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Adapting an Educational Game for Virtual Reality with Integrated Opportunities for Reflective Learning

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ABSTRACT

This thesis investigates the educational application of virtual reality (VR) in teaching mathematical fractions, building upon earlier foundational work on interactivity and immersion in virtual environments. While interactive VR has been shown to enhance engagement and motivation, previous research indicated that it could also hinder reflective processes essential for deep conceptual understanding. To address this, the updated version of the Virtual Playground, designed for standalone VR headsets, incorporates structured reflection moments into the interactive experience. This study aims to further the integration of VR in education by exploring how immersive and interactive environments can effectively teach complex concepts like fractions, while also examining the balance between interaction, reflection, and conceptual understanding in learning.

The starting point of this research is the conversion of the 3D desktop version of virtual playground into a VR game using the Unity Engine. The migration from the obsolete CAVE-hardware to the modern Unity game engine had been conducted previously as an independent project outside the scope of this work. The outcome of that project–a desktop application–was used as the foundation of this work. This task presented a variety of challenges, as transitioning from a desktop game controlled with mouse and keyboard to a VR game designed for the Oculus Quest 2 required significant adjustments. Numerous design and interaction decisions were made to ensure an intuitive and engaging user experience within the virtual environment. Subsequently, the project expanded the Virtual Playground by investigating ways to enhance reflection and real conceptual understanding. To this end, two gameplay modes were designed and developed: **guided instruction** and **self-reflection**. These modes of gameplay aim to foster both active learning and deeper cognitive engagement within the game.

The updated version of the virtual playground was presented and evaluated by a panel comprising three VR experts and two elementary school teachers. Detailed qualitative feedback was collected, documented, and analyzed as part of this thesis. The final chapters present the results of this analysis, along with recommendations and proposed adjustments for researchers who may continue this work in the future.

SUBJECT AREA: Virtual Reality in Education

KEYWORDS: Virtual Reality, Human-Computer Interaction, Game-based Learning, Learning Fractions, Reflection, Scaffolding, Interactivity.

ΠΕΡΙΛΗΨΗ

Η παρούσα διπλωματική εργασία διερευνά την εκπαιδευτική εφαρμογή της εικονικής πραγματικότητας (VR) στη διδασκαλία μαθηματικών κλασμάτων, βασιζόμενη σε προηγούμενες θεμελιώδεις μελέτες σχετικά με την αλληλεπίδραση και την εμβύθιση σε εικονικά περιβάλλοντα. Αν και η διαδραστική εικονική πραγματικότητα έχει αποδειχθεί ότι ενισχύει τη δέσμευση και το κίνητρο των μαθητών, προηγούμενες έρευνες έδειξαν ότι μπορεί επίσης να παρεμποδίσει τις διαδικασίες αναστοχασμού που είναι απαραίτητες για τη βαθύτερη εννοιολογική κατανόηση. Για την αντιμετώπιση αυτού του ζητήματος, η αναβαθμισμένη έκδοση του Virtual Playground, σχεδιασμένη για αυτόνομα VR headsets, ενσωματώνει δομημένες στιγμές αναστοχασμού στην αλληλεπιδραστική εμπειρία. Η παρούσα μελέτη στοχεύει στην περαιτέρω ενσωμάτωση της VR στην εκπαίδευση, διερευνώντας πώς τα εμβυθιστικά και διαδραστικά περιβάλλοντα μπορούν να υποστηρίξουν τη διδασκαλία σύνθετων εννοιών, όπως τα κλάσματα, ενώ παράλληλα εξετάζει την ισορροπία μεταξύ αλληλεπίδρασης, αναστοχασμού και εννοιολογικής κατανόησης στη μαθησιακή διαδικασία.

Αφετηρία αυτής της έρευνας αποτελεί η μετατροπή της επιτραπέζιας 3D έκδοσης του Virtual Playground σε παιχνίδι εικονικής πραγματικότητας, χρησιμοποιώντας τη Unity Engine. Η μετάβαση από την απαρχαιωμένη τεχνολογία του CAVE στη σύγχρονη Unity game engine είχε πραγματοποιηθεί προηγουμένως ως ανεξάρτητο έργο, εκτός του πεδίου αυτής της εργασίας. Το αποτέλεσμα αυτής της μετάβασης – μια επιτραπέζια εφαρμογή – χρησιμοποιήθηκε ως η βάση για τη συνέχεια αυτής της μελέτης. Η διαδικασία αυτή παρουσίασε μια σειρά από προκλήσεις, καθώς η μετατροπή ενός επιτραπέζιου παιχνιδιού, που ελέγχεται με πληκτρολόγιο και ποντίκι, σε ένα παιχνίδι VR σχεδιασμένο για το Oculus Quest 2, απαιτούσε σημαντικές προσαρμογές. Λήφθηκαν πολλαπλές σχεδιαστικές και αλληλεπιδραστικές αποφάσεις προκειμένου να διασφαλιστεί μια διαισθητική και ελκυστική εμπειρία χρήστη στο εικονικό περιβάλλον. Στη συνέχεια, το έργο επεκτάθηκε διερευνώντας τρόπους ενίσχυσης του αναστοχασμού και της πραγματικής εννοιολογικής κατανόησης. Για τον σκοπό αυτό, σχεδιάστηκαν και αναπτύχθηκαν δύο τρόποι παιχνιδιού: **καθοδηγούμενη διδασκαλία** και **αυτο-αναστοχασμός**. Οι τρόποι αυτοί στοχεύουν στην ενίσχυση της ενεργού μάθησης και της βαθύτερης γνωστικής εμπλοκής μέσα στο παιχνίδι.

