respectively. In a similar study by Ye et al. (2014) to investigate optimal luminance under variable ambient illuminance levels, they found that optimal luminance levels for illuminance conditions of 0, 150, 300, 400, 600, and 800 lx were 55, 170, 308, 436, 470, and 496 cd/m², respectively.

Furthermore, Zhang et al. (2013) extended this exploration to outdoor illuminance levels, disclosing optimal screen luminance levels of 354, 734, and 1375 cd/m² under illuminance levels of 10k, 20k, and 50k lx, respectively (Zhou et al., 2021, p. 2). On the other end of the spectrum, Na and Suk (Na & Suk, 2015) explored the optimal luminance under extremely low illuminance levels (less than 1 lx) and identified that optimal levels were 10 cd/m² for initial viewing and 40 cd/m² for continuous viewing conditions.

Examining short-term reading, Yu et al. (Yu et al., 2018) determined optimal luminance levels of 58.5, 66, and 84 cd/m² for illuminance levels of 100, 150, and 300 lx, respectively. In a subsequent study, Yu and Akita. (Yu & Akita., 2020) extended their investigation to prolonged reading durations, revealing optimal luminance zones of 45-90 cd/m² under 100 lx and 45-270 cd/m² under 230 lx illuminance levels.

In addition to the influence of ambient illuminance and screen luminance on visual fatigue, findings by Zhou et al. (2021) revealed that the optimum screen luminance increased accordingly with increasing ambient illuminance levels, which was in accordance with previous studies [Hong-Ting et al., 2013; Ye & Liu, 2014; Yu et al., 2018; Kim et al., 2017; Yu & Akita, 2020]. They also stated that the lower illumination of screens or dimmer ambient illuminance may elicit many visual problems, such as lower reading legibility and higher visual fatigue.

2.10. Effect of lighting conditions on legibility

The interplay between ambient and display luminance also significantly impacts the legibility of text and images on smartphone screens, a critical factor for augmented reality (AR) applications. Legibility, defined as the ease with which text can be read, is influenced by various factors, including luminance contrast between the text and its background, ambient light conditions, and the inherent brightness of the display (Benedetto et al., 2014; Zhou et al., 2021).

Studies have shown that optimal luminance settings enhance readability and reduce visual strain. For instance, Dobres (2017) examined the effects of different ambient illuminance levels on smartphone text legibility. They found that moderate ambient illuminance (300-500 lux) provided the best conditions for reading, as it reduced glare and reflections on the screen while maintaining sufficient light for comfortable reading. Similarly, Zhou et al. (2021) highlighted that high ambient luminance conditions, such as direct sunlight, necessitate higher screen brightness to maintain legibility, thereby increasing power consumption and potentially causing visual discomfort due to high contrast.

In the specific context of AR applications, the challenge of maintaining legibility is further complicated by the dynamic nature of the content and the diverse lighting environments in which AR is used. Lu and Lou (2017) explored the effect of ambient lighting on the readability of AR content overlaid on real-world scenes. Their findings suggested that under low ambient light conditions (less than 100 lux), AR content becomes less readable due to insufficient screen luminance, while high ambient light conditions (greater than 1000 lux) can cause screen glare and reduce contrast, impacting legibility.

Further investigation by Chen et al. (2019) focused on the interaction between screen luminance and ambient lighting in enhancing legibility. They suggested that adaptive luminance adjustment, where the display brightness automatically changes in response to ambient light, significantly improves the readability of AR text. This method helps maintain a consistent contrast ratio, thereby reducing the visual strain associated with frequent changes in lighting conditions.

In addition to static text, the legibility of dynamic AR content, such as moving text or images, is also affected by luminance conditions. A study by Park et al. (2020) found that higher screen luminance levels (around 400 cd/m²) improved the readability of moving text against bright backgrounds, while lower luminance levels (less than 100 cd/m²) were preferable for static content in darker environments. This indicates the need for context-aware luminance adjustments to optimize legibility in different AR scenarios.

2.11. Impact of visual discomfort and legibility on Affective State and Task Performance

The affective state of users, which encompasses their emotional responses such as enjoyment and annoyance, plays a pivotal role in how they interact with and perceive augmented reality (AR) content. This state is not only an indicator of immediate emotional reactions but also reflects the user's overall experience and satisfaction with AR technology. The concept of affective state, rooted in psychology, refers to the experience of feeling or emotion, and it has been extensively studied in various contexts, including human-computer interaction (Russell, 1980).

Affective states are crucial because they influence user engagement, satisfaction, and motivation, which are essential for the effective use of AR applications, particularly in educational and entertainment contexts. According to Russell (1980), affective states can be categorized into dimensions such as pleasure-displeasure and arousal, which help in understanding users' complex emotional responses during their interaction with AR content. Factors like visual comfort and content legibility significantly influence these emotional responses.

Visual discomfort and fatigue, often induced by suboptimal luminance conditions, can negatively impact the user's affective state. For instance, Benedetto et al. (2014)

demonstrated that prolonged exposure to high screen luminance can increase visual fatigue, reducing user satisfaction and enjoyment. Similarly, Dobres & Reimer (2015) found that inappropriate ambient illuminance levels can cause glare and reflections on the screen, leading to visual discomfort and decreased enjoyment during prolonged smartphone use. These findings suggest that visual fatigue directly affects the emotional response to AR content, making users less likely to engage positively with the technology.

Visual discomfort can also significantly affect the users' learning task performance while using AR, as evidenced by studies focusing on quiz performance after engaging with AR content. Park et al. (2020) found that higher screen luminance levels (around 400 cd/m^2) improved the readability of moving text in AR, leading to better performance in subsequent quizzes. Conversely, lower luminance levels (less than 100 cd/m^2) were found to be more suitable for static content, contributing to higher quiz scores and user satisfaction in low-light conditions. Zhou et al. (2021) emphasized that visual fatigue, induced by suboptimal screen and ambient luminance, directly affects cognitive performance and task effectiveness. Their study revealed that optimal screen luminance levels, adjusted for varying ambient illuminance, enhance both user comfort and cognitive performance, as evidenced by improved quiz scores and task completion times.

The legibility of AR content is another critical factor influencing the affective state. Clear and easily readable text and images enhance user engagement and satisfaction, while poor legibility can lead to frustration and annoyance. Lee et al. (2016) highlighted that maintaining moderate ambient illuminance levels (300-500 lux) improves text legibility and reduces visual strain, thereby enhancing user enjoyment and reducing annoyance. In contrast, Lu and Lou (2017) found that high ambient light conditions can reduce AR content visibility, leading to user dissatisfaction and decreased enjoyment.

Moreover, the contrast ratio between AR content and the real-world background is crucial. Nakashima and Kimura (2018) reported that maintaining an optimal contrast ratio between AR content and the background significantly improves user performance in tasks requiring quick and accurate reading. This is particularly important in contexts where users engage with informative AR content, such as quizzes or educational modules. They demonstrated that an optimal contrast ratio of at least 7:1 is necessary to ensure clear visibility of AR elements under varying ambient light conditions.

Adaptive luminance adjustment technologies have been shown to improve both the affective state and task performance by ensuring consistent visual comfort and optimal legibility. Chen et al. (2004) demonstrated that adaptive luminance adjustment, which automatically modifies screen brightness in response to ambient light conditions, significantly enhances the readability of AR content and reduces visual strain. This approach not only improves user satisfaction but also enhances task performance by maintaining a stable visual environment.

2.12. Impact of visual factors on the visitors' experience with smartphone AR in IILPs

The integration of Augmented Reality (AR) technology into Informal Institutional Learning Places (IILPs)—such as museums, science centers, and historical sites—holds significant promise for enhancing the educational and interactive experiences of visitors. The success of AR in these environments largely depends on key visual factors, specifically visual comfort and content legibility. These factors are critical because they directly impact three of the core indicators of visitors' experiences commonly studied in this contextt: intention to revisit, hedonic motivation, and perceived learning outcomes (Chung et al., 2015; Radu, 2014; Wojciechowski & Cellary, 2013). Ensuring visual comfort and clear content legibility can greatly enhance the effectiveness of AR as a tool for education and engagement. Consequently, understanding and addressing these visual factors is essential for maximizing the benefits of AR in these environments.

2.12.1. Visitors' Intention to Revisit

Visitors' intention to revisit an informal learning institution is a crucial metric of user satisfaction and engagement. Intention to revisit is defined as a visitor's likelihood or willingness to return to a particular venue in the future (Oliver, 1980). This intention is strongly influenced by the quality of the initial experience, which encompasses various factors, including visual comfort and content legibility.

Research indicates that a positive initial experience significantly enhances revisit intentions. For instance, Bitner (1992) emphasized the importance of the physical environment, or servicescape, in shaping customers' perceptions and behaviours in service settings. In the context of AR-enhanced informal learning environments, visually comfortable and legible content forms a critical part of this environment. Dobres & Reimer (2017) demonstrated that optimal ambient illuminance and screen luminance levels, which reduce visual discomfort, lead to higher visitor satisfaction and, consequently, stronger intentions to revisit.

Moreover, cognitive evaluation theories suggest that visitors assess their experiences based on the perceived quality of the interaction (Fornell, Johnson, Anderson, Cha, & Bryant, 1996). When AR content is clear and visually pleasing, visitors are more likely to perceive their experience as high-quality, thus increasing their intention to revisit. The positive emotions associated with an enjoyable, strain-free experience reinforce their desire to return.

2.12.2. Hedonic Motivation

Hedonic motivation, which refers to the pursuit of pleasure and enjoyment derived from engaging in an activity (Holbrook & Hirschman, 1982), is another critical factor influenced by the users' emotional or affective state, as discussed earlier in the given context, is affected by the users' visual comfort and legibility. Hedonic motivation is an essential component of the user experience, particularly in informal learning environments where engagement and enjoyment are vital for effective learning and retention.

Holbrook and Hirschman (1982) introduced the concept of hedonic consumption, highlighting that consumers seek experiences that provide sensory pleasure, aesthetic enjoyment, and emotional arousal. In AR contexts, visually comfortable and legible content enhances these sensory experiences, increasing hedonic motivation. Similarly, Mokmin et al., (2024) discuss how augmented reality applications can significantly enhance educational experiences by promoting motivation and interaction among students

The theory of flow, introduced by Csikszentmihalyi (1990), further explains how visually engaging and legible content can lead to a state of deep immersion and enjoyment. Flow occurs when individuals are fully absorbed in an activity, experiencing intrinsic enjoyment and optimal performance. In the context of AR, clear and comfortable visual stimuli reduce distractions and cognitive load, facilitating a flow state that enhances hedonic motivation. This immersive experience not only makes learning more enjoyable but also fosters a positive emotional connection with the learning environment.

Studies on technology acceptance and use, such as the Unified Theory of Acceptance and Use of Technology (UTAUT), also underscore the importance of hedonic motivation in the adoption and continued use of technological innovations (Venkatesh et al., 2012). In informal learning settings, AR applications that provide visually comfortable and legible content are more likely to be enjoyed and, hence, adopted and revisited by users, driven by their intrinsic motivation for pleasure and enjoyment.

2.12.3. Perceived Learning Outcomes

Perceived learning outcomes refer to the learners' self-assessment of the knowledge and skills acquired during an educational experience. The clarity and legibility of AR content significantly influence these outcomes, as they determine how effectively information is communicated and understood. When AR content is visually accessible, visitors are more likely to process and retain the information, leading to higher perceived learning outcomes.

Research by Mayer (2014) on multimedia learning emphasizes the importance of clear and well-organized visual elements in enhancing comprehension and retention. In AR environments, maintaining optimal luminance conditions ensures that text and images are easily readable, reducing cognitive load and allowing learners to focus on the content itself. Sung and Mayer (2012) found that well-designed visual content in educational tools significantly improves learning outcomes, reinforcing the importance of visual comfort and legibility in AR applications.

Furthermore, studies on cognitive load theory (Sweller et al., 2011) indicate that reducing extraneous cognitive load, such as visual strain caused by poor lighting conditions, allows learners to allocate more cognitive resources to processing and understanding the material. This improved cognitive efficiency enhances perceived learning outcomes, as visitors can more effectively engage with and internalize the content presented in AR formats.

2.13. Conclusion

This review has underscored the critical role of lighting conditions, including screen and ambient luminance, in influencing visual discomfort and fatigue. Studies have shown that these lighting conditions also affect the legibility of content presented on screens. Poor lighting can increase visual strain, negatively impacting users' emotional states and overall performance in learning tasks. These adverse effects may consequently influence visitors' intention to revisit the IILP, their hedonic motivation, and their perceived learning outcomes. Therefore, optimizing lighting conditions and display characteristics is essential for enhancing the overall experience of visitors using smartphone AR in IILPs.

Despite the burgeoning popularity of smartphone AR in IILPs, its potential challenges remain relatively understudied. Previous research on AR has explored issues like vergence-accommodation conflict (e.g., Hoffman et al., 2018), but these findings primarily relate to head-worn AR devices rather than smartphone AR. The unique characteristics of smartphone AR necessitate distinct considerations. To bridge this gap, our review included studies on digital displays and e-reading tasks, which provide more relevant context for understanding the visual challenges associated with smartphone AR.

The existing literature offers valuable insights, but there is a notable lack of focused research addressing the specific interaction between lighting conditions and AR usage in IILPs. Most studies to date have concentrated on traditional digital displays or head-worn AR devices, each presenting unique visual and ergonomic challenges distinct from those posed by smartphone AR. Given the unique visual demands and environmental contexts of AR applications, it is crucial to investigate these factors in greater depth.

To address these gaps, further research is essential to explore the impact of display and ambient luminance conditions on visual discomfort and perceived legibility in smartphone AR. Understanding these interactions is vital for improving user experience in IILPs. Consequently, we conducted an experimental study as part of this thesis to systematically examine these variables. The findings and detailed methodology of this study will be discussed in the following chapters. By investigating these aspects, we aim to provide actionable insights that can inform the design and implementation of more effective and user-friendly smartphone AR applications in educational contexts. This research is crucial for ensuring that AR technology can be harnessed to its full potential, enhancing both hedonic and educational outcomes as well as visitor engagement in IILPs.

Chapter 3
Theoretical framework and Hypothesis Development

3.1. Theoretical framework

The Stimulus-Organism-Response (SOR) framework (Figure 4) is a psychological model that explains how individuals react to environmental stimuli. Developed by Albert Mehrabian and James A. Russell in 1974, the SOR model is an extension of the earlier Stimulus-Response (SR) theory, which posited that an individual's behaviour (Response) is directly influenced by external stimuli (Stimulus). However, the SR model did not account for the internal state of the individual (Organism), which Mehrabian and Russell argued plays a crucial mediating role.

Here is a detailed breakdown of the SOR framework:

Stimulus (S): This refers to the external factors that impact an individual. In the context of environmental psychology, these could be elements like colour, light, sound, or temperature. The stimulus is the initial trigger that sets off the process.

Organism (O): The organism component represents the individual's internal state, which includes emotional responses and cognitive processes such as pleasure and arousal.

Response (R): The response is the behaviour resulting from the stimulus's processing by the organism. It can be an action, a verbal reply, or even a physiological reaction. The SOR model suggests that this response can be broadly categorized into approach or avoidance behaviours. Approach behaviours indicate a positive reaction, where the individual is drawn towards the stimulus, while avoidance behaviours suggest a negative reaction, leading the individual to withdraw from the stimulus.

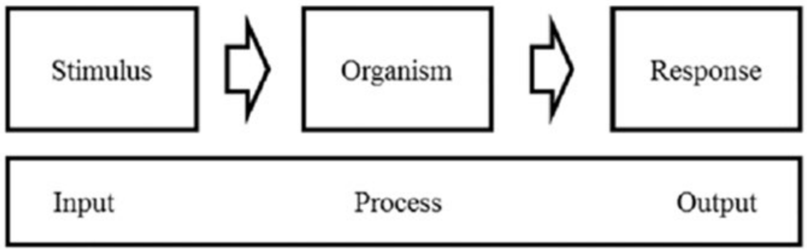

Figure 4: SOR Framework

The S-O-R framework's versatility has enabled its application across numerous domains, including consumer behaviour, marketing, and technology usage. Researchers such as Huang (2023), Wang and Wang (2021), and Do et al. (2020) have utilized the S-O-R model to understand consumer behaviour in contexts like mobile app adoption, retail settings, and online shopping environments. Its utility lies in its ability to elucidate the interplay between external stimuli, internal cognitive processes, emotional responses, and subsequent behavioural outcomes, providing valuable insights for designing compelling user experiences, enhancing product adoption rates, and fostering user engagement and satisfaction (Huang, 2023; Jin et al., 2021; Erensoy et al, 2024).

In the realm of Human-Computer Interaction (HCI), the S-O-R framework has been adapted to study user interactions with digital systems. Here, stimuli refer to interface design elements, interactive features, and content. The organism component represents the user's cognitive and emotional states, while the response encompasses behaviours such as engagement, satisfaction, and usability (Kim & Fesenmaier, 2008). This adaptation has been crucial in understanding and improving how users interact with digital interfaces.

For example, the visual aesthetics of a website (stimuli) can significantly impact a user's perception of usability and satisfaction (organism), which then affects their likelihood of continuing to use the site (response). Interactive features such as navigation ease and response time are critical stimuli that shape a user's overall experience and subsequent behaviour. By leveraging the S-O-R framework, designers can pinpoint which elements of an interface are most influential in shaping user behaviour, thereby enabling the creation of more effective and engaging digital environments.

Research has demonstrated that various elements of web and mobile interfaces can act as stimuli that influence user responses. For instance, Cyr et al. (2009) found that visual appeal, perceived usability, and trustworthiness are significant predictors of user satisfaction and loyalty in online shopping contexts. Similarly, Hassenzahl (2008) emphasized the importance of aesthetic design in eliciting positive emotional responses, which subsequently enhance user experience and engagement.

Furthermore, the S-O-R framework has been applied to study the effects of interactivity and personalization in digital environments. Lee and Koubek (2010) examined how different levels of interactivity in web design impact user satisfaction and engagement. Their findings suggest that higher interactivity levels lead to more positive organismic responses, such as increased enjoyment and perceived control, fostering greater user engagement.

The framework has also been employed to understand user behaviour in mobile applications. For example, Lin and Bhattacherjee (2010) investigated how perceived enjoyment and perceived usefulness (organism) mediate the relationship between system quality (stimulus) and user satisfaction and continuance intention (response) in mobile services. Their study confirmed the applicability of the S-O-R model in predicting user behaviour in mobile contexts.

The application of the S-O-R framework in augmented reality (AR) is particularly compelling due to the immersive and interactive nature of AR experiences. AR technology introduces complex stimuli, such as visual overlays, spatial audio, haptic feedback, and interactive components, that create immersive user experiences by blending real and virtual elements. These stimuli significantly impact users' internal states and subsequent behaviours, aligning well with the S-O-R model's principles.

One notable application of the S-O-R framework in AR is in the tourism industry. Do et al. (2020) conducted a study involving 479 valid samples to investigate how mobile AR apps influence tourist impulse buying behaviour. The study highlighted the pivotal role of factors such as utility, ease-of-use, and interactivity of AR apps in shaping user enjoyment and satisfaction, ultimately driving increased impulse buying behaviour. These findings underscore the importance of well-designed AR stimuli in evoking positive emotional responses and desired behavioural outcomes. Moreover, the study by Do et al. (2020) examined the perceived interactivity of mobile AR apps, revealing a strong correlation between user enjoyment and the interactive features of these apps. This correlation supports the S-O-R framework's emphasis on the role of stimuli in evoking positive organismic responses and subsequent behavioural reactions. Such insights are crucial for AR app developers aiming to enhance user experience and engagement.

Beyond tourism, the S-O-R framework has been applied to other AR contexts, such as retail and education. AR applications enhance the retail shopping experience by providing interactive product information and virtual try-ons. Research by McLean and Wilson (2019) showed that AR stimuli could improve user engagement and satisfaction, although they also noted the potential for increased cognitive load, which can lead to user fatigue if not appropriately managed. AR has been used in educational settings to create immersive learning environments that enhance engagement and learning outcomes. Wu et al. (2017) demonstrated that AR applications could support cognitive apprenticeships in nursing training by providing context-aware, interactive experiences. Their study highlighted how AR stimuli could facilitate learning by making abstract concepts more concrete and engaging.

The S-O-R framework offers a robust theoretical foundation for examining user interactions in augmented reality environments. By understanding the relationship between AR stimuli, internal psychological states, and behavioural outcomes, designers and researchers can create more engaging and effective AR experiences. The continued application and evolution of the S-O-R model in AR will undoubtedly yield more profound insights into optimizing user interactions in this rapidly advancing field.

In this experimental study, we utilize the solid theoretical basis of the SOR framework to explore the effects of the interaction between the display luminance of the device presenting the AR content and the ambient luminance in the IILP (Stimuli) on perceived visual discomfort and legibility of the presented content (Organism). This interaction is hypothesized to influence individuals' affective states and learning task performance, which in turn affect their intention to revisit, hedonic motivation, and perceived learning outcomes (Response).

3.2. Hypothesis Development

3.2.1. Proposed Research Model

The proposed research model shown in Figure 5 postulates that the luminance ratio between the surface luminance of the phone display and ambient luminance would influence the visual discomfort and legibility of the users. These mediating variables would influence the affective state and task performance of the users, in turn affecting their intention to revisit, hedonic motivation and perceived learning outcome. Each of these constructs and hypothesis are explained in detail in the following sections, organized into the sections Stimuli, Organism and Response according to the SOR framework.

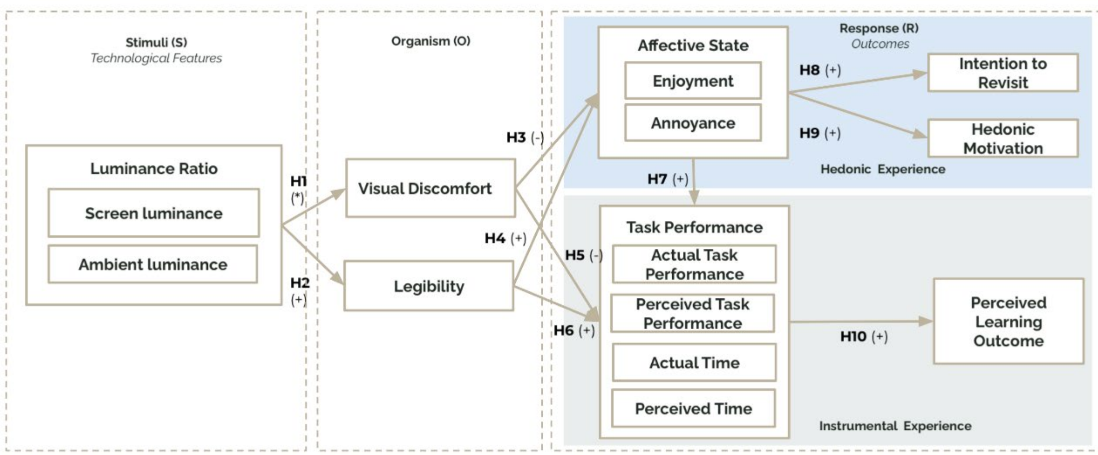

Figure 5: Proposed Research Model

** The directionality of H1 is not hypothesized*

3.2.2. Stimuli

Luminance is the brightness or intensity of light emitted or reflected from a surface, measured in candelas per square meter (cd/m^2) or nits. It quantifies the amount of light emitted or reflected per unit area in a specific direction (Schanda, 2007). For smartphone augmented reality (AR) applications, phone luminance pertains to the screen's brightness, which is adjustable through smartphone settings (Rukzio et al., 2012).

Illuminance, on the other hand, refers to the amount of light that falls on a surface per unit area and is measured in lux (lx), where 1 lux equals 1 lumen per square meter (1 lumen/m^2). It represents the intensity or brightness of the light that reaches a specific surface (Boyce, 2003).

When an AR application is active, the smartphone operates in a see-through mode, capturing the environment with its camera and displaying it on the screen with superimposed virtual elements. The screen's brightness shows the surroundings, adapting based on the camera's input, and hence, varying with the ambient luminance—the light coming from the surface the camera is pointing towards. Thus, the phone's luminance is influenced by both the screen settings and the ambient luminance. This ambient luminance also represents the ambient lighting conditions as it directly relates to ambient illuminance, as discussed in the literature review section.

Hence, in this scenario, **Luminance ratio** serves as a simplified construct that encompasses the interplay of the screen luminance of the smartphone and the ambient lighting conditions represented by ambient luminance. Thus, luminance ratio refers to the ratio between the screen luminance of the phone and the ambient luminance of the surface the user faces.

3.2.3. Organism

Visual fatigue is described as a decrease in the performance of the human visual system due to physiological strain or stress resulting from excessive exertion (Lambooji et al.) Visual discomfort, on the other hand, refers to any subjective sensation or discomfort experienced by an individual due to visual factors. Lambooji et al. distinguished visual fatigue as the objective measurement of the reduction in visual performance and visual discomfort as its subjective counterpart. Hence, these constructs are correlated by definition. Since the experimental study can only have psychometric constructs due to the logistical limitations in a real-world setting, Visual discomfort is used to represent the psychometric nature, while references from the literature that use physiological measures of visual fatigue are still applicable as they are two sides of the same coin.

Previous studies on the inducement of visual discomfort or fatigue have been varied and inconclusive; where some studies found that lower ambient illuminance will lead to higher visual fatigue (Wang et al., 2010), other studies suggest that medium illuminance (e.g., 500 or 600 lx) is most beneficial for enhancing visual performance [Lin, 2014; Liu et al., 2017], while contrasting research indicates no significant improvement with ambient illuminance [Chen et al., 2016; Huang et al., 2017] and even a preference for low illuminance (200 lx) over high (700 lx) in terms of visual recognition performance [Chen & Lin, 2004; Zhou et al., 2021] Additionally, it has been noted that visual comfort remains stable at a comfortable illuminance threshold (Chinazzo et al., 2019), with high illuminance (e.g., 1000 lx) potentially causing dissatisfaction, discomfort, and increased visual fatigue [Zhang et al., 2020; Wolska & Switula, 1999]. These findings indicate that low to medium ambient illuminance levels could enhance visual comfort and minimize visual fatigue.

Similarly, some studies show that Objective Visual fatigue will increase as the screen luminance of the phone increases (Benedetto et al.) Studies have shown that higher screen luminance is associated with improved visual display quality and task performance by reducing image distortion and improving image quality [Lin & Huang, 2006; Buchner & Baumgartner, 2007] (Zhou et al., 2021, p. 2). However, a review of several studies has shown that prolonged exposure to high screen luminance may lead to increased visual fatigue (Rosenfield, 2011). The Screen-to-ambient Luminance Ratio, as explored by Yu and Akita, underscores that a larger disparity between ambient and surface luminance corresponds to higher rates of CFF (Critical Flicker Fusion) variation and heightened fatigue.

Considering all the inconclusive and varied results in previous literature as well as the unique and understudied nature of the precise topic, we hypothesize without any particular directionality that:

H1: Luminance ratios will have a significant effect on visual discomfort.

Legibility, as defined by the Merriam-Webster dictionary and cited by Yu and Akita (2020), refers to the capacity of presented text to be read or deciphered. This concept is pivotal in understanding how different visual settings impact the readability of digital content.

Previous research has explored the relationship between digital screens' luminance ratios and text legibility. Yu and Akita (2020) conducted a study highlighting that at an ambient luminance of 15 cd/m², a tablet screen appeared dark at a luminance ratio of 1:1. When the luminance ratios were increased to 1:6 and 1:9, participants reported glare at both 15 cd/m² and 45 cd/m² ambient luminance levels. Furthermore, text readability was notably compromised at a luminance ratio of 1:9. Their findings suggest that optimal legibility is achieved within luminance ratio ranges of 1:1 to 1:6 for an ambient luminance of 15 cd/m², and below 1:6 for an ambient luminance of 45 cd/m².

Other studies corroborate these findings. For example, Rea and Ouellette (1991) found that higher luminance contrast enhances visual performance, but excessive contrast can cause visual discomfort and glare, negatively affecting legibility. Similarly, Boyce (2003) noted that both very low and very high luminance ratios can impair readability, with optimal performance occurring at moderate contrast levels. Additionally, research by Buchner and Baumgartner (2007) supports that high luminance contrast can cause visual discomfort, emphasizing the need for balanced luminance conditions to maintain legibility.

Extremely low luminance ratios, where both the surface in front of the screen and the phone screen exhibit low luminance levels, can result in the screen appearing excessively dark, reducing legibility. Conversely, exceedingly high luminance ratios may induce glare, further hampering legibility. Both scenarios underscore the importance of maintaining an optimal luminance ratio to ensure text readability.

Our study investigates AR in interactive, immersive learning platforms (IILPs), which present unique conditions not fully addressed in the existing literature. Firstly, ambient illuminance levels in IILPs may vary more widely than those documented in previous studies, sometimes exceeding or falling below typical indoor lighting conditions.

Secondly, the smartphone's see-through mode attempts to replicate the ambient illuminance and luminance of the surface directly in front of it, dynamically adjusting to the surrounding environment. This adaptability necessitates focusing on the luminance ratio rather than ambient illuminance or screen luminance alone.

Furthermore, it is more challenging to reach high luminance ratios as the display luminance adapts itself according to the ambient luminance, thus reducing the difference in luminance between the two and lowering the luminance ratio. Given the usual indoor settings of IILPs, reaching the high luminance ratio levels necessary for glare is also much more difficult. As such, a lower luminance ratio is a more relevant concern here that might affect the legibility of the presented content, while a higher luminance ratio should typically indicate better legibility. Considering all these factors, we hypothesize that:

H2: A greater luminance ratio positively affects legibility.

3.2.4. Response

Enjoyment is conceptualized as a subjective state of pleasure, satisfaction, or happiness derived from engaging in activities that are pleasurable, meaningful, or fulfilling (Csikszentmihalyi, 1990). This state is associated with positive emotional responses such as contentment, joy, or delight, contributing to an individual's overall well-being (RM, 2001).

In contrast, **Annoyance** is a feeling of discomfort or irritation that arises from an unwanted or bothersome stimulus (Koelega, 1987). Environmental psychology literature often examines annoyance within negative contexts such as noise pollution, where it is described as an interference with feelings, thoughts, and daily activities, accompanied by stress-related symptoms and negative responses like exhaustion, displeasure, and anger (Zaman et al., 2022).

Interactions with novel media such as augmented reality (AR) and 3D content have the potential to heighten visitor enjoyment. However, they can also introduce elements of visual discomfort that may elevate annoyance levels (Zhadnov et al., 2019). This phenomenon has been observed in several studies on new media technologies. For instance, Häkkinen et al. (2006) found that users of stereoscopic 3D displays often experience visual discomfort, which can reduce overall enjoyment and increase annoyance. Similarly, Gobba et al. (1988) highlighted that poor lighting conditions in digital displays can cause visual fatigue, leading to decreased user satisfaction.

Thus, enjoyment and annoyance are not mutually exclusive and may coexist, influencing the overall affective state of individuals (Bower, 1981). **Affective state** refers to any sentimental condition wherein one's feelings exert influence over their consciousness (N., Sam M.S., 2013). The concept of affective state, rooted in psychology, refers to the experience of feeling or emotion and has been extensively studied in various contexts, including human-computer interaction (Russell, 1980). It is typically represented by a lower affective state indicating negative sentimental conditions and a higher affective state indicating positive sentimental conditions.

Visual discomfort resulting from lighting conditions may significantly impact subjects' emotional reactions. Previous research indicates that adverse visual stimuli, such as those encountered in poorly designed AR experiences, can lead to negative emotional reactions, thereby decreasing the overall affective state (Gobba et al., 1988). They found that poor lighting conditions in visual display terminals can lead to visual fatigue and discomfort, impacting overall user satisfaction and emotional well-being. Similarly, Häkkinen et al. (2010) reported that visual discomfort from stereoscopic displays could lead to negative emotional responses, further supporting the negative association between visual discomfort and affective state. Moreover, research by Valtchanov et al. (2010) indicates that poorly designed visual environments can induce stress and discomfort, reducing overall enjoyment and increasing annoyance. Therefore, we hypothesize that:

H3: Visual discomfort is negatively associated with affective state.

Previous research has explored the relationship between content characteristics, including legibility, and emotional responses. Schreiner, Fischer, and Riedl (2019) conducted a comprehensive review of studies examining the impact of content characteristics on behavioural engagement in social media. Their findings suggest that arousing content, which is typically more legible and clear, tends to increase engagement behaviour, indicating a potential mediating effect of emotional responses.

To further elucidate this relationship, Berlyne (1971) proposed that the arousal potential of stimuli is a crucial determinant of emotional response. According to Berlyne's theory of aesthetics and psychobiology, stimuli that are easily processed, such as legible text, are more likely to elicit positive emotional responses due to reduced cognitive load. This aligns with fluency theory, which posits that easily processed information is often perceived more favourably (Reber, Schwarz, & Winkielman, 2004). Research by Halberstadt and Rhodes (2003) supports this view by showing that stimuli that are easier to process are often perceived more positively.