Η αναβαθμισμένη έκδοση του Virtual Playground παρουσιάστηκε και αξιολογήθηκε από μια επιτροπή που αποτελείται από τρεις ειδικούς στην εικονική πραγματικότητα και δύο δασκάλους πρωτοβάθμιας εκπαίδευσης. Συλλέχθηκαν, τεκμηριώθηκαν και αναλύθηκαν λεπτομερή ποιοτικά δεδομένα στο πλαίσιο αυτής της διπλωματικής εργασίας. Τα τελικά κεφάλαια παρουσιάζουν τα αποτελέσματα αυτής της ανάλυσης, μαζί με προτάσεις βελτίωσης και προσαρμογές που μπορούν να ληφθούν υπόψη από μελλοντικούς ερευνητές που θα συνεχίσουν την παρούσα μελέτη.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Εικονική Πραγματικότητα στην Εκπαίδευση

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: Εικονική Πραγματικότητα, Αλληλεπίδραση Ανθρώπου-Η/Υ, Παιγνιώδης Μάθηση, Μάθηση Κλασμάτων, Αναστοχασμός, Μάθηση με υποστήριξη –Scaffolding, Διαδραστικότητα.

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CONTENTS

LIST OF FIGURES

PREFACE

This thesis describes the research that has been conducted as part of my Master studies at the Department of Informatics and Telecommunications, National and Kapodistrian University of Athens.

1. INTRODUCTION

1.1 The Research Problem

The purpose of this thesis is to propose new ideas on how to create moments of reflection that enhance conceptual understanding in virtual environments. A key feature introduced to achieve this goal is the presence and interaction of an intelligent agent within the virtual space. It is an extension of the Virtual Playground [1]. The Virtual Playground aimed to examine whether engaging in an immersive virtual environment can help children gain a deeper understanding of mathematical fractions [2]. The experiments that were carried out to study the effect of interactivity on solving and understanding fractions problems, consisted of three scenarios: an active one, where the student interacted with the virtual environment on their own; a passive one, where they watched a robot performing the tasks; and a non-digital version of the virtual playground using Lego blocks instead of virtual elements. In the main findings, it was shown that the passive VR environment, where the student was an observer of the problem-solving process, demonstrated prospects for reflection and sustained conceptual change. Furthermore, the physical presence of instructors and the feedback they provided produced the same effect. Moments of reflection were observed in some participants during the experiments, but they were not adequate to lead to a deep understanding of the mathematical puzzles they just solved.

Based on these remarks, we designed an extension of that work to evaluate the contribution of a virtual instructor to this virtual educational experience. The integration of virtual assistants into applications of educational content is widely implemented though. Studies have proved the importance of these assistants in the learning process. Our research focuses on addressing the tension between interaction and reflection in virtual learning environments. Specifically, this work investigates how the integration of structured reflection moments into the gameplay experience can support meaningful learning outcomes. Rather than evaluating the interaction of children with the game, the updated version of the Virtual Playground was designed for the Oculus Quest headset and assessed by experts and elementary school teachers. Their feedback was analyzed to determine whether the balance between interaction and reflection effectively supports cognitive engagement and conceptual understanding. This evaluation provides a foundation for future iterations of the game and its potential use in educational contexts.

1.2 Scope of the Thesis

The foundation of this thesis is previous research on interactivity and learning in a virtual environment [1]. This research could be considered a continuation of the Virtual Playground implemented for the CAVE environment. Children benefit from interacting inside the Virtual Environment, which urges ability growth and puzzle-solving improvement. Among the three scenarios that were examined (active, passive, and no VR), the passive one proved to be the most efficient, in which the student was observing a robot solving the tasks.

Considering the conclusions, the concept of a virtual assistant's integration inside the game came naturally. In the new version of the game, two scenarios were integrated. The first one is based on the original version of Virtual Playground with the addition of an assistant. This assistant is present throughout the whole experience providing feedback and acting as a medium of knowledge and reflection. The second scenario constitutes a separate game flow. The presence of the virtual assistant is a game asset, but no feedback is shared. Our goal was to design and construct a game that promotes reflecting processes and fosters deeper conceptual understanding.

As far as the VR technology used, the technical implementation of the game is narrowed to standalone, consumer VR headsets, such as the Meta Quest, as these are more widely available and suitable for general or non-enterprise use, especially educational contexts. The technical capabilities and performance of the Meta Quest 2 were proven adequate to conduct this research. Therefore, the game is tailor-made for these headsets.

Eventually, it is worth mentioning that, during the stage of brainstorming, other subjects and ideas came to the surface that could equally work as scenarios. Specifically, the possibility of removing the controllers of the VR headset was discussed. Subtracting the usage of controllers is equivalent to the obligatory use of the student's hands and only, to move, interact, and solve the mathematical problems inside the virtual world. Johnson-Glenberg emphasizes the significance of embodiment in learning procedures, arguing that changing the form, size, and position of physical content inside a virtual environment can positively affect education [3].

Conclusively, we assumed that using the hands as a means to interact with objects, instead of controllers, would lead to more effective embodied learning. On the contrary, this venture would require excellent implementation in the technological aspect of the game leading to many technical challenges. One of the challenges, for example, would be the lack of feeling something tangible or some texture when the participant grabs or touches an item. Finally, it was decided to follow the more educational-oriented direction that we believed would offer a fresh aspect about teacher-tutor relationships, social robots in VR, and reflection in learning.

1.3 Contributions

This thesis contributes to the advancement of virtual reality (VR) as an educational tool, with a particular focus on integrating structured reflection into immersive learning environments for teaching mathematical fractions. It addresses key technological, pedagogical, and empirical challenges, aiming to enhance both the usability and learning effectiveness of VR-based instruction. Through the modernization of the Virtual Playground, the study explores how interactive learning can be refined to balance engagement with reflective thought, ensuring deeper conceptual understanding.

A significant technological contribution of this work is the transition of the Virtual Playground from an outdated platform to a standalone VR system, enhancing accessibility, usability, and performance. This transition required substantial technical reconfiguration, ensuring that the new version retains the core educational principles while improving interaction mechanics and interface design. Furthermore, the study introduces structured reflection mechanisms within the game's interactive experience, allowing users to engage in reflective pauses without disrupting immersion. By implementing two distinct instructional modes—the Didactic Mode, which provides guided instructional support, and the Self-Reflection

Mode, which encourages learners to review their problem-solving process independently—this research expands the pedagogical design space of VR learning applications. These contributions align with current trends in adaptive learning environments, which emphasize the importance of tailoring instructional methods to the needs of individual learners.

Beyond its technological advancements, this thesis provides valuable pedagogical insights into how VR fosters conceptual learning. It examines the role of reflection in interactive learning and explores how structured scaffolding can improve comprehension of mathematical fractions. Through the integration of guided problem-solving and delayed feedback mechanisms, the study evaluates whether providing students with opportunities to reflect on their answers enhances their ability to internalize abstract concepts. Additionally, the research considers the role of embodiment in learning by assessing whether allowing students to physically manipulate and categorize virtual objects strengthens their numerical reasoning. Another key pedagogical contribution is the investigation of the extent to which a virtual tutor can substitute for the presence of a human educator in an immersive learning environment. The findings suggest that while interactive guidance can assist learners in navigating the game, the presence of an instructor may remain beneficial in reinforcing conceptual reflection.

Empirically, this work presents a qualitative analysis of user interactions, exploring how learners engage with the game, solve mathematical puzzles, and navigate the instructional modes. By analyzing user behavior and problem-solving approaches, the study identifies common patterns, misconceptions, and learning strategies that emerge in immersive educational environments. The findings provide insights into the balance between engagement and structured learning, highlighting potential challenges and best practices in the design of VR-based learning applications. Additionally, the study evaluates the usability and effectiveness of the Virtual Playground through expert reviews, collecting feedback from educators and VR specialists to refine the interaction design and improve the overall learning experience. Based on these findings, the thesis outlines design principles and practical recommendations for future VR educational applications, offering guidance on how interactivity, reflection, and instructional support can be effectively integrated to maximize learning outcomes.

Through these contributions, this research advances the field of VR-based education by demonstrating how structured reflection, adaptive instructional design, and embodied learning principles can be leveraged to enhance conceptual understanding in immersive environments. It provides a foundation for future work in the development of VR learning applications, supporting both technological innovation and pedagogical refinement in digital education.

1.4 Limitations of the Study

While this thesis advances the integration of structured reflection within immersive VR learning environments, certain limitations should be acknowledged. One constraint is the limited sample size used for empirical evaluation. The user studies primarily involved expert reviews and small-scale testing, which may not fully capture the diverse range of learner interactions, particularly among younger students with varying levels of familiarity with VR technology. A larger-scale user study involving a more representative population of students could provide additional insights into the effectiveness and adaptability of the instructional modes.

Another limitation relates to the reliance on qualitative analysis for assessing learning effectiveness. While expert evaluations and user observations provide valuable insights into usability, engagement, and pedagogical impact, the study does not include long-term retention assessments or standardized learning outcome measurements. Future research could employ controlled experimental designs with pre- and post-tests to quantitatively measure the impact of VR-based reflection on conceptual understanding.

Technological constraints also played a role in shaping the study. The Virtual Playground was designed to function on a standalone VR headset, which, while improving accessibility and ease of use, imposes hardware limitations in terms of processing power, graphical fidelity, and interaction complexity. More advanced VR systems could allow for greater realism, improved tracking, and richer interactivity, which may enhance the effectiveness of embodied learning principles.

Additionally, the study assumes that structured reflection moments can be effectively integrated into immersive experiences without disrupting engagement. However, the extent to which reflection can coexist with high interactivity remains an open question. Some users may prioritize immediate interaction and exploration over structured reflection, potentially affecting learning outcomes. Further research is needed to refine the balance between engagement and reflection in different VR-based learning contexts.

Finally, while this thesis explores the potential for a virtual tutor to replace human guidance in a VR educational setting, the findings suggest that teacher presence may still play a crucial role in guiding reflection and ensuring deeper understanding. The degree to which AI-driven or virtual tutoring systems can fully substitute for human educators remains an area for future exploration.

By acknowledging these limitations, this study provides a foundation for further research and development in VR-based education, offering pathways for refining instructional design, improving technological integration, and expanding empirical validation of immersive learning methodologies.

1.5 Terminology and Notation

Throughout this thesis, specific terms are used interchangeably for clarity and consistency. The terms virtual assistant, intelligent agent, and tutor all refer to the same entity within the virtual application, represented by the owl. The virtual reality (VR) and education experts who participated in the study are collectively referred to as users.

The term virtual environment is used interchangeably with VR. Additionally, this work is referenced using different terms depending on the context, including game, VR experience, research, and thesis.

2. BACKGROUND AND RELATED WORK

This chapter explores the foundational concepts and relevant research that underpin the development of the Virtual Playground application. The first section provides an overview of virtual reality and its contributions to education, with a particular focus on the teaching and learning of mathematical fractions in recent decades. The primary objective of this research was to design and implement a VR application that fosters reflection and a deeper understanding of mathematical fractions through experiential learning, facilitated by the presence of a virtual tutor. The tutor's role is expected to have a meaningful impact on children's learning outcomes.

Existing research was analyzed and processed to establish a theoretical foundation for the study. Before presenting the methodology, it is essential to examine key concepts such as immersion, embodiment, reflection, and interactivity, as well as their interconnections. The following sections define these terms and provide relevant literature references to contextualize their significance in the study.

2.1 Definitions of relative terms

2.1.1 Immersion & Presence

Slater insists on the separation of these two definitions. As immersion, Slater defines the capabilities computers have to deliver a deceptive depiction of the real world and to what extent they can manage it, in terms of how well they can make the user stand aside from reality, the number of modes of senses the user utilizes, how lively the experience can be and how broad the visual spectrum of the virtual reality can be [16].

Sanchez-Vives and Slater in their work in 2005 present immersion as the extent of a system to accurately correlate the human body proprioception with the manufactured data the virtual environment can provide. Better representation of the human sensory systems means higher immersion [17].

On the other hand, presence is the feeling of being in a virtual environment. Achieving a higher presence equals a more believable virtual experience. In America, the confusion of these two names is regular [16]. According to Sanchez-Vives and Slater, the concept of presence can have a different perspective suggesting that presence is about successfully supported action within the environment. Reality is perceived through action rather than mental filters, emphasizing functionality over appearances. The sense of ’being there’ is linked to the ability to act within the virtual environment. For example, if a participant navigates into a virtual environment by walking, the sense of presence will increase when visual cues of walking are closely aligned with the actual movements of their body. Experiments that took place proved this positive relationship between presence and body engagement, meaning that the greater the body usage the better ’feeling of being there' is achieved.