Lidwell et al., (2010) provide further evidence by demonstrating that visual clarity and legibility significantly affect consumer emotions and attitudes. Their study found that clear and legible content enhances positive emotional responses, influencing overall attitudes towards the content. Similarly, Wang and Emurian (2005) highlighted that clear, well-organized text increases user satisfaction and positive affective responses, underscoring the importance of legibility in digital content. Shaikh (2005) also indicates that typography affects readability and user experience, leading to more positive emotional responses and greater satisfaction.

Additionally, Piepenbrock, Mayr, and Buchner (2013) demonstrated that positive display polarity, which improves legibility, benefits both younger and older adults regarding cognitive and emotional processing. This supports the notion that legibility can enhance affective states across different age groups. Drawing on these insights, we hypothesize that

H4: legibility is positively associated with affective state.

Visual discomfort, manifesting as visual fatigue, can significantly impair learning **task performance**. Research by Mizuno et al. (2021) demonstrated that low visual information-processing speed and attention are predictors of fatigue, affecting learning task performance. Similarly, van Bommel (2019) discussed how visual performance for tasks of varying difficulty is influenced by lighting conditions, which can affect task efficiency. Aul et al. (2023) highlighted the functional relevance of visuospatial processing speed across the lifespan, noting its critical role in everyday tasks and its decline with age.

Visual discomfort not only impacts performance but also the perception of task difficulty and time. For instance, Han, Shin, and Jeong (2016) found that increased visual discomfort from screen glare and poor ergonomics can lead to longer task completion times and the perception that tasks are more time-consuming. Additionally, Wickens et al. (2015) suggest that visual discomfort can deplete cognitive resources necessary for efficient task execution, leading to decreased actual and perceived performance.

Benedetto et al. (2013) found that visual discomfort from digital screens can significantly reduce reading comprehension and speed. Similarly, Sheedy, Hayes, and Engle (2003) demonstrated that visual discomfort from screen flicker and poor contrast can lead to increased errors and slower performance in computer-based tasks. These findings suggest that the adverse effects of visual discomfort extend to various types of tasks and settings, further highlighting its impact on both objective and subjective performance metrics.

Moreover, the implications of visual discomfort are particularly pertinent in the context of augmented reality (AR) and virtual reality (VR) environments. According to LaViola (2000), prolonged use of AR and VR systems can cause significant visual discomfort and fatigue, affecting user performance and overall experience. This is further reflected by research from Mittelstaedt et al. (2019), who found that visual fatigue from VR headsets can lead to decreased cognitive function and slower reaction times.

It can be inferred that visual discomfort depletes cognitive resources necessary for task execution, leading to decreased actual and perceived performance. Additionally, discomfort may cause individuals to take longer to complete tasks and perceive that more time has elapsed, indicating reduced task efficiency. Based on these findings, we propose the following hypotheses:

H5a: Visual discomfort is negatively associated with actual task performance.

H5b: Visual discomfort is negatively associated with perceived task performance.

H5c: Visual discomfort is positively associated with task time.

H5d: Visual discomfort is positively associated with perceived task time.

The scientific literature underscores a robust correlation between task performance and legibility. Clear legibility not only bolsters readability but also expedites and refines information processing, which in turn enhances comprehension and task completion efficiency (Gabbard, Swan, & Hix, 2006). This relationship is corroborated by empirical observations, where tasks are performed more effectively when information is legible and comprehensible (Weintraub, 2023).

Further supporting this relationship, Bernard et al. b(2003) demonstrated that users read and comprehend text faster when presented in a legible format, leading to better task performance. Similarly, Shaikh (2005) found that font type and size significantly impact readability and task efficiency, highlighting the importance of typographic choices in enhancing legibility. Moreover, research by Larson and Picard (2005) indicates that legibility directly affects user engagement and satisfaction, which are crucial for maintaining high task performance.

Studies also show that legibility impacts perceived task performance and time. For instance, Ling and van Schaik (2002) observed that participants reported higher satisfaction and perceived efficiency when interacting with well-designed, legible text. This is consistent with findings by Hartley (2004), who reported that clear and legible text can reduce perceived cognitive load, thereby making tasks seem less time-consuming.

In the context of digital interfaces, Rello and Baeza-Yates (2013) highlighted the importance of legibility for users with dyslexia, showing that legible fonts significantly improve reading speed and comprehension for this population. Furthermore, research by

Ghafourian et al., (2005) found that the readability of website content significantly influences user engagement and behaviour, supporting the notion that legibility can enhance both actual and perceived task performance in online environments.

It is thus clear that legibility facilitates cognitive processing, thereby positively influencing both the actual and perceived efficiency of task performance. Moreover, legible content will likely reduce the time required to complete tasks and the perceived duration of task engagement, reflecting a streamlined cognitive workload (Dobres, Wolfe, & Chahine, 2018). Based on these principles and findings, we posit the following hypotheses:

H6a: Legibility is positively associated with actual task performance.

H6b: Legibility is positively associated with perceived task performance.

H6c: Legibility is negatively associated with task time.

H6d: Legibility is negatively associated with perceived task time.

Affective state, in turn, may significantly influence task performance. There is robust theoretical support in experimental social psychology to suggest that positive moods can enhance memory and cognitive tasks such as problem-solving (Fredrickson, 1998; Isen, 1987; Pe et al., 2008). Additionally, research by Hawes et al. (2013) found that changes in mood predicted performance on cognitive tasks, with individuals exhibiting reduced depression ratings in a given condition also demonstrating faster reaction times.

Further supporting this relationship, research by Lyubomirsky, King, and Diener (2005) conducted a meta-analysis demonstrating that positive affect is linked to various favourable outcomes in life, including higher levels of cognitive performance. Ashby, Isen, and Turken (1999) proposed that positive affect promotes cognitive flexibility, which enhances problem-solving abilities and creativity. Similarly, Estrada, Isen, and Young (1994) showed that physicians in a positive mood were more efficient and accurate in their diagnoses, emphasizing the practical implications of affective states on task performance.

Empirical studies have also documented the impact of affective states on perceived task performance and time. For instance, research by Kuhl (1986) indicates that positive moods can reduce the perceived effort required for a task, thereby enhancing subjective task performance and efficiency. This is corroborated by findings from Forgas (2000), who demonstrated that mood influences cognitive processing styles, with positive moods fostering a more global processing approach that can improve perceived task performance.

In educational psychology, Pekrun et al. (2002) found that students' affective states significantly influenced their academic achievement, suggesting that positive emotions can enhance both actual and perceived performance. Moreover, research by Beal et al. (2005) highlights that positive affect can reduce perceived task difficulty and time, aligning with the notion that a good mood can make tasks seem easier and quicker to complete.

It can be concluded that positive affective states facilitate cognitive processes, thereby improving both actual and perceived task performance and reducing the time required to complete tasks. Positive moods are likely to lower the perceived duration of task engagement, reflecting a more efficient and enjoyable task experience. Given these findings and theoretical underpinnings, we posit the following hypotheses:

H7a: Affective state is positively associated with actual task performance.

H7b: Affective state is positively associated with perceived task performance.

H7c: Affective state is negatively associated with task time.

H7d: Affective state is negatively associated with perceived task time.

Intention to revisit refers to an individual's readiness or willingness to make a repeat visit to the same destination (Tosun et al., 2015). The relationship between enjoyment and the intention to revisit in hedonic contexts, such as tourism or leisure activities, is well-documented in the scientific literature. Enjoyment, as a positive emotion experienced during an activity, can significantly influence a person's desire to relive that experience.

Several key findings support this relationship. For instance, research by Lee & Qu (2020) discovered that satisfaction, a construct closely related to enjoyment, significantly affects visitors' intention to revisit. Similarly, Pakhalov et al. (2021) confirmed a positive relationship between positive emotions and intention to revisit. These findings align with the theory of planned behaviour (Ajzen, 1991), which posits that positive attitudes towards a behaviour significantly enhance the intention to perform that behaviour.

Moreover, empirical studies emphasize the role of emotional experiences in shaping revisit intentions. For example, a study by Baker and Crompton (2000) found that positive emotional responses during a leisure activity strongly predict tourists' intentions to return. This is corroborated by Lee, Kyle, and Scott (2012), who demonstrated that emotional attachment to a destination fosters repeat visitation.

The link between enjoyment and revisit intention is also supported by the concept of flow, described by Csikszentmihalyi (1990) as a state of optimal experience and deep engagement in an activity. Flow experiences, characterized by high levels of enjoyment and satisfaction, have been shown to significantly enhance the desire to revisit the activity or destination (Chen et al., 2016).

Additionally, Chiu et al. (2014) identified that the enjoyment derived from social interactions during an activity positively influences the intention to revisit. Their study on theme park visitors highlighted that social enjoyment and the overall pleasantness of the experience were crucial determinants of repeat visits. This is further supported by findings from Wu and Li (2017), who found that the overall enjoyment of an experience, including aspects of novelty and excitement, significantly predicts revisit intentions in tourism contexts.

Further empirical support comes from a study by Yoon and Uysal (2005), which showed that tourist satisfaction, heavily influenced by positive emotional experiences during the trip, directly impacts the intention to revisit. Similarly, Prayag and Ryan (2012) demonstrated that tourists' positive emotional responses to a destination's atmosphere and activities significantly increased their likelihood of return.

In a more specific context, Hosany and Prayag (2013) found that tourists' emotional experiences, particularly joy and love, were significant predictors of their intention to revisit. This finding underscores the importance of creating emotionally engaging experiences to encourage repeat visits. Positive affective states, including enjoyment and satisfaction, enhance the intention to relive an experience by reducing perceived effort and increasing the overall desirability of the activity. Given these insights and established relationships, we hypothesize that:

H8: Participants' intention to revisit is positively associated with their affective state.

Hedonic motivation in the context of technology is defined as the fun or pleasure derived from technology use (Venkatesh et al., 2012). This concept is particularly relevant in understanding user engagement and satisfaction with technological interfaces and applications.

Several theoretical models in psychology and technology adoption emphasize the importance of the affective state in influencing hedonic motivation. The Unified Theory of Acceptance and Use of Technology (UTAUT2) by Venkatesh et al. (2012) incorporates hedonic motivation as a critical predictor of technology use, highlighting the role of emotional factors in driving user behaviour. According to Venkatesh et al., users are more likely to engage with and continue using technology that provides pleasurable experiences.

Empirical studies also support the positive relationship between affective state and hedonic motivation. For instance, research by Kim & Kim (2020) demonstrated that positive emotions significantly enhance users' enjoyment and motivation to engage with mobile applications. Their findings suggest that when users experience positive affective states, their intrinsic motivation to use technology for pleasure increases.

Similarly, Lin and Bhattacherjee (2010) found that users' positive affective responses to online gaming environments were strongly correlated with their hedonic motivation. Their study indicates that emotional satisfaction derived from gaming experiences significantly boosts users' engagement and willingness to continue using the platform.

A study by Deng and Yu (2023) found that users' hedonic motivations significantly influenced their flow experiences and continued use intentions of social media platforms like TikTok. This study highlighted that positive emotions, such as joy, were crucial predictors of users' motivation to engage with the platform. Another study by Zhang et al., (2020) explored the role of perceived enjoyment in users' mobile engagement, concluding that positive emotional states such as joy significantly impacted users' engagement and overall satisfaction. This suggests that emotional enjoyment directly influences users' motivation to engage with and derive pleasure from social media.

In the educational technology domain, research by Stephan et al., (2019) investigated students' emotions in online learning and found that positive emotions significantly contribute to engagement and motivation in technology-mediated learning environments. Their study supports the notion that emotionally engaging content can enhance students' intrinsic motivation. Another study by Espino et al., (2021) explored how positive emotions during learning activities, including e-learning, are linked to better academic outcomes and higher motivation.

Additionally, studies on consumer behaviour, such as those by Driediger and Bhatiasevi (2019), indicate that positive affective states experienced during online shopping significantly increase consumers' hedonic motivation. Their findings suggest that enjoyable shopping experiences lead to higher levels of user satisfaction and repeat purchase intentions.

These empirical findings align with established psychological theories, such as the broaden-and-build theory of positive emotions proposed by Fredrickson (2001). This theory posits that positive emotions expand individuals' thought-action repertoires, enhancing their intrinsic motivation to engage in pleasurable activities. Given these theoretical foundations and empirical evidence, we hypothesize that:

H9: Participants' hedonic motivation is positively associated with their affective state.

The concept of **perceived learning outcome**, as defined by Alavi, Marakas, and Yoo (2002), encompasses the changes in the learner's perceptions of their skill and knowledge levels before and after the learning experience. This perception is crucial as it reflects the individual's subjective assessment of their learning progress and understanding. Perceived learning outcome is vital in educational research, providing insight into how learners internalize and reflect on their educational experiences (Alavi, Marakas, & Yoo, 2002).

Task performance is often considered a direct indicator of a participant's learning outcome. In educational psychology, it is widely accepted that task performance serves as a tangible measure of the extent to which knowledge and skills have been acquired and retained through the learning process (Schunk, 1991; Bandura, 1997). The relationship between perceived learning outcomes and task performance has been extensively studied, showing that individuals who perceive themselves as having learned effectively tend to perform better on related tasks (Zimmerman, 2000; Pajares, 1996). This is because their self-assessment aligns with their actual capability to execute learned tasks.

Moreover, cognitive theories, such as those proposed by Anderson (1982), suggest that learning outcomes are directly tied to the cognitive processes involved in task execution. As individuals gain more knowledge and skills, their cognitive structures become more efficient, leading to better task performance. Empirical studies support this, indicating that perceived learning outcomes strongly predict actual task performance (Pintrich, 2003).

Research suggests that individuals who believe they have learned effectively are more likely to demonstrate higher performance levels (Pintrich & De Groot, 1990; Schunk, 1984). This positive association is underpinned by self-efficacy theory, which posits that confidence in one's learning enhances performance (Bandura, 1986). Additionally, studies by Sitzmann et al. (2010) have shown that learners' perceptions of their knowledge and skills significantly correlate with their perceived performance. Cognitive load theory supports this notion, suggesting that well-learned skills require less cognitive effort, thereby reducing task time (Sweller, 1988). Research by Ericsson, Krampe, and Tesch-Römer (1993) indicates that learners who perceive higher learning outcomes are expected to complete tasks more efficiently due to their enhanced understanding and skills. Furthermore, those who feel they have learned well also perceive that they can perform tasks more quickly, reflecting their confidence in their abilities (Sitzmann, Ely, Brown, &

Bauer, 2010). Artino (2012) found that perceived efficiency in task completion is often linked to higher perceived learning outcomes.

Given these intricate relationships, we hypothesize the following:

H10a: Participants' perceived learning outcome is positively associated with their actual task performance.

H10b: Participants' perceived learning outcome is positively associated with their perceived task performance.

H10c: Participants' perceived learning outcome is negatively associated with their task time.

H10d: Participants' perceived learning outcome is negatively associated with their perceived task time.

In summary, the hypotheses discussed in this chapter are visually represented in the research model illustrated in Figure 5 above. This model encapsulates the constructs and relationships central to our investigation of the effects of visual factors while using smartphone AR in informal learning settings. The subsequent chapter will delve into the experimental design and methodologies employed to test these hypotheses, providing a comprehensive overview of the procedures and analytical techniques utilized in this research.

Chapter 4
Experimental Design and Methods

4.1. Introduction

In this chapter, we present a detailed account of the methodological framework utilized in our study, which aimed to investigate the impact of screen and ambient luminance on various factors, including visual discomfort, legibility, affective state, task performance, intention to revisit, hedonic motivation, and perceived learning outcome while interacting with smartphone AR in Informal Institutional Learning Places (IILPs) within the real-world setting of an insectarium, which is a form of a science museum. We employed a two-factor within-subject experimental design to systematically manipulate the screen and ambient luminance and observe their effects on various aspects of the visitors' experience. This chapter provides insights into the sample characteristics, experimental design, materials and measures, augmented reality (AR) stimuli, experimental setup, and statistical analysis techniques employed. By offering a thorough explanation of our methodology, we ensure the transparency and reproducibility of our study, thereby contributing to the validation of our findings.

4.2. Sample

Twenty-eight healthy participants (twelve females; sixteen males; zero non-binaries), aged between 18 to 45 years (M = 23.67 years, SD = 3.43) were recruited for this study. Participants were drawn from the general population through various recruitment channels, including word-of-mouth, social media, and Panelfox, the university student participant panel. Inclusion criteria stipulated that participants must be at least 18 years old, possess normal or corrected-to-normal vision, and have proficiency in the French language, as the official language and primary demographic of the region is French-speaking, and hence, the experiment was designed in French to cater to the majority. Exclusion criteria included a history of neurological or psychiatric disorders, facial paralysis, or refusal to provide informed written consent. The study was conducted at an insectarium, a type of science museum in a major North American city, with each experimental session lasting approximately 50 minutes. All participants provided written informed consent and received $50 as compensation for their participation. Ethical approval was obtained from the institution's Research Ethics Board (Project #: 2023-5269), and participants were informed of their right to withdraw from the experiment at any time while retaining their compensation.

4.3. Experimental Design

A two-factor within-subject experimental design was employed to manipulate Screen Luminance and Ambient Luminance, resulting in a 2 x 2 design (Low Screen Luminance vs. High Screen Luminance; Low Ambient Luminance vs. High Ambient Luminance). Each participant was randomly exposed to all four conditions to control for order effects.

Each of the four experimental blocks involved the participants interacting with two augmented reality (AR) stimuli sequentially. After interacting with an AR stimulus for a maximum of 5 minutes, they were presented with eight quiz questions, during which they could still interact with the AR stimuli. Each block consisted of two such AR stimuli and quizzes. At the end of each block, participants completed a post-task survey to provide feedback on their experience. After completing the survey, there was a 1-minute rest period during which participants were instructed to keep their eyes closed to mitigate any potential carryover effects of visual discomfort or fatigue before proceeding to the following experimental block. The duration of 5 minutes per stimulus and the 1-minute rest intervals were determined through rigorous pre-testing to ensure feasibility while minimizing carryover effects.

The experiments were conducted in an insectarium that remained open to visitors, which imposed limitations on the manipulation of ambient lighting conditions. Direct control over the lighting was not possible due to restrictions set by the insectarium authorities. Instead, two distinct areas within the insectarium with relatively darker and brighter ambient lighting were identified, and their luminance levels were measured. This decision also helped maintain the naturalistic conditions for the participants within the insectarium.

Screen luminance was manually adjusted to low (20%) and high (100%), with the auto-brightness feature disabled to ensure consistent and accurate luminance settings. These levels were selected to represent typical variations in smartphone screen brightness encountered during everyday use. The luminance values of the smartphone screen were measured to confirm the settings. This manual adjustment ensured that the screen luminance conditions were reliably maintained across the experimental blocks for all participants.

4.4. Experimental Blocks

Table 2 provided below summarizes the screen luminance and ambient luminance conditions and measured luminance values for each experimental block.

Table 2: Experimental Blocks and Conditions

Block	**Screen luminance condition**	**Ambient luminance condition**	**Ratio value (Screen luminance / Ambient luminance)**
1.	Low Brightness set: 20% Observed value: 4.33lx (1.38 cd/m2)	High Observed value: 132.07lx (42.06 cd/m2)	0.03
2.	High Brightness set: 100% Observed value: 146.9lx (46.78 cd/m2)	High Observed value: 132.07lx (42.06 cd/m2)	1.11
3.	Low	Low	0.23

	Brightness set: 20% Observed value: 1.95lx (0.62 cd/m2)	Observed value: 8.58lx (2.73 cd/m2)	
4.	High Brightness set: 100% Observed value: 68.9lx (21.94 cd/m2)	Low Observed value: 8.58lx (2.73 cd/m2	8.03

4.5. Materials and Measures

The study employed an exclusively psychometric approach due to technological and logistical constraints in an out-of-lab experimental setting of an insectarium. Consequently, the hardware consisted of a smartphone, an AR marker (printed QR code on a tripod stand), and an iPad tablet. The QR code size was standardized at 10x10 cm, adhering to industry standards for AR markers, and the tripod stand's height was adjustable between 5 and 6 feet to accommodate variations in participants' heights. The software comprised an AR application, quizzes based on displayed content, and questionnaires. While the AR application and questionnaires were delivered in English, the briefing, instructions, and interviews were conducted in French to accommodate the majority of the participants.

All surveys were administered in French using the Qualtrics experience management (XM) online software and were deployed on an iPad tablet's browser web page. The study comprised a pre-experiment survey, quiz questions for each block, and a post-task survey after each block.

The pre-experiment survey assessed participants' basic demographics (i.e., age, gender, education level, occupation, marital status, nationality, ethnicity) and their suitability for the experiment (e.g., vision, allergies). During the experiments, participants answered eight quiz questions for each AR stimulus presented, totaling 2 AR stimuli per block. After completing each block, participants answered a short survey to assess various constructs, including visual discomfort, perceived learning outcome, affective state, hedonic motivation, legibility, intention to revisit, perceived task performance, and perceived task time. This post-block survey was completed four times, once after each condition block.

Table 3 outlines the various constructs assessed during the experiment, their respective assessment methods, and timing of administration. The Questionnaire items are translated to English for the thesis. The original Assessment items are presented in French and provided in Appendix B.

Table 3: Assessment of Constructs

Construct	**Assessment**	**Questionnaire items**	**Timing**
Visual Discomfort	7-point Likert scale with self-report items from the Visual Fatigue Subjective Assessment Scale (Heuer et al., 1989)	Based on the tasks you have just completed, please assess your level of visual discomfort: 1. I have trouble seeing (Totally agree / Totally disagree) 2. I feel an unusual sensation around my eyes. (Totally agree / Totally disagree) 3. I experience eye fatigue. (Totally agree / Totally disagree) 4. I'm feeling numb. (Totally agree / Totally disagree)	end of each block

		5. I have a headache. (Totally agree / Totally disagree) 6. I feel dizzy looking at the screen. (Totally agree / Totally disagree)	
Legibility	6 bipolar items from Yu and Akita assessed on a 9 point scale.	1. The phone screen is (Hard to see/Easy to see) 2. The text is (Difficult to read / Easy to read) 3. It's easy to (lose focus / Stay focused) 4. There were reflections on the screen (Totally disagree / Totally agree) 5. The phone screen is (Dark / Bright) The lighting in the room is (Dark / Bright)	end of each block
Annoyance	100-point Annoyance scale by Pawlaczyk-Łuszczyńska et al. (2005)	Move the slider to indicate your level of discomfort when interacting with the augmented reality application. (Scale from Not annoyed to Very annoyed)	end of each block

Enjoyment	Affective slider by Betella & Verschure (2016)	Move the slider to indicate your level of pleasure as you interact with the augmented reality application. The further you move the slider to the right, the greater the intensity of the emotion felt.	end of each block
Task Performance	Actual Task Performance: Accuracy of responses per block (average number of correct answers from 0-8).	Measured / calculated value	during each block
	Perceived Task Performance: Perceived accuracy of responses per block (number of correct answers from 0-8).	Based on the 8 last questions, how many questions do you think you have the right answer to? (0-8)	end of each block
	Perceived Time: Participants' perceived time taken to complete each block (0-100 Slider).	With reference to the previous 2 insects, please rate your perception of the time elapsed during the tasks. (Very slow – Very fast)	end of each block
	Task Time: Average time taken to complete a quiz consisting of 8	Measured / calculated value	during each block

	questions per block (in seconds).		
Intention to Revisit	7-point Likert scale with self-report items on selected questions from Bonn et al.,	Please indicate to what extent you agree with the following statements: 1. I will visit this establishment again. (Very Unlikely – Very likely) 2. If I had the chance, I would choose to return to this establishment. (Very Unlikely – Very likely)	end of the first block
Hedonic Motivation	7-point Likert scale with self-report items on selected questions from the Hedonic Motivation questionnaire by Shen et al.	Based on your experience with Augmented Reality (AR), please assess your preferences. 1. Using the AR application is fun. (Not at all / Completely) 2. It's great to be able to use the AR application to learn. (Not at all / Completely) 3. Using the AR app to learn is fun. (Not at all / Completely)	end of each block
Perceived Learning Outcome	7-point Likert scale on selected questions from Pallud et al.	Based on your experience with augmented reality (AR), please rate your experience.	end of each block

		1. Using the augmented reality application helped me to identify the main characteristics of the insects. (Not at all / Completely) 2. The augmented reality app helped me better understand insect color, shapes, habitats and prey. (Not at all / Completely) 3. The augmented reality application enabled me to deepen my knowledge of insects. (Not at all / Completely)	

4.5.1. Operationalization of Measures

Some of the constructs needed operationalization in order to align with the research model. They were calculated as described below.

Luminance Ratio: The luminance ratio acts as a simplified construct that captures the interaction between the surface luminance of a smartphone display and the ambient lighting conditions, represented by ambient luminance. It is operationalized using the following formula:

Luminance Ratio = Screen Luminance / Ambient Luminance

Affective state: Affective state refers to the experience of feeling or emotion. A lower affective state indicates negative sentimental conditions and higher otherwise. In this study, two different constructs, Enjoyment and Annoyance were measured, and the Affective state was derived using the formula:

Affective State (Aff State) = (Enjoyment + 101 - Annoyance)/2

Task Performance: The construct Task performance represents the four constructs, Actual Task Performance, Perceived Task Performance, Task Time and Perceived Task Time. Since they refer to different aspects of their actual and perceived performance in the learning activity, they are grouped together in a single construct. However, the four constructs are hypothesized and tested individually.

4.6. AR Stimuli

The AR stimuli (Figure 6) was developed for this experiment by the author using Unity Game Engine Software (Version 2021.3.20f1) and was presented to participants on an Android smartphone (Google Pixel 7). A marker-based approach was utilized, whereby scanning a corresponding QR code triggered the display of a 3D model and a textual description of an insect below it in French. A total of 16 QR codes were integrated into the application. The production environment of the AR stimuli is visualized in Appendix C.

The acquired 3D models were meticulously crafted true-to-life representations of real insects developed using the Photogrammetry technique by Yuichi Kano (2022). Given that the experiment was conducted at an insectarium, the selection of insects aimed to maintain a natural visitor experience within the experimental setting.

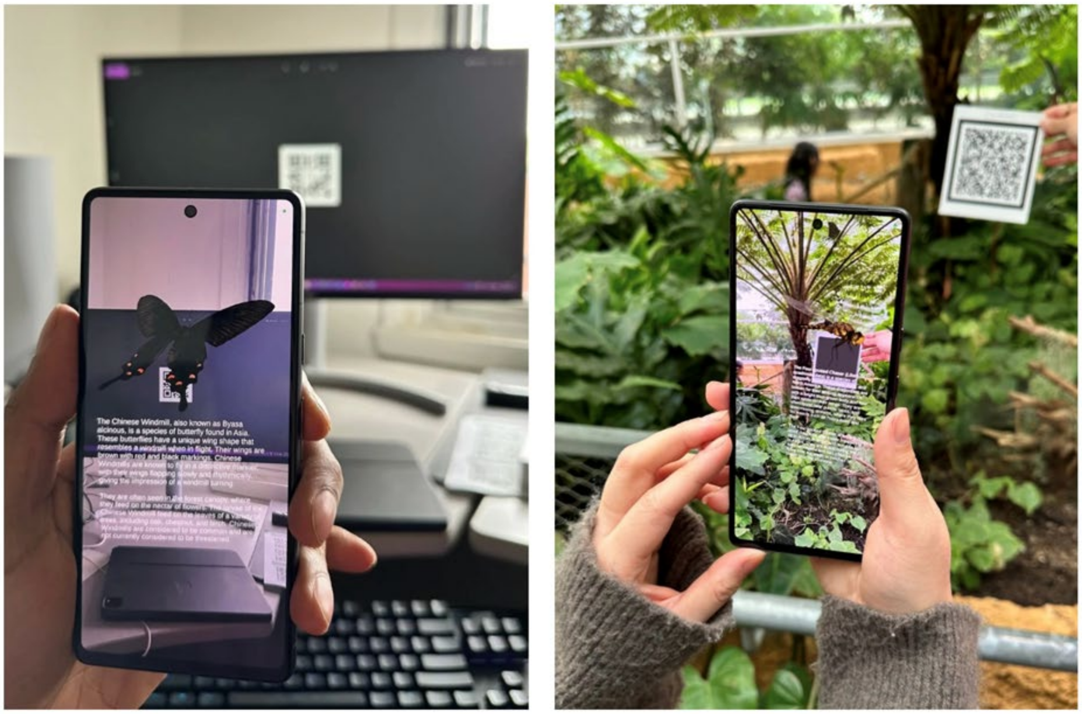

Figure 6: The AR stimuli

The dimensions of the QR code were standardized at 10 cm x 10 cm, aligning with industry standards for AR markers, particularly considering the low light conditions prevalent in the environment. Participants were encouraged to move around freely but were expected to maintain a distance of approximately 1-2 meters from the QR code. The QR codes were placed on a tripod stand and its height was adjustable to accommodate the different heights of the participants.

Upon scanning, the 3D models and accompanying texts were positioned 1 meter away from the screen in 3D space, with their sizes adjusted accordingly to ensure easy visibility from the given distance. These adjustments were verified through multiple pre-tests to optimize the viewing experience, accounting for factors such as screen size and participant proximity.

4.7. Experimental Setup and Procedure

4.7.1. Setup

The experiments took place in an Insectarium, open to regular visitors during the experiments. However, the participants had access to a private room for initial briefing, final debriefing and signing the forms. Two predetermined locations, one relatively dark and one relatively bright were selected inside the insectarium as shown in Figure 7.

Figure 7: Location with bright ambient luminance (Left) and dark ambient luminance (Right)

4.7.2. Lighting Pre-tests

Prior to the main study, we conducted lighting pretests to precisely measure the luminance of both the mobile AR device display and the surrounding environment at designated locations within the IILP. Using a (URCERI MT-912) light meter (Figure 8), we captured display surface luminance by fixing the mobile phone to a tripod with the AR application activated (Figure 9) and taking five measurements: one at each corner of the screen and one at the center, with the light meter held 1 cm in front of the screen. To measure ambient luminance or the luminance of the surface the mobile device was directly facing, we took four readings with the light meter touching each corner of the phone screen but remaining outside the device's bounds to avoid interference, as illustrated in Figure 10. The light meter was pointed in the same direction as the mobile device to capture the luminance of the target surface. As the light meter provided measurements in the units for illuminance (lux) rather than for luminance (nits or cd/m2), we converted the lux values to nits by dividing them by π (pi), assuming an even diffusion of light across the surfaces for the sake of simplicity. This conversion factor accounts for the geometric difference between spherical and flat surface area measurements used for luminance and illuminance, respectively (Friedman, 2024; DisplayCAL, 2023). These pretests and the subsequent conversion allowed us to calculate the luminance ratio between the AR device display and the surrounding environment at each designated location.

Figure 8: Light meter used for luminance measurements

Figure 9: Setup for luminance measurements

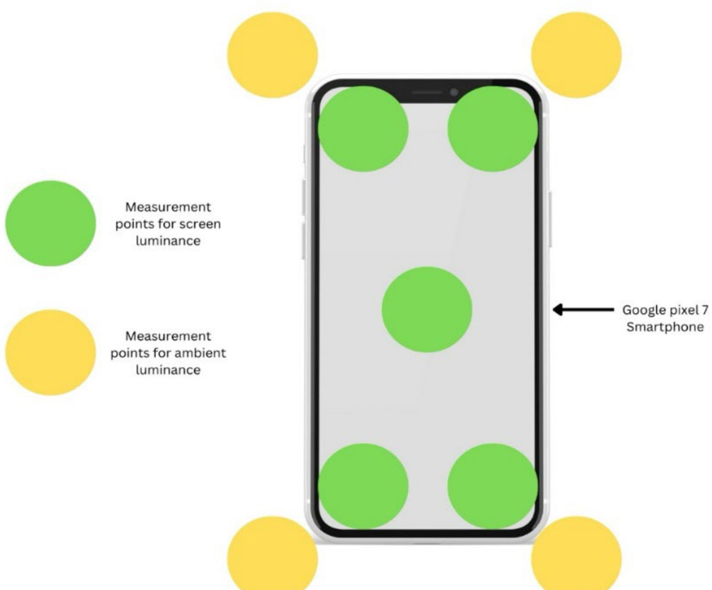

Figure 10: Measurement points for screen and ambient luminance

4.7.3. Procedure

After arriving and completing the initial briefing and signing the consent form in a private room, the participants were accompanied by a research assistant to the insectarium and tasked with positioning themselves at predetermined locations for each block, determined based on the ambient luminance present there. Here, they were provided with a smartphone and asked to scan a QR code held on a tripod placed there. Scanning the QR code activated the display of a 3D model of an insect, accompanied by a brief description. Participants were allowed to select their viewing angle and position for comfort and were free to move as needed throughout the experiment to maintain naturalistic conditions.