In another work of his, Slater et al. (2009) make the distinction between presence and immersion clearer, comparing immersion as the wavelength distribution, which is considered objective, and presence as each person’s conception of the same color, how it makes them feel and what is their affective reaction. In conclusion, presence is a form for the human to respond to immersion [18].

Gutierrez, Vexo & Thalmann (2008) claim immersion is closely linked to the physical design of the user interface within a VR application. VR systems can be classified into three types: fully immersive, which utilize head-mounted displays (HMD); semi-immersive, which employ large projection screens, and non-immersive, which are desktop-based. This classification is based on the degree to which users can perceive the real world through their senses –sight, sound, and touch- during the virtual experience [7].

In the same work, these researchers refer to the concept of presence. Presence is established when the brain processes multimodal simulations – such as visual, auditory, and tactile feedback – into a unified and coherent environment that facilitates activity and interaction. Presence is attained when the user, whether consciously or subconsciously, perceives themselves to be within a virtual environment (VE). For instance, in a video game, even though the user is aware that they are not in the real world, their behavior continues to reflect the environment as if it were real. However, presence can take place in situations where the user realizes that this world, they are interacting with is fictional.

John V. Draper and his colleagues define presence in the context of synthetic environments (SEs) as the extent to which users lose their awareness of the actual, physical world and instead feel immersed in a computer-generated environment. This phenomenon involves users focusing their sensory and cognitive resources on the virtual environment, leading to a strong sense of being physically present in that space [19].

By creating an immersive environment that accurately mirrors real-world sensory inputs and aligns with the user's proprioceptive feedback, the application aims to achieve high levels of immersion. This ensures that the virtual setting is not only engaging but also convincing enough for the children to feel physically present within it.

The sense of presence is further amplified through interactive elements that allow children to perform actions within the virtual environment, such as manipulating the number and the form of the cube islands on the playground with the touch controllers of Oculus Quest. This action-based interaction supports the findings of the work I have already displayed above where the ability to perform meaningful actions in the virtual world enhances the feeling of 'being there'.

A steady low latency connection between sensory information and proprioception is one of Slater's main conditions for reserving the presence in a virtual environment [18]. Additionally, he states the importance of behavior-response correlations: Presence can be enhanced and sustained over time through appropriate correlations between participants' states and behaviors and the responses within the environment, ensuring the environment responds suitably to participants' actions. The technological equipment of Meta Quest provides a stable environment of low latency with smooth motion and a high frame rate (at least 72Hz), reaching the above-mentioned conditions. As a result, a considerable number of benefits of high presence and immersion in the virtual playground application are shown.

First, a high level of presence and immersion keeps children engaged and motivated, making the learning experience more enjoyable and effective. When students feel as if they are physically present in the virtual environment, they are more likely to be attentive and invested in the learning experience. Research has shown that immersive VR environments can capture students' attention better than traditional methods, thus enhancing their overall learning experience [23]. Psotka (1994) states that convenience immersion adds to learning [6]. Students showed significantly increased interest in school courses such as algebra and geometry when VR was used.

2.1.2 Interactivity

Interactivity is a fundamental characteristic of digital learning environments, influencing user engagement, immersion, and knowledge retention. In virtual reality (VR) applications, it plays a crucial role in enhancing cognitive and experiential learning by allowing users to actively engage with the virtual environment rather than passively receiving information.

The concept of interactivity has been extensively studied in the fields of human-computer interaction (HCI), educational technology, and digital media. Early research in HCI emphasized the importance of designing interactive systems that optimize usability and user experience. In the context of VR-based education, interactivity contributes to constructivist learning, where learners actively build knowledge through direct interaction with virtual objects and systems.

In educational VR environments, interactivity can be categorized into three main types. The first type is user-system interactivity, which refers to direct engagement between the user and the virtual environment. In the Virtual Playground, this includes manipulating objects, receiving feedback from the tutor (owl), and progressing through the learning activities based on the user's actions. The goal is to create a responsive system that encourages problem-solving and exploration. The second type is user-environment interactivity, which involves the user’s ability to navigate, observe, and interact with the VR space. Factors such as locomotion mechanics, object physics, and interaction design determine how intuitively users engage with the learning content. Research has shown that natural interaction mechanisms, such as hand tracking and spatial awareness, improve user engagement and reduce cognitive load [16]. The third type is user-tutor interactivity, which is particularly relevant in guided learning VR applications. Virtual agents or tutors play a role in facilitating interaction by guiding the learner, providing hints, and prompting reflection. Studies indicate that intelligent tutoring systems in VR improve learning outcomes by fostering scaffolding techniques and adaptive feedback mechanisms [13].

Interactivity in VR-based educational applications must balance two key aspects. On one hand, it increases motivation and active participation, which are crucial in game-based learning [14]. On the other hand, excessive interactivity can lead to cognitive overload, reducing knowledge retention [15]. Research suggests that interactive learning alone is not always sufficient for conceptual understanding [28]. Incorporating structured reflection moments, such as those integrated into the Virtual Playground, allows learners to process their actions, evaluate their understanding, and improve their problem-solving strategies [25].

As VR continues to evolve, studies emphasize the need for well-designed interactive mechanics that support meaningful learning experiences rather than relying solely on immersion and engagement. In the case of the Virtual Playground, interaction is designed not only to enhance user experience but also to encourage cognitive reflection and conceptual understanding of mathematical fractions.

2.1.3 Reflection

Since the early 1980s, reflection has been a prominent topic in scientific literature, particularly in professional education [25]. The concept has been defined in various ways depending on the disciplinary perspective. Dewey describes reflection as "active, persistent, and careful consideration of any belief or supposed form of knowledge in the light of the grounds that support it and the further conclusions to which it tends" [22]. Other interpretations include "active contemplation of doing something while doing it" [25], "reflective learning" [32], and "a method to comprehend and interpret experiences in complex and multifaceted situations that cannot be simplified by the application of teachable concepts and frameworks" [22]. These definitions are intentionally broad, as they aim to apply to various professional and educational contexts.

Reflection is considered fundamental in several domains, including healthcare, education, and design. A deeper understanding of reflection itself, along with methods for evaluating and fostering it, is essential for the design of interactive systems that aim to facilitate reflective processes in these fields [30].