After the maximum allowed 5 minutes to interact with the 3D model and read the accompanying text per insect or upon indicating readiness, participants were presented with a set of 8 quiz questions related to the observed insect on an iPad tablet. The participants could still look at the 3D model and textual description while answering the quiz. Two insects and corresponding quizzes were presented per block, with the order of the blocks and the QR codes presented randomized, as shown in Table 4. to minimize biases. Following each block, participants completed a brief survey on the iPad tablet before closing their eyes and resting for one minute in preparation to move to the subsequent block. The smartphone brightness was changed during this time to adjust its luminance condition for the following block. After completing all four experimental blocks and accompanying surveys, the participants moved to the private room where they were debriefed about the experiment and their experience and provided with the compensation form to read and sign carefully. Once finished, they were escorted back to the exit and their compensation was electronically transferred within a week. The complete experimental procedure is illustrated in Figure 11.

Table 4: Block and QR code randomization sequence

Participant id	Block id	Block sequence	QR code sequence
1	A	1234	3 7 / 5 2 / 8 1 / 6 4
2	B	2134	4 2 / 7 6 / 1 3 / 8 5

3	C	1243	6 1 / 8 4 / 2 7 / 3 5
4	D	2143	5 8 / 1 3 / 7 2 / 4 6
5	E	3412	2 5 / 6 8 / 1 4 / 7 3
6	F	4312	7 3 / 4 5 / 6 1 / 2 8
7	G	3421	1 6 / 2 7 / 4 5 / 8 3
8	H	4321	8 4 / 3 1 / 5 6 / 2 7
9	I	1234	6 7 / 1 8 / 3 2 / 4 5
10	J	2134	3 5 / 4 1 / 7 6 / 2 8
11	K	1243	2 8 / 6 3 / 5 7 / 4 1
12	L	2143	4 3 / 5 7 / 8 2 / 1 6
13	M	3412	7 1 / 8 6 / 4 3 / 5 2
14	N	4312	5 2 / 7 4 / 6 8 / 3 1
15	O	4321	1 4 / 2 5 / 3 8 / 6 7
16	P	3421	8 6 / 3 2 / 1 5 / 7 4
17	Q	1234	4 7 / 1 8 / 6 2 / 3 5
18	R	2134	3 8 / 6 1 / 5 7 / 2 4
19	S	1243	6 2 / 4 3 / 7 5 / 1 8
20	T	2143	2 1 / 8 5 / 7 4 / 6 3
21	U	3412	7 4 / 5 6 / 2 1 / 8 3
22	V	4312	1 3 / 7 2 / 4 6 / 8 5
23	W	3421	5 6 / 3 4 / 8 1 / 7 2
24	X	4321	8 5 / 2 7 / 3 6 / 1 4

25	Y	1234	2 6 / 8 3 / 1 4 / 7 5
26	Z	2134	8 1 / 4 5 / 3 7 / 6 2
27	AA	1243	5 7 / 3 8 / 1 4 / 2 6
28	AB	2143	7 4 / 8 2 / 6 5 / 3 1
29	AC	3412	1 2 / 3 4 / 5 6 / 7 8

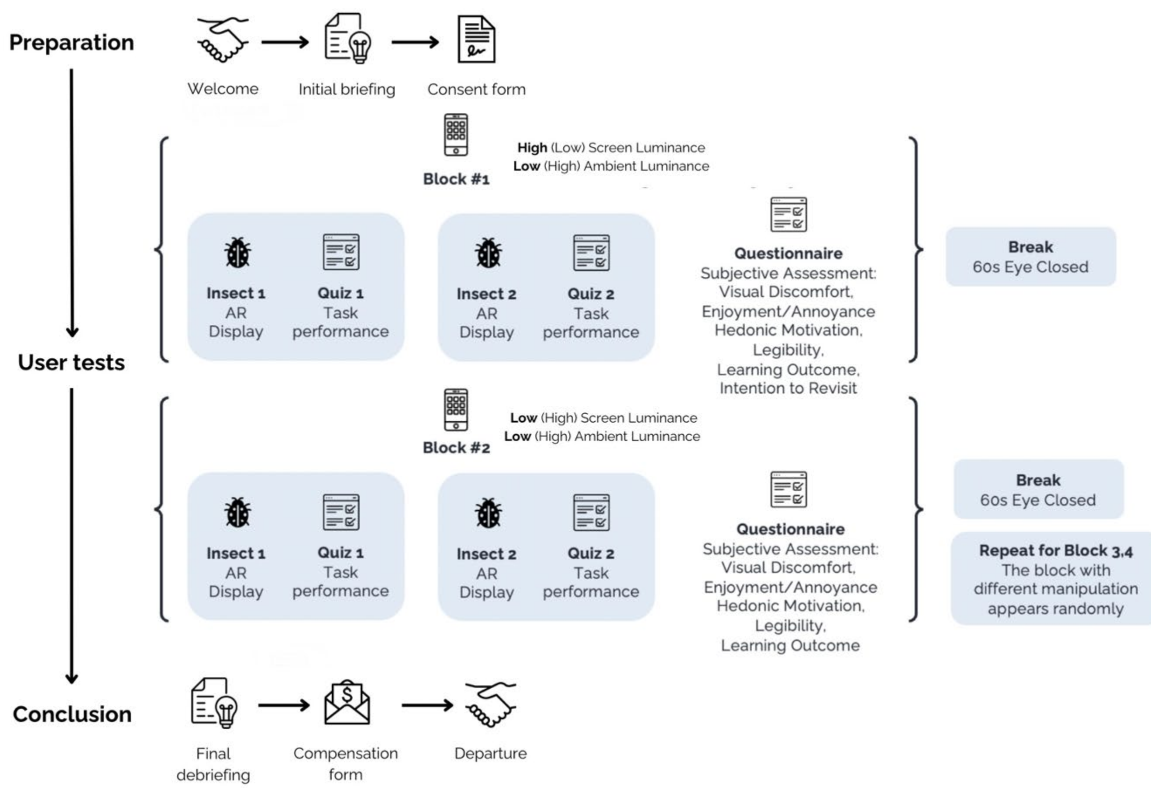

Figure 11: Experimental Procedure

4.7.4. Statistical Analysis

Statistical analyses were conducted using SAS OnDemand for Academics (SAS Institute Inc., Cary, NC, USA), a comprehensive online statistical software suite. Psychometric data collected through Qualtrics were meticulously exported and organized in Microsoft Excel for initial aggregation and reordering. This preprocessing ensured the data were correctly formatted and ready for subsequent analysis in SAS.

Given the nature of our data, several preprocessing steps were necessary. Data were exported from Qualtrics and imported into Excel, where they were cleaned and aggregated. This step involved checking for and handling missing values and outliers and ensuring the consistency and accuracy of the data entries. A Binary Median Split transformation was applied for heavily skewed data, particularly those measuring visual discomfort, affective state, and specific aspects of task performance. This transformation converted continuous variables into binary categorical variables based on the median value, allowing for more robust analysis through logistic regression.

Two primary statistical models were employed to analyze the data, each chosen based on the distribution and nature of the dependent variables. The logistic regression with random intercept model was applied to datasets where the dependent variables were binary due to the Binary Median Split transformation. This model assessed the impact of various independent variables on the likelihood of a particular outcome. The random intercept component accounted for potential variability between subjects that could influence the dependent variable, thus providing more accurate and generalizable results. The threshold for statistical significance was set at $p < 0.05$.

The linear regression with random intercept model was used for datasets with continuous and normally distributed dependent variables. This model evaluated the relationship between independent variables and the dependent continuous outcomes. The random intercept allowed for subject-level variations, enhancing the model's robustness in handling repeated measures or clustered data. As with logistic regression, the threshold for significance was $p < 0.05$.

The alpha level for determining statistical significance was set at 0.05, meaning that results with p-values less than 0.05 were considered statistically significant, indicating a less than 5% probability that the observed effects were due to chance. For both logistic and linear regression models, the significance of predictors was assessed by examining the p-values associated with each predictor variable. Significant predictors were those with p-values below the 0.05 threshold, suggesting a meaningful relationship between the predictor and the dependent variable.

Chapter 5
Results

5.1. Introduction

This chapter presents the results of the study, starting with the descriptive statistics and correlation analysis followed by hypothesis testing. Each section details the analysis performed, the statistical methods used, and the outcomes in relation to the proposed hypotheses, with a detailed examination of whether each hypothesis was supported or rejected.

5.2. Descriptive Statistics and Correlation analysis

5.2.1. Descriptive Statistics

The study examined various variables across four experimental conditions, manipulating screen luminance and ambient luminance. Across these conditions, several key variables were measured, including Visual Discomfort, Legibility, Affective state, Actual Task Performance, Perceived Task Performance, Task Time, Perceived Time, Intention to revisit, Hedonic Motivation, and Perceived Learning Outcome. The descriptive statistics are presented in Table 5.

Table 5: Descriptive Statistics

N Obs	Variable	Label	N	Mean	Std Dev	Minimum	Maximum
100	VD	Visual Discomfort	97	1.77	0.87	1.00	4.00
	Legi	Legibility	97	4.30	0.88	2.25	6.00
	Aff	Affective state	85	75.90	18.41	26.50	98.00
	Perform	Actual Task Performance	97	7.31	0.86	4.00	8.00
	pPerform	Perceived Task Performance	97	6.90	1.06	4.00	8.00
	Time	Task time	97	7.57	2.41	3.03	16.11
	pTime	Perceived Time	85	63.64	17.85	19.00	100.00
	int_revisit	Intention to revisit	24	5.27	1.69	1.50	7.00
	HM	Hedonic Motivation	97	4.97	1.44	1.33	7.00
	PLO	Perceived Learning Outcome	85	4.83	1.70	1.00	7.00

Block	N Obs	Variable	Label	N	Mean	Std Dev	Minimum	Maximum
1	25	VD	Visual Discomfort	24	1.92	0.97	1.00	3.83
		Legi	Legibility	24	4.07	1.08	2.25	6.00
		Aff	Affective state	21	73.98	19.35	29.50	97.50
		Perform	Actual Task Performance	24	7.08	0.72	6.00	8.00
		pPerform	Perceived Task Performance	24	6.75	1.22	4.00	8.00
		Time	Task time	24	7.89	2.78	3.44	16.11
		pTime	Perceived Time	21	62.33	18.35	23.00	97.00
		int_revisit	Intention to revisit	6	5.17	1.94	2.00	7.00
		HM	Hedonic Motivation	24	4.79	1.50	1.33	6.67
		PLO	Perceived Learning Outcome	21	4.59	1.71	1.00	7.00
2	25	VD	Visual Discomfort	24	1.75	0.85	1.00	3.67
		Legi	Legibility	24	4.20	0.83	2.50	5.25
		Aff	Affective state	21	73.02	19.46	26.50	98.00
		Perform	Actual Task Performance	24	7.29	1.00	5.00	8.00
		pPerform	Perceived Task Performance	24	6.83	1.13	5.00	8.00
		Time	Task time	24	8.08	2.07	5.05	12.63
		pTime	Perceived Time	21	59.67	19.74	19.00	98.00
		int_revisit	Intention to revisit	8	5.50	0.85	4.50	7.00
		HM	Hedonic Motivation	24	4.94	1.43	1.33	6.67
		PLO	Perceived Learning Outcome	21	4.67	1.74	1.00	7.00
3	25	VD	Visual Discomfort	24	1.60	0.75	1.00	3.67
		Legi	Legibility	24	4.40	0.83	3.00	5.50
		Aff	Affective state	21	79.74	16.19	34.00	98.00
		Perform	Actual Task Performance	24	7.54	0.59	6.00	8.00
		pPerform	Perceived Task Performance	24	6.96	1.00	5.00	8.00
		Time	Task time	24	7.49	2.45	3.64	11.78
		pTime	Perceived Time	21	65.81	18.50	34.00	100.00
		int_revisit	Intention to revisit	6	4.92	2.67	1.50	7.00
		HM	Hedonic Motivation	24	5.06	1.41	2.00	7.00
		PLO	Perceived Learning Outcome	21	5.19	1.55	1.33	7.00
4	25	VD	Visual Discomfort	25	1.79	0.94	1.00	4.00
		Legi	Legibility	25	4.54	0.73	3.25	5.50
		Aff	Affective state	22	76.82	19.00	27.50	97.50
		Perform	Actual Task Performance	25	7.32	1.03	4.00	8.00
		pPerform	Perceived Task Performance	25	7.04	0.89	5.00	8.00
		Time	Task time	25	6.85	2.24	3.03	14.18
		pTime	Perceived Time	22	66.59	14.99	36.00	100.00
		int_revisit	Intention to revisit	4	5.50	1.29	4.00	7.00
		HM	Hedonic Motivation	25	5.07	1.49	2.00	7.00
		PLO	Perceived Learning Outcome	22	4.88	1.84	1.00	7.00

Visual discomfort showed relatively consistent means across conditions, ranging from 1.60 to 1.92, suggesting generally low levels of visual discomfort. The standard deviations

(0.75 to 0.97) indicate moderate variability in responses. Notably, the highest mean VD (1.92) was observed in block 1 (high ambient luminance, low screen luminance), while the lowest mean visual discomfort (1.60) was observed in block 3 (low ambient luminance, low screen luminance).

Legibility, however, varied a bit more noticeably, with means ranging from 4.07 to 4.54 (SD = 0.73 to 1.08), indicating that participants generally found the text legible, with the highest mean legibility (4.54) reported in block 4 (high screen luminance, low ambient luminance) and lowest (4.07) reported in block 1 (low screen luminance, high ambient luminance).

The Affective state, calculated from the Enjoyment and Annoyance measures and measured on a 100-point scale, showed generally high mean values across conditions, ranging from 73.02 to 79.74. However, there was considerable variability in responses (SD = 16.19 to 19.46). The highest mean Affective state (79.74) was observed in Block 3 (Low screen luminance, low ambient luminance), while the lowest (73.02) was in Block 2 (High screen, high ambient luminance condition.

Perceived Task Performance demonstrated high mean values across all conditions (6.75 to 7.04 on an 8-point scale), indicating participants generally felt they performed well. Actual Task Performance, also on an 8-point scale, showed consistently high mean values (7.08 to 7.54) across conditions, aligning with participants' perceptions and indicating that participants generally performed well on the assigned tasks regardless of the block.

Actual time spent on tasks varied across conditions, with mean values ranging from 6.85 minutes for block 4 (high screen luminance, low ambient luminance)to 8.08 minutes for block 2 (high screen luminance, high ambient luminance). The standard deviations (2.07 to 2.78) indicate substantial variability in task completion times among participants. A similar trend was observed for Perceived Time, measured on a 100-point scale. Mean values ranged from 59.67 to 66.59, with high variability (SD = 14.99 to 19.74).

Intention to revisit, Hedonic Motivation, and Perceived Learning Outcome showed less dramatic variations across conditions.

Intention to revisit, measured on a 7-point scale, had its' mean values ranging from 4.92 for block 3 (low screen luminance, low ambient luminance) to 5.50 for block 4 (high screen luminance, low ambient luminance) with moderate variability (SD = 1.52 to 1.72)

Hedonic Motivation, also measured on a 7-point scale, showed consistent mean values across conditions, ranging from 4.79 to 5.07 (SD = 1.41 to 1.50). This suggests generally positive levels of motivation among participants.

Perceived Learning Outcome also demonstrated consistent mean values across conditions (4.59 to 5.19 on a 7-point scale), with standard deviations between 1.55 and 1.84. This indicates that participants generally perceived moderate to high learning outcomes, with some variability in responses.

5.2.2. Correlation Analysis

Upon analyzing the correlation table presented in Table 6, several significant relationships emerge among the variables.

Table 6: Correlation Analysis

Pearson Correlation Coefficients
Prob > |r| under H0: Rho=0
Number of Observations

	VD	Legi	Aff	Perform	pPerform	Time	pTime	int_revisit	HM	PLO
VD **Visual Discomfort**	1.00000 97	-0.42418 <.0001 97	-0.40356 0.0001 85	-0.11781 0.2504 97	-0.28777 0.0043 97	0.10677 0.2979 97	0.18556 0.0891 85	0.14298 0.5051 24	-0.30030 0.0028 97	-0.23352 0.0315 85
Legi **Legibility**	-0.42418 <.0001 97	1.00000 97	0.37410 0.0004 85	0.05012 0.6259 97	0.37411 0.0002 97	0.02618 0.7991 97	0.11832 0.2808 85	-0.21475 0.3136 24	0.17254 0.0910 97	0.16462 0.1322 85
Aff **Affective state**	-0.40356 0.0001 85	0.37410 0.0004 85	1.00000 85	-0.06336 0.5645 85	-0.06821 0.5351 85	-0.10724 0.3286 85	0.35161 0.0010 85	0.22857 0.3190 21	0.75699 <.0001 85	0.69953 <.0001 85
Perform **Actual Task Performance**	-0.11781 0.2504 97	0.05012 0.6259 97	-0.06336 0.5645 85	1.00000 97	0.34598 0.0005 97	-0.22979 0.0236 97	-0.05842 0.5953 85	-0.09797 0.6488 24	-0.07284 0.4783 97	0.01239 0.9104 85
pPerform **Perceived Task Performance**	-0.28777 0.0043 97	0.37411 0.0002 97	-0.06821 0.5351 85	0.34598 0.0005 97	1.00000 97	-0.05484 0.5937 97	0.00916 0.9337 85	-0.21323 0.3171 24	-0.18523 0.0693 97	-0.13994 0.2015 85
Time **Task time**	0.10677 0.2979 97	0.02618 0.7991 97	-0.10724 0.3286 85	-0.22979 0.0236 97	-0.05484 0.5937 97	1.00000 97	-0.30877 0.0040 85	-0.13159 0.5399 24	-0.37901 0.0001 97	-0.17721 0.1047 85
pTime **Perceived Time**	0.18556 0.0891 85	0.11832 0.2808 85	0.35161 0.0010 85	-0.05842 0.5953 85	0.00916 0.9337 85	-0.30877 0.0040 85	1.00000 85	-0.11146 0.6305 21	0.30452 0.0046 85	0.42879 <.0001 85
int_revisit **Intention to revisit**	0.14298 0.5051 24	-0.21475 0.3136 24	0.22857 0.3190 21	-0.09797 0.6488 24	-0.21323 0.3171 24	-0.13159 0.5399 24	-0.11146 0.6305 21	1.00000 24	0.25590 0.2275 24	0.12838 0.5792 21
HM **Hedonic Motivation**	-0.30030 0.0028 97	0.17254 0.0910 97	0.75699 <.0001 85	-0.07284 0.4783 97	-0.18523 0.0693 97	-0.37901 0.0001 97	0.30452 0.0046 85	0.25590 0.2275 24	1.00000 97	0.78926 <.0001 85
PLO **Perceived Learning Outcome**	-0.23352 0.0315 85	0.16462 0.1322 85	0.69953 <.0001 85	0.01239 0.9104 85	-0.13994 0.2015 85	-0.17721 0.1047 85	0.42879 <.0001 85	0.12838 0.5792 21	0.78926 <.0001 85	1.00000 85

Visual Discomfort (VD) shows significant negative correlations with several variables. There is a moderate negative correlation with legibility ($r = -0.42418$, $p < .0001$), suggesting that as visual discomfort increases, perceived legibility decreases. VD also negatively correlates with Affective state ($r = -0.40356$, $p = .0001$), indicating that higher visual discomfort is associated with less positive affect. Interestingly, VD has a weak but significant negative correlation with Perceived Task Performance ($r = -0.28777$, $p = .0043$), implying that visual discomfort may slightly impact users' perception of their performance.

Legibility demonstrates positive correlations with several variables. It has a moderate positive correlation with Affective state ($r = 0.37410$, $p = .0004$) and Perceived Task

Performance ($r = 0.37411$, $p = .0002$). This suggests that better legibility is associated with more positive affect and higher perceived performance, which aligns with expectations about the importance of readable text.

Affective state shows strong positive correlations with Hedonic Motivation ($r = 0.75699$, $p < .0001$) and Perceived Learning Outcome ($r = 0.69953$, $p < .0001$). These relationships highlight the importance of positive emotional states in enhancing motivation and perceived learning.

Actual Task Performance has a moderate positive correlation with Perceived Task Performance ($r = 0.34598$, $p = .0005$), indicating some alignment between actual and perceived performance. However, the correlation is not as strong as expected, suggesting that other factors influence users' perceptions of their performance.

Perceived time shows a moderate positive correlation with Perceived Learning Outcome ($r = 0.42879$, $p < .0001$), suggesting that participants who perceived spending more time on tasks also reported higher learning outcomes. This could indicate that engagement with the task, as reflected in the perceived time spent, may contribute to a sense of accomplishment or learning. However, Actual Task time had a moderate negative correlation with Hedonic Motivation ($r = -0.37901$, $p = 0.0001$) and a weak negative correlation with Actual Task Performance ($r = -0.22979$, $p = .0236$).

Hedonic Motivation demonstrates strong positive correlations with both Affective state ($r = 0.75699$, $p < .0001$) and Perceived Learning Outcome ($r = 0.78926$, $p < .0001$). These relationships underscore the interconnected nature of enjoyment, motivation, and perceived learning, highlighting the potential benefits of creating engaging and enjoyable learning environments.

Intention to revisit shows relatively weak correlations with most variables, with the strongest being a positive correlation with Affective state ($r = 0.22857$, $p = .3190$). However, this correlation is not statistically significant at the $p < .05$ level.

5.3. Hypothesis Testing

In this section, we present the results of our hypothesis testing. The data analysis involved various statistical methods tailored to the nature and distribution of our data. Here, we detail the outcomes of our primary hypotheses and respective significance values, regardless of whether the data supported them. The results are summarized in Table 7 and the validated research model with supported hypothesis are illustrated in figure 14.

H1: Luminance ratios will have a significant effect on visual discomfort.

Given the substantial skewness and non-normal distribution of the data points for visual discomfort, a median split was used to categorize the data into a binary distribution. Contrary to our expectations, logistic regression analysis indicated that the luminance ratio did not significantly influence visual discomfort ($F(1, 71) = 1.07$, $p = 0.3036$), leading to the rejection of Hypothesis 1. A pairwise comparison test was also performed, and none of the pairs had any statistically significant difference between them. Nonetheless, a trend was observed suggesting that higher luminance ratios correlate with reports of reduced visual discomfort, although this did not achieve statistical significance. Figure 12 shows the box plot of the distribution of visual discomfort levels for different luminance ratio conditions.

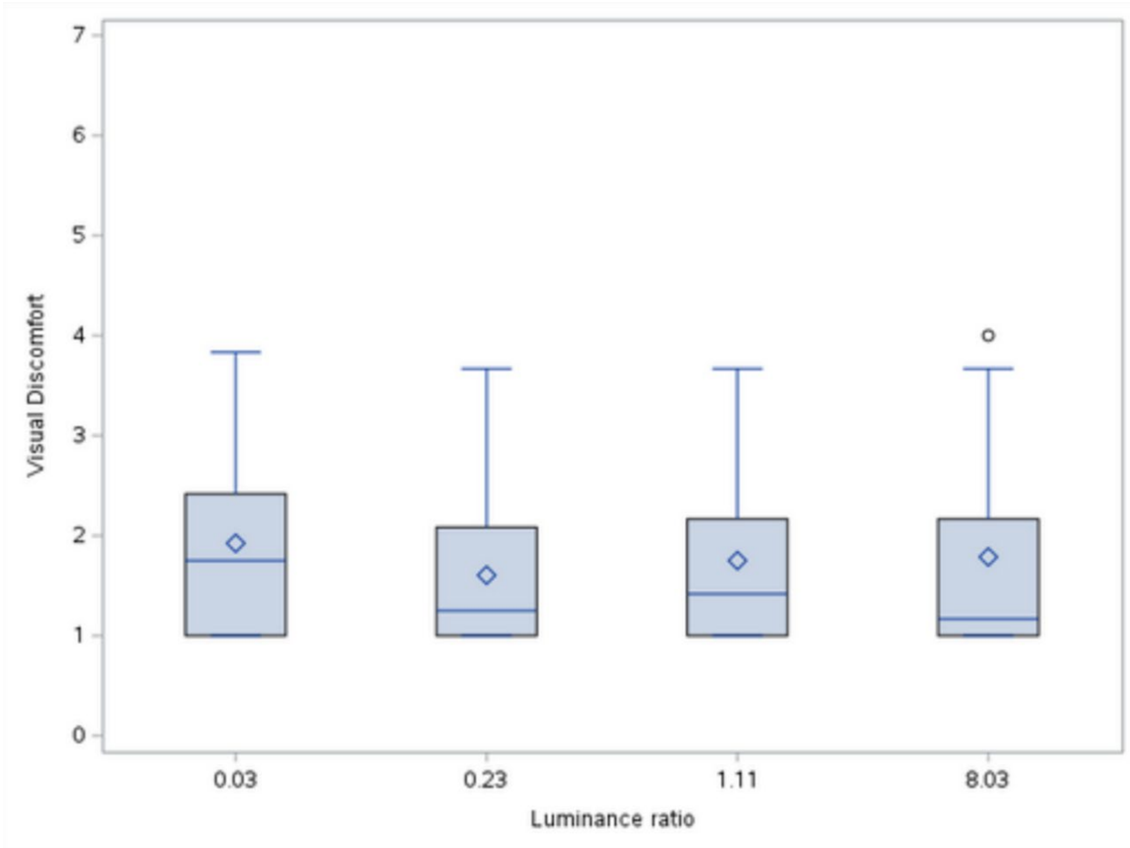

Figure 12: Box plot of Visual discomfort levels for different Luminance ratio conditions

H2: A greater luminance ratio positively affects legibility.

A linear regression model was utilized to assess the impact of luminance ratio on perceived content legibility. The analysis yielded a statistically significant main effect ($F(1, 71) = 5.45$, $p = 0.0224$), indicating that legibility was significantly better under conditions with higher luminance ratios. This finding supports Hypothesis 2 and corroborates existing literature on the subject. A pairwise comparison was also performed, and the only pair with significant statistical difference was between the luminance ratio of 0.03 and 8.03, with an estimate of -0.4508 and a p-value of 0.0395. Figure 13 shows the box plot of the distribution of reported legibility for different luminance ratio conditions.

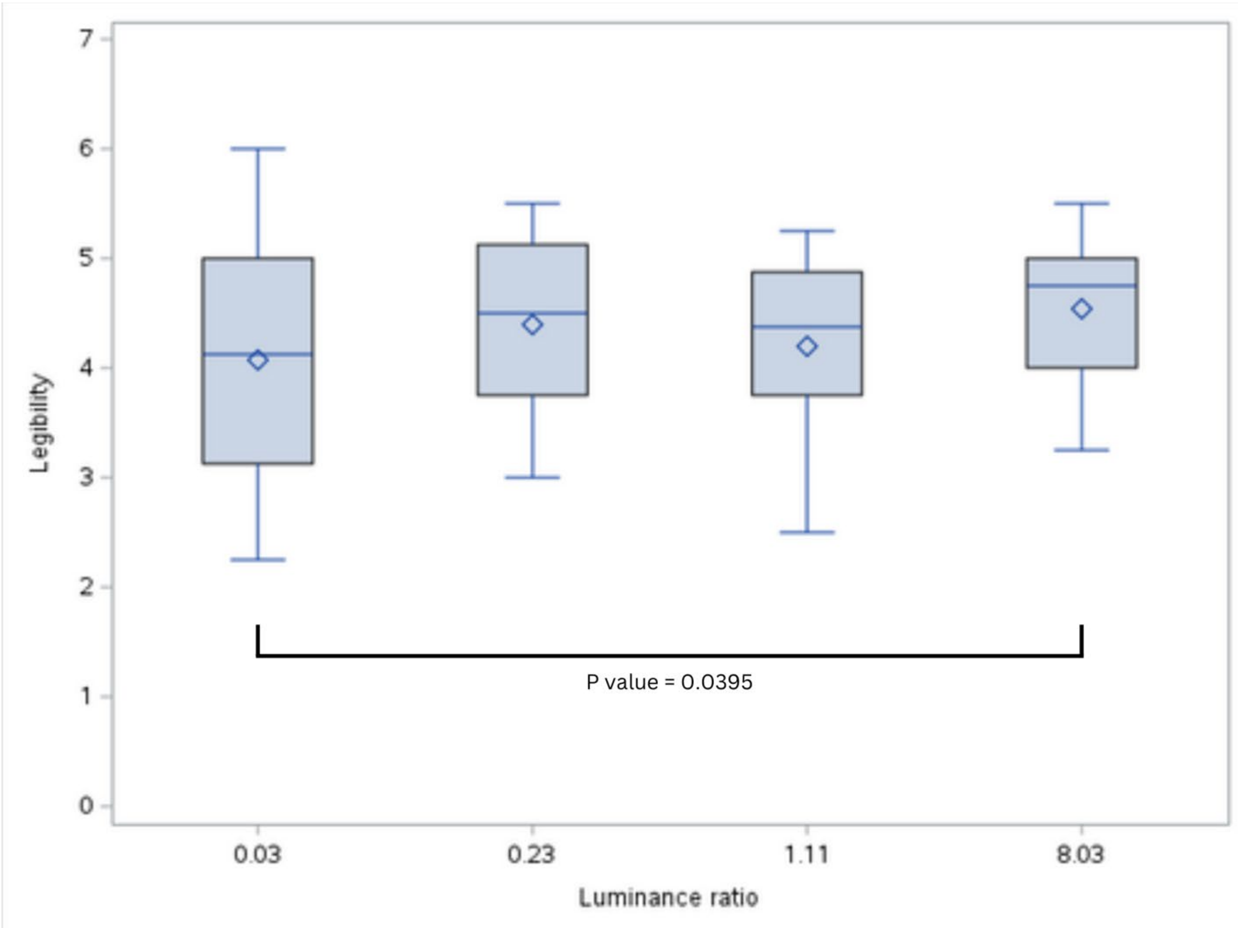

Figure 13: Box plot of Legibility for different Luminance ratio conditions

H3: Visual discomfort is negatively associated with affective state.

H4: Legibility is positively associated with affective state.

Given the skewed data points for affective state, a median split was applied to achieve a binary distribution. The subsequent analysis using a logistic regression model revealed that both visual discomfort ($F(1, 62) = 3.96$, $p = 0.0511$) and legibility ($F(1, 62) = 4.90$, $p = 0.0306$) exerted notable effects on participants' affective states. Specifically, visual discomfort was associated with a negative impact, whereas legibility contributed positively. These findings support Hypotheses 3 and 4.

H5a: Visual discomfort is negatively associated with actual task performance.

H5b: Visual discomfort is negatively associated with perceived task performance.

H5c: Visual discomfort is positively associated with task time.

H5d: Visual discomfort is positively associated with perceived task time.

Task performance encompasses actual task performance, perceived task performance, task time, and perceived task time. While task time and perceived task time followed a normal distribution and were analyzed using a linear regression model, actual and perceived task performance were heavily skewed, necessitating the use of a binary distribution logistic regression model. Contrary to expectations, visual discomfort did not have a significant effect on task performance, leading to the rejection of Hypotheses 5a, 5b, 5c, and 5d.

H6a: Legibility is positively associated with actual task performance.

H6b: Legibility is positively associated with perceived task performance.

H6c: Legibility is negatively associated with task time.

H6d: Legibility is negatively associated with perceived task time.

However, legibility exerted a partial influence on task performance. Specifically, it significantly impacted perceived task performance ($F(1, 71) = 4.17$, $p = 0.0448$) and perceived time ($F(1, 62) = 5.67$, $p = 0.0203$), thereby supporting Hypotheses 6b and 6d, while rejecting Hypotheses 6a and 6c.

H7a: Affective state is positively associated with actual task performance.

H7b: Affective state is positively associated with perceived task performance.

H7c: Affective state is negatively associated with task time.

H7d: Affective state is negatively associated with perceived task time.

Furthermore, affective state exhibited a partial effect on task performance, notably influencing perceived time ($F(1, 62) = 4.99$, $p = 0.0291$). Interestingly, the observed effect contradicted the hypothesized relationship, with participants reporting higher perceived time when experiencing a more positive affective state. Consequently, Hypotheses 7a, 7b, 7c, and 7d were all rejected based on these findings.

H8: Participants' intention to revisit is positively associated with their affective state.

Given the heavily skewed distribution of data points, a binary distribution logistic regression model was employed to analyze the intention to revisit. The analysis revealed no significant effect of affective state on participants' intention to revisit ($F(1, 19) = 1.39$, $p = 0.2529$), thereby rejecting Hypothesis 8.

H9: Participants' hedonic motivation is positively associated with their affective state.

Utilizing a linear regression model, the analysis indicated a significant impact of participants' affective state on their hedonic motivation. Participants reported higher hedonic motivation values when their affective state scores were higher ($F(1, 62) = 6.55$, $p = 0.0129$), providing support for Hypothesis 9.

H10a: Participants' perceived learning outcome is positively associated with their actual task performance.