Moon distinguishes between different types of reflective learning, describing reflection as a cognitive process similar to thinking, which is employed to achieve a goal or attain a desired outcome. However, reflection can also lead to unexpected insights and conclusions. Within an academic setting, reflection—whether in the context of reflective learning or reflective writing—is characterized by a deliberate and articulated intention to reflect, with a clear objective of acquiring knowledge, taking action, or gaining clarity [32]. This process is often structured and externalized, typically in a visible format such as written documentation, which allows for evaluation by others [32].

Schön introduces two primary modes of reflection: reflection-in-action and reflection-on-action. Reflection-in-action refers to the process of analyzing and modifying actions while they are occurring, whereas reflection-on-action involves assessing the outcomes of an action based on pre-established objectives after the fact [25]. These distinctions highlight the role of reflection as both an immediate and retrospective process, contributing to deeper understanding and improved decision-making in professional and educational settings.

2.1.4 Scaffolding

Scaffolding refers to the process of supporting a child or an inexperienced individual in solving a problem, completing a task, or achieving a goal that would otherwise be beyond their independent capabilities. Wood et al. (1976) defined scaffolding as an interactive exchange system in which the tutor utilizes an implicit understanding of the learner's actions to capture attention, limit the complexity of the task to manageable levels, provide guidance in problem-solving, highlight important aspects, manage frustration, and demonstrate solutions when necessary [35].

The concept of scaffolding originated from studies examining the role of mothers in facilitating language acquisition in toddlers and engaging them in structured activities such as peekaboo. The term itself is a metaphor that draws from the temporary structures used in construction, which provide necessary support until the building is stable enough to stand on its own. Similarly, in the educational context, scaffolding represents the support provided to a learner until they can perform tasks independently. Another interpretation of the metaphor suggests that scaffolding enables individuals to accomplish tasks that would otherwise be beyond their reach without such support [36].

In educational research, the concept of scaffolding has gained increasing relevance in recent decades. A key aspect of the term is its strong association with effective teaching, which involves the active and responsive engagement of a teacher in a student's learning process [57]. Although originally applied to direct interactions between a tutor and a student, the notion of scaffolding has since expanded to include collaborative learning, peer scaffolding, and whole-class instructional settings. Additionally, the role of instructional design has become a central focus, with various educational resources being conceptualized as scaffolds. While scaffolding was initially introduced for problem-solving contexts, such as constructing a pyramid, its application in mathematics education developed more gradually over time [37].

2.1.5 Constructivism

Constructivism is a learning theory that integrates principles from both behaviorism and cognitive science, emphasizing that learning is an active process of constructing meaning rather than passively receiving information. It describes how individuals interpret and understand their experiences by building upon their existing knowledge. According to Mvududu and Thiel-Burgess, constructivism is particularly relevant in assessing children's comprehension and fostering cognitive development, enabling learners to progress towards higher-order thinking [38].

Constructivist approaches in education emphasize the importance of active participation in the learning process. Teachers are encouraged to take into account students’ prior knowledge and provide real-world, interactive experiences that help them apply this knowledge in meaningful ways. In the context of VR-based learning, constructivism is highly relevant, as immersive environments offer students opportunities for exploratory and experiential learning, reinforcing the idea that knowledge is actively constructed through engagement with the environment.

Kanselaar (2002) identified two primary branches of constructivism: cognitive constructivism and social constructivism. Cognitive constructivism, based on the work of Jean Piaget [21], emphasizes the individual construction of knowledge through experience. Piaget proposed that cognitive development occurs in stages, predicting how children's understanding evolves as they grow [39]. In contrast, social constructivism, rooted in the theories of Lev Vygotsky, highlights the role of social interaction and cultural context in learning. Vygotsky argued that knowledge is co-constructed through interaction with others and that language plays a central role in cognitive development. Unlike Piaget, who suggested that development precedes learning, Vygotsky believed that learning drives development, emphasizing the importance of guidance and collaboration in the learning process. His concept of the Zone of Proximal Development (ZPD) suggests that learners can achieve higher levels of understanding with appropriate scaffolding and instructional support.

In the context of virtual reality education, constructivist principles align well with interactive and immersive learning environments. VR-based educational experiences provide opportunities for learners to actively explore, manipulate objects, and engage in problem-solving, fostering deeper conceptual understanding through experiential learning. Furthermore, the integration of intelligent tutoring systems and virtual assistants in VR applications supports Vygotsky's idea of scaffolding, enabling students to receive guidance as they engage with complex concepts.

Due to the broad application of constructivism, scholars debate whether it should be regarded as a learning theory, an epistemological theory, or a pedagogical philosophy. Despite this, its emphasis on active, student-centered learning makes it a fundamental approach in modern educational research and instructional design [38].

2.1.6 Defining grounding cognition and embodiment

Research in cognitive science and psychology has increasingly emphasized that cognition is not solely an abstract process confined to the brain but is deeply rooted in bodily interactions with the environment. This perspective, known as embodied cognition, suggests that learning is enhanced when sensory-motor engagement is coordinated with cognitive processes, allowing individuals to construct knowledge more effectively [20], [31].

Grounded cognition, a related framework, extends this idea by asserting that cognitive processes are shaped by perceptual and motor experiences rather than by abstract, amodal symbols. According to Barsalou, traditional cognitive theories view knowledge as being stored in abstract symbolic representations, detached from sensory experience. In contrast, grounded cognition argues that knowledge is constructed from real-world interactions, where perception, action, and mental representations are interwoven [20], [31].

In educational research, embodiment plays a fundamental role in enhancing engagement, conceptual understanding, and retention of knowledge. The idea that bodily states and movements influence learning has been extensively explored in various domains, including mathematics and science education. Several studies highlight the impact of embodied learning environments. In 2014, researchers compared mixed reality learning environments with traditional classroom instruction. Their findings indicated that students interacting in an immersive environment achieved significantly higher levels of conceptual learning due to the integration of movement and spatial interaction [33]. In another study, Glenberg and Romanowicz examined gesture-based learning in physics education. Participants were divided into two groups: one that answered questions using a keyboard and another that used gestures, such as swiping motions. Their results demonstrated improved cognitive performance in the gesture-based group, reinforcing the idea that embodied engagement strengthens learning outcomes [34].