H10b: Participants' perceived learning outcome is positively associated with their perceived task performance.

H10c: Participants' perceived learning outcome is negatively associated with their task time.

H10d: Participants' perceived learning outcome is negatively associated with their perceived task time.

Due to the heavily skewed distribution of data points, a binary distribution logistic regression model was employed to analyze perceived learning outcome. However, no significant effect of actual task performance, perceived task performance, task time, or perceived task time was observed, leading to the rejection of Hypotheses 10a, 10b, 10c, and 10d.

Table 7: Hypothesis testing results

Hypothesis	**Description**	**Estimate (Path coefficient)**	**T Value**	**P Value**	**Level of significance** * = < 0.05 m.s. = marginally significant (0.05 – 0.1) n.s. = not significant (> 0.1)
H1	Luminance ratios will have a significant effect on visual discomfort.	-0.09074	-1.04	0.3036	n.s.
H2	A greater luminance ratio positively affects legibility.	0.04121	2.33	0.0224	*
H3	Visual discomfort is negatively associated with affective state.	-1.3240	-1.99	0.0511	m.s.
H4	Legibility is positively associated with affective state.	2.6032	2.21	0.0306	*
H5a	Visual discomfort is negatively associated with actual task performance.	-0.3154	-1.28	0.2062	n.s.
H5b	Visual discomfort is negatively associated with perceived task performance.	-0.6254	-1.54	0.1290	n.s.
H5c	Visual discomfort is positively associated with task time.	0.5068	1.43	0.1566	n.s.

H5d	Visual discomfort is positively associated with perceived task time.	0.3121	0.14	0.8926	n.s.
H6a	Legibility is positively associated with actual task performance.	0.1421	0.59	0.5540	n.s.
H6b	Legibility is positively associated with perceived task performance.	0.7489	2.04	0.0448	*
H6c	Legibility is negatively associated with task time.	-0.1579	-0.57	0.5687	n.s.
H6d	Legibility is negatively associated with perceived task time.	3.7063	2.38	0.0203	*
H7a	Affective state is positively associated with actual task performance.	-0.00829	-0.69	0.4899	n.s.
H7b	Affective state is positively associated with perceived task performance.	-0.00077	-0.03	0.9734	n.s.
H7c	Affective state is negatively associated with task time.	-0.01276	-0.64	0.5216	n.s.
H7d	Affective state is negatively associated with perceived task time.	0.2884	2.23	0.0291	*

H8	Participants' intention to revisit is positively associated with their affective state.	0.03197	1.18	0.2529	n.s.
H9	Participants' hedonic motivation is positively associated with their affective state.	0.01759	2.56	0.0129	*
H10a	Participants' perceived learning outcome is positively associated with their actual task performance.	0.3516	0.94	0.3531	n.s.
H10b	Participants' perceived learning outcome is positively associated with their perceived task performance.	0.09868	-0.25	0.8005	n.s.
H10c	Participants' perceived learning outcome is negatively associated with their task time.	-0.1814	-0.97	0.3352	n.s.
H10d	Participants' perceived learning outcome is negatively associated with their perceived task time.	0.02402	0.92	0.3601	n.s.

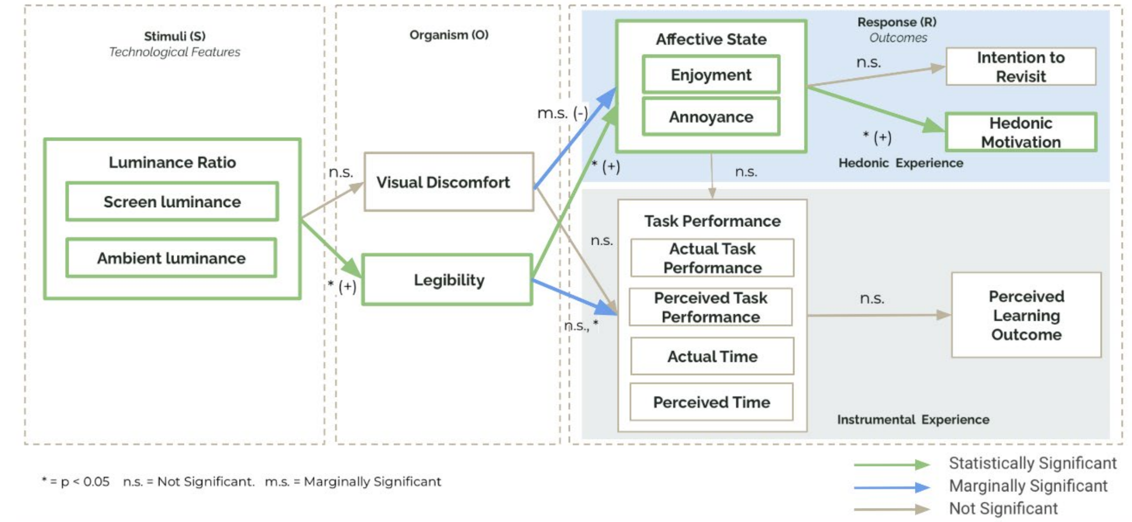

Figure 14: Validated Research model

Chapter 6
Discussion

This study investigated the impact of relatively extreme display and ambient luminance conditions typically found in Institutional Informal Learning Places (IILPs) such as museums and insectariums on visitors' experience with smartphone Augmented Reality (AR) technology. Specifically, we examined how variations in display luminance relative to ambient luminance, referred to as the luminance ratio, influenced the users' perceived visual discomfort and legibility. Consequently, we were also interested in uncovering whether it affected their affective state, actual and perceived learning task performance, and, in turn, their intention to revisit, hedonic motivation and perceived learning outcomes

The theoretical underpinning of this research was that following the SOR framework, the experience of using AR technologies, especially smartphone AR in Institutional Informal Learning Places (IILPs) like museums and science centers may be influenced by the interplay between the display luminance of the device and the ambient luminance where the AR artifacts are presented in such places, called the luminance ratio acting as the stimuli. Any changes within the organism in the form of their perceived visual discomfort or perceived legibility of the presented content due to this ratio would initiate a chain reaction affecting their response in the form of their affective state, in turn influencing their hedonic experience, including their hedonic motivation and intention to revisit, as well as their actual and perceived learning performances and in turn, their perceived learning outcome. To reiterate, the literature review and empirical study aimed to address two research questions.

RQ 1. To what extent do ambient and display luminance affect the visual discomfort/fatigue levels in individuals interacting with smartphone AR in IILPs?

RQ 2. What other factors consequently impact the visitors' interaction with smartphone AR and their overall experience in IILPs?

6.1. Summary of the experimental results

The experimental results provided valuable insights into the effects of luminance ratios on various aspects of user experience with smartphone AR in Institutional Informal Learning Places (IILPs). Contrary to our initial hypothesis (H1), the luminance ratio did not significantly affect visual discomfort. This unexpected result might be due to the short duration of the experimental tasks, which may not have been sufficient to induce noticeable visual discomfort. Additionally, participants' individual tolerance levels for different lighting conditions could have varied, potentially masking the effects of luminance ratios.

In support of Hypothesis 2, the study found a significant positive relationship between luminance ratio and perceived legibility. This finding aligns with existing literature and underscores the importance of appropriate display brightness relative to ambient lighting conditions for optimal readability in AR applications.

The study also revealed significant associations between visual factors and affective state. Both visual discomfort and legibility were found to influence participants' affective states (H3 and H4), with visual discomfort having a negative impact and legibility contributing positively. These findings highlight the intricate relationship between visual perception and emotional response in AR experiences.

Regarding task performance, the results were mixed. Visual discomfort did not significantly impact any aspect of task performance (rejecting H5a-d), which could be attributed to participants' ability to adapt to minor discomfort during short-term use or the tasks not being sufficiently demanding to show performance decrements due to visual discomfort. Legibility showed partial effects, positively influencing perceived task performance and perceived time (supporting H6b and H6d) but not actual task performance or task time (rejecting H6a and H6c). This discrepancy between perceived and actual performance might indicate that improved legibility enhances confidence in one's performance without necessarily improving objective outcomes.

The affective state demonstrated a partial effect on task performance, notably influencing perceived time, albeit in a direction contrary to our hypothesis (rejecting H7a-d). This unexpected result could suggest that positive emotions might lead to greater engagement with the task, causing participants to perceive time as passing more slowly.

Interestingly, the study found no significant relationship between affective state and intention to revisit (rejecting H8). This could be due to other factors, such as content interest or personal preferences, having a more decisive influence on revisit intentions than momentary affective states. However, a strong positive association was observed between affective state and hedonic motivation (supporting H9), emphasizing the role of positive emotional experiences in enhancing user engagement with AR technology.

Lastly, contrary to our expectations, no significant relationships were found between perceived learning outcomes and various aspects of task performance (rejecting H10a-d). This surprising result might be explained by the complexity of learning processes in informal settings, where factors such as prior knowledge, personal interest, or the novelty of AR technology could overshadow the immediate effects of task performance on perceived learning outcomes.

6.2. Theoretical Contributions

This study provides several important theoretical contributions to our understanding of AR experiences in Institutional Informal Learning Places (IILPs), particularly regarding the impact of display and ambient luminance conditions on visual factors and ultimately the user experience and learning outcomes.

Firstly, our findings challenge the simplistic assumption that luminance ratios directly and significantly affect visual discomfort in short-term AR use. While we observed a trend suggesting that higher luminance ratios might reduce visual discomfort, the lack of statistical significance highlights the complexity of visual perception in AR environments. This result adds nuance to existing theories on visual ergonomics in digital displays, suggesting that other factors, such as individual differences or task duration, may play a more significant role than previously thought in short-term AR interactions.

The study confirms that higher luminance ratios enhance perceived legibility, thereby positively impacting users' affective states and their overall hedonic experience, even if visual discomfort does not significantly change over short-term use. When the display luminance exceeds the ambient luminance (high luminance ratio), users report better legibility, aligning with existing literature on readability and display contrast (LaViola, 2000). This improved legibility reduces cognitive load, leading to a more relaxed and positive affective state (Sheedy et al., 2003). This relationship is crucial because it suggests that environmental factors can be manipulated to improve user experience indirectly.

The study further validates the Stimulus-Organism-Response (SOR) framework by demonstrating that the affective state acts as a significant mediator between the luminance ratio (stimulus) and hedonic motivation (response). The affective state influenced by improved legibility enhances users' overall enjoyment and motivation to engage with AR content. This finding extends existing literature by empirically connecting environmental and device lighting conditions to user experiences in AR settings, which had not been explicitly addressed before. Theoretical models of usability can now incorporate these findings to better predict user engagement and satisfaction (Aul et al., 2023; Wilkins et al., 2021).

6.3. Practical Contributions

From a practical perspective, the results highlight the importance of optimizing luminance ratios in AR applications within IILPs to enhance visitor engagement and satisfaction. While the adjustable brightness feature of modern smartphones can mitigate some discomfort caused by environmental lighting changes, ensuring high luminance ratios can significantly improve content legibility. This, in turn, enhances the overall visitor experience by fostering a more positive emotional state and greater hedonic motivation, encouraging further engagement with AR exhibits.

The research suggests that museums and similar institutions can leverage these insights to create more engaging AR experiences. By controlling ambient lighting or advising visitors to adjust their device settings, institutions can improve the perceived quality of

AR exhibits. This practical application is supported by data showing increased user engagement and satisfaction under optimal luminance conditions. Implementing these strategies can result in higher revisit intentions and more positive word-of-mouth, which is crucial for the sustained success of IILPs.

Institutions might also consider conducting user research studies to gather feedback on lighting conditions and AR experiences. This data could inform more precise adjustments to ambient lighting and display settings to meet different visitor demographics' specific needs and preferences.

For AR content developers, these findings suggest specific design considerations. Applications should be tested under various lighting conditions to ensure legibility and comfort. Developers can also include features that allow users to adjust brightness easily or use adaptive brightness algorithms that respond to ambient light changes. Such features would enhance the user experience by maintaining optimal luminance ratios automatically.

Further practical recommendations could include developing AR applications incorporating real-time feedback mechanisms to alert users when optimal luminance ratios are not maintained. Additionally, providing guidelines or tutorials within the AR app on adjusting settings for different environments could empower users to optimize their experience.

6.4. Methodological Contributions

Firstly, this study emphasizes the value of psychometric measures in capturing the nuanced aspects of user experience. While objective metrics like task performance and physiological indicators are valuable, they may not fully reflect the subjective and emotional dimensions crucial for a comprehensive understanding of AR interactions. By employing self-reported questionnaires and scales, the research captures users' perceptual and emotional responses, providing deeper insights into their experiences and the factors influencing them. This approach, combined with objective measures such as physiological data would allow for a holistic understanding of the user experience by integrating both subjective and objective data.

Secondly, by using a controlled experimental setup to manipulate luminance ratios, we were able to isolate the effects of display and ambient luminance conditions on user experience variables. This experimental design adds robustness to our findings, offering clear evidence of causality between luminance ratios and user outcomes such as perceived legibility and affective state.

Thirdly, the use of smartphone AR in our experiments reflects real-world usage scenarios more accurately than previous studies using specialized AR hardware. This increases the ecological validity of our findings and ensures that the results are more generalizable to everyday AR applications in IILPs. The choice of a smartphone-based AR platform aligns with the widespread adoption and accessibility of such devices, making our insights directly applicable to the current technological landscape (Tomiuc, 2014; Bresciani et al., 2018).

Finally, our methodological framework, including the detailed operationalization of luminance ratios and the systematic assessment of their impacts, can serve as a reference for future research. Researchers can adopt and adapt our experimental setup to explore other environmental factors and their effects on AR experiences, thereby expanding the body of knowledge in this field.

6.5. Limitations and Future Directions

6.5.1. Limitations

While this study provides valuable insights into the influence of lighting on smartphone AR experiences in Institutional Informal Learning Places (IILPs), several limitations must be acknowledged.

Firstly, we could not collect physiological measures such as eye tracking or heart rate variability due to logistical constraints. These measures could have provided valuable insights into users' physical responses to varying lighting conditions and AR content. For instance, eye-tracking data might have revealed patterns of visual attention and fatigue, while heart rate variability could have indicated levels of cognitive load and stress experienced by participants. Future studies incorporating such physiological measures could yield a more comprehensive understanding of the relationship between lighting, AR experiences, and user responses.

Secondly, the duration of the experiment was relatively short (50 minutes). While this timeframe allowed us to capture immediate responses to lighting conditions and AR content, it may not have been sufficient to evaluate the potential long-term effects of these factors on visual discomfort, fatigue, and learning outcomes. Future studies could consider employing longer experiment durations or longitudinal designs to investigate the sustained impact of lighting on AR experiences in IILPs.

Thirdly, the sample size in this study was relatively small and may not be representative of the diverse population of IILP visitors. Future research endeavours should aim for more extensive and diverse samples to enhance the generalizability of findings. This could involve recruiting participants from various age groups, backgrounds, and levels of familiarity with AR technology.

Additionally, while conducting the study in a naturalistic setting increased ecological validity, it also introduced potential confounding variables beyond our control. Variations in individual smartphone settings, ambient noise levels, and visitor traffic within the IILP could have influenced participants' experiences. Future studies could adopt more controlled settings to minimize the influence of such extraneous variables.

Lastly, this study focused primarily on the effects of relatively extreme dark and bright lighting conditions. While these extremes are encountered in some IILPs, future research should also explore the impact of more moderate lighting variations on user experience. This approach would provide a more nuanced understanding of how lighting can be optimized across a broader range of IILP environments.

6.5.2. Future Directions

Future research could address several key areas to build upon the findings of this study. Firstly, investigating the long-term effects of different luminance ratios on visual discomfort and user experience is crucial, as our study was limited to short-term interactions. This could involve longitudinal studies or experiments with extended task durations to better understand how visual fatigue develops over time in AR applications. Additionally, exploring individual differences in light sensitivity and their impact on AR experiences could provide valuable insights for personalizing AR interfaces. Future studies could also consider a broader range of ambient lighting conditions to more accurately reflect the diverse environments found in IILPs.

Researchers could employ more diverse and sensitive measures of cognitive load and learning to further unravel the complex relationships between visual comfort, affective state, and learning outcomes. This could include physiological measures, such as eye-tracking or EEG, to complement self-report data. Moreover, investigating the role of content type and task complexity in mediating the effects of luminance ratios on user experience and learning outcomes would be beneficial. This could involve comparing different types of AR applications across various informal learning contexts.