Virtual Reality (VR) provides a unique medium for leveraging embodied cognition. Unlike traditional digital learning environments that rely on symbolic representations, such as text or images, VR enables learners to physically interact with digital objects, enhancing sensory-motor integration and deepening conceptual understanding. Johnson-Glenberg defines four pillars of embodiment, which serve as design principles for immersive learning: sensory-motor involvement, coherence between learning content and actions, presence in the learning environment, and adaptability to user actions [3], [33], [34]. Sensory-motor involvement reinforces memory and cognitive engagement, while coherence between bodily actions and the subject matter improves conceptual understanding. Additionally, presence in the learning environment enhances focus and motivation, which are essential for reflection and knowledge retention.

The Virtual Playground integrates embodied cognition principles by allowing users to physically manipulate objects, explore spatial relationships, and receive real-time feedback from a virtual assistant. This approach aligns with grounded cognition theories, which emphasize that knowledge is constructed through direct interaction with the environment rather than passive observation. By leveraging motion-based interactions, the Virtual Playground provides opportunities for structured reflection, helping learners deepen their conceptual understanding of mathematical fractions.

2.2 Virtual environments

The concept of Virtual Reality (VR) has evolved significantly since its early definitions. One of the first references to VR came from Lanier, Minsky, Fisher, and Druin (1989), who described it as "a simulation of reality that can surround a person, created with computerized clothing" [4]. Early references to "a special pair of eyeglasses" and a "glove" represented an initial vision of immersive technology, which has since evolved into more sophisticated virtual environments.

VR environments can be classified based on their level of immersion and the hardware utilized. Desktop environments display the virtual world on a monitor, keeping the user aware of their physical surroundings. Projected environments involve VR projected onto surfaces, such as CAVE systems. Augmented reality (AR) environments integrate virtual objects into the real world.

Psotka (1995) classifies VR into two primary categories: sensory immersive VR and text-based VR [6]. Sensory immersive VR offers a visually engaging experience where users interact with their surroundings through head and eye movements, commonly using head-mounted displays (HMDs). In contrast, text-based networked VR consists of real-time textual environments, where users interact through written commands over the internet. While text-based VR has proven valuable in distance education, it does not provide the same level of sensory immersion as visual VR systems.

A more recent definition by Gutierrez, Vexo, and Thalmann (2008) describes VR as three-dimensional environments where users can move and interact with virtual objects [7]. The defining characteristics of these environments are immersion and presence, which determine how users perceive and engage with the virtual space. Based on the level of immersion, VR systems can be categorized as fully immersive, semi-immersive, and desktop-based. Fully immersive systems, such as those using HMDs, offer high engagement but may cause cybersickness. Semi-immersive systems, such as CAVE environments, respond to user movement while providing a lower degree of immersion. Desktop-based systems, while cost-effective and widely accessible, offer a reduced immersive experience compared to HMDs.

Although various forms of VR exist, fully immersive VR has gained the most interest in research and practical applications due to its ability to create a compelling sense of presence. This thesis focuses on immersive VR in educational contexts, particularly how VR environments can foster reflection and conceptual understanding through interaction with virtual assistants.

Kaur (1998) defines a virtual environment as a space created through three-dimensional graphics, modeled to resemble either real or fictional worlds, where users can navigate and interact with objects [5]. Such applications may involve:

- Hand-held devices, such as joysticks and data gloves, allowing movement in three dimensions.
- Head-mounted displays (HMDs), which provide an immersive stereoscopic experience.
- Tactile feedback devices, which simulate touch, weight, or force.
- Three-dimensional audio systems, which offer spatialized sound for deeper immersion.

As shown in Figure 1, various VR equipment components, such as headsets, controllers, and tracking devices, contribute to the level of immersion and interactivity in virtual environments. These technologies enhance user engagement by providing real-time feedback and simulating realistic interactions within the virtual world.

While many technological advancements enhance VR interactions, this research primarily focuses on immersive VR using HMDs as a medium for learning, with particular attention to how virtual environments can be designed to encourage reflection and deeper understanding.

Figure 1 VR equipment. Source: https://www.azooptics.com/Article.aspx?ArticleID=2166

2.3 Virtual Reality in Education

Since the introduction of microcomputers in 1977, digital technologies have increasingly been recognized as valuable tools in education. With the evolution of immersive technologies, VR has emerged as a powerful medium to enhance learning experiences. Winn (1993) explored the role of VR in education, concluding that immersive virtual environments allow students to engage with content through direct, first-person experiences rather than abstract symbolic representations [8]. This shift from traditional passive learning to experiential learning has positioned VR as an innovative tool in modern educational frameworks.

One of VR's key advantages is its ability to transport learners to otherwise inaccessible locations, such as historical sites, space, or the human body. This capability fosters deeper engagement and enhances understanding through interactive exploration [9]. VR also supports personalized learning, allowing students to navigate virtual environments at their own pace while receiving tailored feedback, which can improve knowledge retention and conceptual understanding.

Javidi (1993) identified three core elements of VR's contribution to education: immersion, interaction, and engagement [10]. Immersion removes the barrier between the learner and the digital content, creating an alternative learning experience where abstract concepts become tangible. Interaction is critical in the learning process, as it enables students to actively manipulate objects, test hypotheses, and engage with their environment. Engagement enhances cognitive processing, making learning more intuitive and natural compared to traditional classroom instruction.

Moreover, VR encourages collaborative learning by allowing students to interact with peers within shared virtual spaces. This fosters teamwork, problem-solving, and critical thinking skills while also promoting social learning principles. A study by Cho (2018) examined VR's impact on memory retention, demonstrating that participants using spatial memory techniques in virtual environments performed significantly better in recall tasks compared to those using conventional study methods. These findings highlight VR's potential to optimize knowledge acquisition by leveraging the principles of embodied cognition and active engagement.

2.3.1 Education methodologies

Educational methodologies have evolved alongside technological advancements, transitioning from behaviorist learning theories to cognitive and constructivist approaches. With the introduction of virtual reality (VR), a new paradigm has emerged, allowing for immersive, interactive, and experiential learning environments.