Future research could explore the potential of adaptive AR interfaces that automatically adjust display parameters based on ambient lighting conditions and user preferences. This could lead to more accessible and practical AR experiences in diverse IILP settings. Additionally, examining the interaction between luminance ratios and other AR design elements, such as colour schemes, text size, and interaction modalities, could provide a more comprehensive understanding of optimal AR design for informal learning environments.

Researchers could investigate the impact of AR on different age groups, as visual perception and learning processes may vary across demographics. This could help in developing age-appropriate AR applications for IILPs. Furthermore, exploring the use of AR in combination with other emerging technologies, such as virtual reality or haptic feedback, could open new avenues for enhancing informal learning experiences.

Another important area for future research is the development of standardized metrics for assessing visual comfort and learning outcomes in AR-enhanced informal learning environments. This would facilitate more consistent comparisons across studies and aid in establishing best practices for AR implementation in IILPs. Additionally, investigating the potential of AR to support different learning styles and accommodate diverse learner needs could contribute to more inclusive informal learning experiences.

Future studies could investigate the long-term impact of AR experiences on learning retention and transfer and users' attitudes toward AR technology in educational settings. This could involve follow-up assessments and interviews to gauge the lasting effects of AR-enhanced informal learning experiences. Researchers could also explore the potential of AR to foster collaboration and social learning in IILPs, examining how shared AR experiences might enhance engagement and knowledge construction among visitors.

Lastly, future research could focus on developing guidelines for the ethical use of AR in informal learning environments, addressing issues such as privacy, data security, and equitable access to AR technologies. This could help ensure that the implementation of AR in IILPs is responsible and beneficial for all users.

By addressing these areas, future research can contribute to developing more effective and user-friendly AR applications for IILPs, ultimately enhancing the educational potential of this technology in informal learning contexts. This comprehensive approach will help bridge the gap between theoretical understanding and practical implementation of AR in diverse learning environments.

Chapter 7
Conclusion

This thesis addressed two key research questions: The first is “How do ambient and display luminance affect the visual discomfort/fatigue levels in individuals interacting with smartphone AR in Informal Institutional Learning Places (IILPs)?”. The second, on the other hand is “What other factors are consequently affected by the users' interaction with smartphone AR and visitors' overall experience in IILPs?”

To address the first research question, our findings indicated that luminance ratios had no significant effect on visual discomfort. While descriptive statistics suggested that higher luminance ratios might be associated with lower levels of visual discomfort, this trend did not achieve statistical significance. This outcome suggests that short-term interactions with varying luminance ratios did not significantly alter users' visual discomfort levels, contrary to our initial hypothesis. This result aligns with some of the broader literature, indicating that while extreme luminance conditions can cause discomfort, moderate variations within the tested range do not elicit significant differences in discomfort levels (Benedetto et al., 2013).

Several hypotheses were examined for the second research question, and the study's results offer valuable insights into the broader impacts of luminance ratios on user experience in smartphone AR interactions. Firstly, higher luminance ratios were found to enhance the perceived legibility of AR content significantly. This supports the hypothesis that increased contrast between display and ambient lighting improves readability, thereby facilitating easier interaction with AR content. Improved legibility enhances the user experience and reduces cognitive load, contributing to a more relaxed and positive affective state. This finding is consistent with prior research suggesting that better readability and reduced cognitive effort are crucial for maintaining user engagement and satisfaction (Mittelstaedt et al. (2019); Sheedy et al., 2003).

Additionally, the study found that the affective state of users, influenced by improved legibility, significantly enhances the users' hedonic motivation to engage with AR content. This result validates the Stimulus-Organism-Response (SOR) framework in the context of AR interactions, highlighting the role of environmental factors in shaping user experiences. The study extends the existing literature on AR usability and user engagement by demonstrating that the affective state mediates the relationship between luminance ratios and hedonic motivation (Wickens et al., 2015).

The findings from this study provide significant contributions to both theory and practice. Theoretically, the research extends the SOR framework by empirically demonstrating the mediating role of affective states between environmental stimuli (luminance ratios) and user responses (engagement and motivation). This underscores the complex interplay between environmental factors and user psychology in the context of AR applications.

From a practical perspective, these findings underscore the importance of optimizing luminance ratios in AR applications within IILPs to enhance visitor engagement and satisfaction. Ensuring high luminance ratios can significantly improve content legibility, fostering a more positive emotional state and greater motivation to engage with AR exhibits. This practical application is supported by data showing increased user engagement and satisfaction under optimal luminance conditions, which can lead to higher revisit intentions and more positive word-of-mouth, crucial for the sustained success of IILPs. Institutions like museums can leverage these insights by controlling ambient lighting or advising visitors to adjust their device settings to improve the perceived quality of AR exhibits. Conducting user research studies to gather feedback on lighting conditions and AR experiences can inform more precise adjustments to meet the specific needs of different visitor demographics. AR content developers should consider testing applications under various lighting conditions to ensure legibility and comfort. Including features that allow users to adjust brightness easily or using adaptive brightness algorithms can enhance user experience by automatically maintaining optimal luminance ratios.

Methodologically, this study emphasizes the value of psychometric measures in capturing the nuanced aspects of user experience. By employing self-reported questionnaires and scales, the research captures users' perceptual and emotional responses, providing deeper insights into their experiences. Combined with objective measures such as physiological data, this approach allows for a holistic understanding of user experience. Additionally, the controlled experimental setup used to manipulate luminance ratios offers clear evidence of causality between luminance conditions and user outcomes, enhancing the robustness and ecological validity of the findings (Tomiuc, 2014; Bresciani et al., 2018).

While the study offers valuable insights, it is essential to acknowledge its limitations. The experimental setup, although rigorous, was conducted in controlled environments that may not fully capture the variability of real-world settings. This limitation suggests that future research should incorporate more naturalistic environments to enhance the ecological validity of the findings. Additionally, the sample size and diversity were limited, which might affect the generalizability of the findings. A broader and more diverse sample could provide a more comprehensive understanding of how different demographic groups experience AR under varying lighting conditions.

Future studies should aim to incorporate physiological measures such as eye-tracking and heart rate variability to gain deeper insights into users' physical responses to AR experiences under varying lighting conditions. These measures could provide more objective data on visual discomfort and engagement levels. Extending the duration of experiments and conducting longitudinal studies could reveal the long-term effects of these conditions on visual discomfort and learning outcomes. Such studies would be instrumental in understanding how prolonged exposure to AR under different lighting conditions affects user experience and educational outcomes. Moreover, increasing sample diversity and conducting research in more varied and naturalistic settings would enhance the generalizability of the findings. Exploring moderate lighting variations and content-specific responses to lighting conditions could also provide more comprehensive guidelines for AR application design, ensuring that the findings apply to various educational contexts and AR applications.

In conclusion, this study underscores the critical role of lighting conditions in shaping user experiences with AR in educational and informal learning contexts. By systematically investigating the impact of luminance ratios, the research provides valuable contributions to both theory and practice, offering practical recommendations for enhancing AR usability. The research highlights the necessity for AR developers and educators to consider lighting conditions as a fundamental aspect of AR design. Building on these findings, future research can further our understanding of optimal AR design, ultimately enriching the educational experiences in IILPs and beyond. This comprehensive examination of lighting conditions and their effects on AR experiences within IILPs fills a significant gap in the existing literature and sets the stage for future innovations in educational technology. By enhancing our understanding of these dynamics, we can create more engaging and effective AR applications that inspire and educate users meaningfully. The ultimate goal is to leverage AR technology to foster an engaging, immersive, and educationally enriching environment for all learners, paving the way for more advanced and user-centred educational tools in the future.

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Appendix

Appendix A. Ethics Approval Certificate

HEC MONTRÉAL

Comité d'éthique de la recherche

Le 13 février 2023

À l'attention de :
Pierre-Majorique Léger
Professeur titulaire, HEC Montréal

Objet : Approbation éthique de votre projet de recherche

 # Projet : 2023-5269

Titre du projet de recherche : Confort visuel et expérience utilisateur

Source de financement : 32 153 300 22 - R2997 - Contrat de recherche

Titre de la subvention : Confort visuel - Essilor

Votre projet de recherche a fait l'objet d'une évaluation en matière d'éthique de la recherche avec des êtres humains par le CER de HEC Montréal.

Un certificat d'approbation éthique qui atteste de la conformité de votre projet de recherche à la *Politique relative à l'éthique de la recherche avec des êtres humains* de HEC Montréal est émis en date du 13 février 2023. Prenez note que ce certificat est **valide jusqu'au 13 février 2024.**

Vous devrez obtenir le renouvellement de votre approbation éthique avant l'expiration de ce certificat à l'aide du formulaire *F7 - Renouvellement annuel*. Un rappel automatique vous sera envoyé par courriel quelques semaines avant l'échéance de votre certificat.

Lorsque votre projet est terminé, vous devrez remplir le formulaire *F9 - Fin de projet (ou F9a - Fin de projet étudiant sous l'égide d'un autre chercheur)*, selon le cas. **Les étudiants doivent remplir un formulaire F9 afin de recevoir l'attestation d'approbation éthique nécessaire au dépôt de leur thèse/mémoire/projet supervisé.**

Si des modifications sont apportées à votre projet, vous devrez remplir le formulaire *F8 - Modification de projet* et obtenir l'approbation du CER avant de mettre en oeuvre ces modifications.

Notez qu'en vertu de la *Politique relative à l'éthique de la recherche avec des êtres humains de HEC Montréal*, il est de la responsabilité des chercheurs d'assurer que leurs projets de recherche conservent une approbation éthique pour toute la durée des travaux de recherche et d'informer le CER de la fin de ceux-ci. De plus, toutes modifications significatives du projet doivent être transmises au CER avant leurs applications.

Vous pouvez dès maintenant procéder à la collecte de données pour laquelle vous avez obtenu ce certificat.

Nous vous souhaitons bon succès dans la réalisation de votre recherche.

Le CER de HEC Montréal

NAGANO www.semiweb.ca Approbation du projet par le comité d'éthique suite à l'approbation conditionnelle
Comité d'éthique de la recherche - HEC Montréal 1 / 2

Exporté le 2024-07-21 05:25 par Mohapatra, Amritam --- CODE DE VALIDATION NAGANO: hec-a511e006-9f15-4f91-8562-ca2d578e3f64https://cer.hec.ca/verification/hec-a511e006-9f15-4f91-8562-ca2d578e3f64

CERTIFICAT D'APPROBATION ÉTHIQUE

La présente atteste que le projet de recherche décrit ci-dessous a fait l'objet d'une évaluation en matière d'éthique de la recherche avec des êtres humains et qu'il satisfait aux exigences de notre politique en cette matière.

Projet # : 2023-5269

Titre du projet de recherche : Confort visuel et expérience utilisateur

Chercheur principal :
Pierre-Majorique Léger,
Professeur titulaire, Technologies de l'information, HEC Montréal

Cochercheurs :
Sylvain Sénécal; François Courtemanche; David Brieugne; Frédérique Bouvier; Xavier Côté; Salima Tazi

Date d'approbation du projet : 13 février 2023

Date d'entrée en vigueur du certificat : 13 février 2023

Date d'échéance du certificat : 13 février 2024

Maurice Lemelin
Président
CER de HEC Montréal

Signé le 2023-02-13 à 15:07

Appendix B. Assessment Items for Subjective measures

Visual Discomfort

En vous basant sur les tâches que vous venez de compléter, veuillez s'il vous-plaît évaluer votre niveau d'inconfort visuel :

	Totalement en désaccord	Principalement en désaccord	Plutôt en désaccord	Ni en accord, ni en désaccord	En partie en d'accord	Principalement d'accord	Totalement d'accord
J'ai des difficultés à voir	○	○	○	○	○	○	○
Je ressens une sensation inhabituelle autour de mes yeux	○	○	○	○	○	○	○
Je ressens de la fatigue occulaire	○	○	○	○	○	○	○
Je me sens engourdi	○	○	○	○	○	○	○
J'ai des maux de tête	○	○	○	○	○	○	○
Je me sens étourdi en regardant l'écran	○	○	○	○	○	○	○

Legibility

1.L1

L'écran du téléphone est...

Difficile à voir | ○ ○ ○ ○ ○ ○ ○ | Facile à voir

1.L2

Le texte est...

Difficile à lire | ○ ○ ○ ○ ○ ○ ○ | Facile à lire

1.L3

Il est facile de...

se déconcenter | ○ ○ ○ ○ ○ ○ ○ | Rester concentrer

1.L4

Il y a des reflets sur l'écran

Totalement en désaccord | ○ ○ ○ ○ ○ ○ ○ | Totalement en accord

1.M1

L'écran du téléphone est...

Sombre | ○ ○ ○ ○ ○ ○ ○ | Lumineux

1.M2

L'éclairage de la pièce est...

Sombre | ○ ○ ○ ○ ○ ○ ○ | Lumineux

Enjoyment


Déplacez le curseur pour indiquer votre niveau de plaisir pendant votre interaction avec l'application de réalité augmentée. Plus vous déplacez le curseur vers la droite, plus l'intensité de l'émotion ressentie est grande.

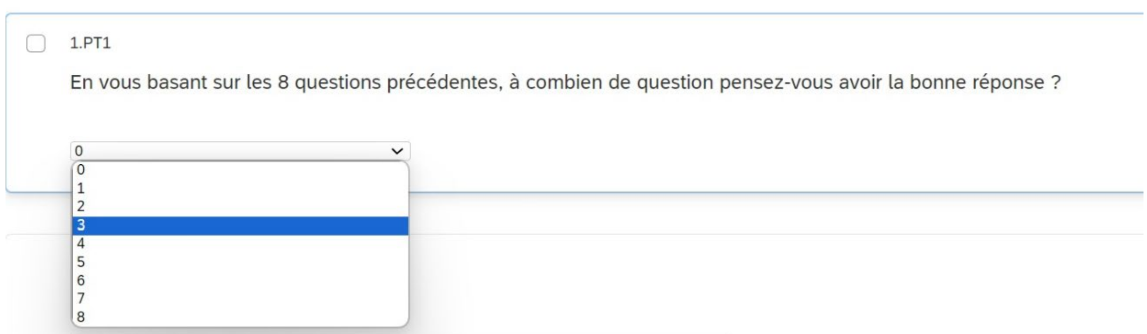
Annoyance


Déplacez le curseur pour indiquer votre niveau de gêne lors de l'interaction avec l'application de réalité augmentée

Pas Agacé | Légèrement Agacé | Plutôt Agacé | Agacé | Très Agacé

0 | 25 | 50 | 75 | 100

Perceived Task Performance


1.PT1

En vous basant sur les 8 questions précédentes, à combien de question pensez-vous avoir la bonne réponse ?

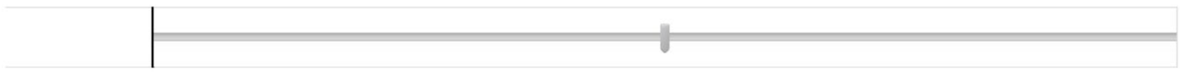
0

0
1
2
3
4
5
6
7
8

Perceived Time

À propos des 2 insectes précédents, veuillez évaluer votre perception du temps écoulé durant les tâches.

Très lent — Tres Rapide



Intention to Revisit

Veuillez indiquer à quelle point vous êtes en accord avec les affirmations suivantes :

	Très peu probable	Peu probable	Plutôt improbable	Neutre	Plutôt probable	Probable	Très probable
Je visiterai à nouveau cet établissement.	○	○	○	○	○	○	○
Si j'en avais la possibilité, je choisirais de retourner dans cet établissement.	○	○	○	○	○	○	○

Hedonic Motivation

En vous basant sur votre expérience en Réalité Augmentée (RA), veuillez évaluer vos préférences.

	Pas du tout	Très peu	Un peu	Modérément	Assez	Beaucoup	Énormément
Utiliser l'application RA est amusant.	○	○	○	○	○	○	○
Utiliser l'application RA pour apprendre est appréciable.	○	○	○	○	○	○	○
Utiliser l'application RA pour apprendre est divertissant.	○	○	○	○	○	○	○

Perceived Learning Outcome

D'après votre expérience de la réalité augmentée (RA), veuillez évaluer votre expérience.

	Pas du tout	Très peu	Un peu	Modérément	Assez	Beaucoup	Énormément
L'utilisation de l'application de réalité augmentée m'a aidé à identifier les principales caractéristiques des insectes.	○	○	○	○	○	○	○
L'application de réalité augmentée m'a aidé à mieux comprendre la couleur, les formes, les habitats et les proies des insectes.	○	○	○	○	○	○	○
L'application de réalité augmentée m'a permis d'approfondir mes connaissances sur les insectes.	○	○	○	○	○	○	○

Appendix C. Production Environment of the AR Stimuli