The evolution of educational technology can be traced through four distinct generations. The first generation, influenced by behaviorist theories, emphasized repetitive drills and structured knowledge transfer. The second and third generations, shaped by cognitive learning theories, introduced intelligent tutoring systems that aimed to facilitate knowledge acquisition through optimized instructional design. The fourth generation, guided by constructivist principles, marked a shift toward experiential and discovery-based learning, where students actively construct knowledge through interaction and exploration [8]. According to Winn, constructivism has become the predominant educational model, surpassing previous frameworks in its ability to support active engagement and meaningful learning [8].

In the context of virtual environments, Dede [11] has argued that constructivist learning aligns seamlessly with VR applications. Much like Alice's journey through the Looking Glass, learners in VR settings immerse themselves in digital environments, engaging in collaborative and exploratory learning activities. The ability to manipulate virtual objects and interact with dynamic scenarios allows learners to construct knowledge through firsthand experience.

Bricken [12] further supported this perspective by emphasizing that VR fundamentally changes the way students interact with educational content. Unlike traditional methods, which rely on symbolic representations that require prior comprehension, VR enables direct engagement with abstract concepts in a more intuitive manner. The removal of the conventional computer interface dissolves the boundary between learner and content, fostering a more immersive and interactive experience. This approach has significant implications for subjects such as mathematics, where spatial representations can facilitate understanding without requiring students to first master symbolic notation.

The integration of virtual reality into educational settings is grounded in several key learning theories. Constructivist learning, as introduced by Piaget, posits that learners generate new knowledge based on their experiences and prior understanding [40]. Virtual reality embodies this principle by providing immersive environments where students actively engage with content, manipulate virtual objects, and explore concepts through trial and error. This form of learning promotes deeper cognitive processing and allows for more meaningful knowledge construction.

Experiential learning further supports the efficacy of VR-based education. As outlined by Kolb [41], the experiential learning cycle consists of four stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation. Virtual reality facilitates each of these stages by providing hands-on interaction, enabling learners to reflect on their experiences, conceptualize new ideas, and test their understanding in dynamic settings. The ability to engage with simulations and real-world scenarios enhances knowledge retention and fosters critical thinking.

Flow theory, developed by Csikszentmihalyi [42], highlights the importance of immersion and engagement in learning. A state of flow occurs when individuals are fully absorbed in an activity that challenges their skills while providing immediate feedback. Virtual reality creates optimal conditions for achieving flow by eliminating external distractions, offering interactive challenges, and maintaining a balance between difficulty and user competence. Research has demonstrated that VR-based learning environments can enhance cognitive engagement and motivation, leading to improved educational outcomes [43].

Another relevant pedagogical approach is gamification, which integrates game-like elements into learning experiences to enhance engagement and motivation [43]. Virtual reality allows for the seamless incorporation of gamification techniques, such as reward systems, interactive challenges, and real-time feedback. By transforming learning into an interactive and enjoyable experience, VR-based gamification has been shown to increase learner motivation and retention [44].

John Dewey's philosophy of learning by doing underscores the significance of practical, experience-based learning in the educational curriculum [45]. Virtual reality provides an ideal medium for implementing this approach, as it enables learners to engage with simulations, manipulate objects, and experiment with different scenarios in a risk-free environment. This methodology has been particularly effective in fields such as science, engineering, and medicine, where hands-on experience is crucial for skill development.

Social constructivism, as proposed by Vygotsky [56], underscores the role of collaboration and peer interaction in learning. Virtual reality facilitates social constructivist learning by enabling students to participate in shared virtual spaces, engage in real-time discussions, and collaborate on problem-solving tasks. The presence of virtual instructors or AI-driven tutors further enhances the learning experience by providing guidance and feedback in an interactive manner.

The application of these educational methodologies in virtual reality extends across various disciplines. In mathematics education, for example, VR-based spatial algebra allows students to manipulate equations visually, making abstract concepts more accessible [47]. In science and engineering, virtual laboratories provide safe and controlled environments for conducting experiments [58]. Medical training programs leverage VR simulations to allow students to practice procedures in realistic settings without the risks associated with real-life scenarios [48]. Language learning applications utilize immersive VR simulations to enhance vocabulary retention and pronunciation through interactive dialogues [52].

These methodologies demonstrate the transformative potential of virtual reality in education. By combining constructivist, experiential, and gamified learning approaches, VR has the capacity to create engaging and effective educational experiences. However, challenges remain in optimizing VR-based learning environments to ensure accessibility, usability, and pedagogical effectiveness. Future research should continue to explore how virtual reality can be refined to support diverse learning styles and enhance educational outcomes.

2.4 Related Work

Several research projects have explored the potential of VR in education, each with distinct methodologies and learning objectives. This section presents a comparison of prior work, highlighting similarities and differences in their design, application, and learning outcomes.

2.4.1 Theoretical Foundations: How VR Supports Learning

Virtual reality (VR) applications in education are grounded in cognitive and embodied learning theories, which emphasize interactive and experiential learning as key drivers of conceptual understanding. According to Cognitive Load Theory, learning is most effective when cognitive resources are optimized, reducing unnecessary mental strain. VR minimizes extraneous load by providing real-time, interactive visualizations of abstract mathematical concepts, such as fractions, allowing learners to manipulate fraction models spatially rather than relying solely on symbolic representation [49]. By aligning numerical concepts with intuitive spatial interactions, VR reduces cognitive effort and facilitates deeper comprehension.

Another foundational principle is embodied learning, which posits that cognitive development is closely linked to physical interaction with learning materials. Hamari et al. (2016) demonstrated that interactive VR applications, such as dividing a virtual pizza into fractional parts or adjusting ingredient measurements in a simulated kitchen, significantly improve long-term fraction recall and comprehension [50]. These interactions engage sensorimotor processes, fostering a deeper connection between abstract fraction concepts and real-world applications.

Recent studies have reinforced these theoretical underpinnings by analyzing VR's role in supporting constructivist and reflective learning approaches. Pellas, Mystakidis, and Kazanidis (2021) conducted a systematic review of VR applications in K-12 and higher education, concluding that immersive environments enhance engagement and spatial cognition while enabling students to actively explore mathematical concepts in problem-solving contexts [54]. Their findings highlight that VR's ability to simulate real-world scenarios improves knowledge retention, particularly in mathematics and STEM education. However, they also identify key challenges, including motion sickness, accessibility concerns, and the need for structured reflection to prevent learners from focusing solely on immersion at the expense of conceptual processing.

Soilis, Bhanji, and Kinsella (2024) extend this discussion by examining how VR fosters critical reflection and transformative learning through experiential immersion [46]. Their research highlights the importance of structured reflection in enhancing conceptual understanding, emphasizing that VR alone does not guarantee deep learning unless learners are prompted to analyze and internalize their experiences. The study identifies several design elements that facilitate reflection, including guided debriefing after VR interactions, time-delayed feedback to encourage reconsideration of past decisions, and role-playing scenarios that challenge pre-existing knowledge. By integrating these reflective strategies, VR applications can move beyond engagement and actively support meaningful conceptual change.

Lawson and Marchand Martella (2023) further emphasize the role of instructional design and scaffolding in ensuring that VR-based learning leads to meaningful outcomes [24]. Their study argues that unstructured immersion may cause students to focus more on novelty and interactivity rather than on learning objectives. Instead, they highlight the necessity of structured scaffolding mechanisms, such as progressive difficulty adjustments, instructional prompts, and adaptive feedback, to enhance comprehension and retention. Without such instructional support, students—particularly in complex domains like mathematics—may struggle to construct knowledge independently.

Collectively, these studies underscore the necessity of integrating interactive, reflective, and scaffolded learning strategies into VR educational applications. While VR excels at enhancing engagement and providing immersive experiences, its full educational potential is realized only when combined with structured reflection and instructional guidance. These insights directly inform the present study, which seeks to develop a reflection-driven VR learning environment for mathematical fraction comprehension, ensuring that interaction is balanced with deeper cognitive processing.

2.4.2 Comparative Studies: VR vs Traditional Learning

Several studies have evaluated the effectiveness of VR in mathematics education compared to traditional teaching methods. Liu et al. (2019) conducted a controlled study involving 120 middle school students, comparing two groups: one that learned fractions using interactive

VR lessons and another using conventional classroom methods. The results showed that the VR group exhibited a 25 percent higher improvement in problem-solving accuracy and conceptual understanding, attributed to the interactive and spatially engaging nature of VR-based learning [51]. Additionally, the VR group displayed higher engagement and motivation, which correlated positively with improved test performance.

A meta-analysis by Chen et al. (2020) synthesized data from 18 studies on VR in mathematics education, concluding that VR significantly enhances mathematical learning efficiency, particularly in subjects such as fractions and geometry [53]. The findings emphasized that VR-based fraction learning helps students develop intuitive reasoning skills by allowing them to dynamically manipulate, compare, and deconstruct fractions in a virtual environment.

Further supporting these findings, Wu et al. (2020) conducted a meta-analysis evaluating the impact of immersive VR using head-mounted displays on learning outcomes across multiple disciplines, including mathematics. Their study found that VR-based instruction generally leads to higher retention and deeper understanding compared to traditional learning methods, particularly in subjects requiring strong spatial reasoning [26].

Similarly, Makransky et al. (2021) investigated the role of immersion in science learning, comparing an immersive VR simulation with a traditional desktop-based learning experience. Their results indicated that while immersive VR significantly increased student engagement and motivation, the learning benefits depended on the integration of structured instructional strategies. This highlights the importance of pedagogical design in ensuring that VR is not just engaging but also supports deeper conceptual understanding [27].

Akman and Çakır (2020) further contribute to this discussion by examining the impact of a VR-based educational game on primary school students' mathematics achievement and engagement. Their study found that students using the VR game performed significantly better in mathematical assessments compared to those in traditional classroom environments. The highly immersive and interactive nature of VR facilitated deeper conceptual understanding and problem-solving abilities. Additionally, the engagement levels of students in the VR group were notably higher, with participants showing increased motivation and sustained attention. However, some students experienced motion sickness and cognitive overload, which underscores the importance of gradual adaptation mechanisms in VR learning environments [63].

Atsikpasi and Fokides (2022) provide additional insights into the impact of six degrees of freedom (6DoF) head-mounted displays (HMDs) in educational settings. Their review indicates that immersive VR enhances spatial awareness, problem-solving abilities, and embodiment in STEM education, making it particularly effective for visualizing abstract mathematical concepts. The study also highlights that VR-based learning results in higher engagement and motivation compared to traditional teaching methods, reinforcing the role of interactivity in deepening conceptual understanding. However, the authors stress that while immersion contributes to better retention, it must be balanced with structured instructional approaches to prevent cognitive overload [55].

Soilis, Bhanji, and Kinsella (2024) further highlight the challenges associated with balancing interactivity and reflection in VR learning. Their study discusses how cognitive overload can prevent meaningful reflection if interactivity is not carefully structured. They emphasize the importance of designing intervention points within VR applications that encourage learners to pause and reflect, ensuring that they do not simply engage passively with the content. Additionally, the study underscores the need for inclusivity in VR-based education, ensuring that learners with diverse cognitive and physical needs can fully engage with immersive environments [46].

Beyond pedagogical considerations, the study also raises ethical concerns regarding the intensity of VR learning experiences. Overly immersive or emotionally charged simulations may induce stress or anxiety, particularly if learners are not given structured debriefing opportunities to process their experiences effectively. The researchers argue that educators must integrate reflection mechanisms within VR applications to help learners analyze and internalize knowledge, rather than becoming overwhelmed by the novelty and immersion of the experience.

Pellas, Mystakidis, and Kazanidis (2021) further contribute to the comparative analysis of VR versus traditional learning methods, highlighting both the advantages and challenges of immersive VR. Their findings emphasize that VR-based learning significantly enhances engagement, spatial learning, and conceptual retention, particularly in mathematical and STEM subjects. However, their review also identifies key barriers, such as accessibility constraints, usability challenges, and the potential for cognitive overload if instructional strategies are not carefully designed. The study underscores the necessity of embedding structured learning experiences within VR environments, ensuring that students do not become overly focused on interactivity without deeper conceptual engagement [54].

Lawson and Marchand Martella (2023) provide further insights into the necessity of balancing immersion with structured learning guidance. Their findings indicate that unstructured VR experiences can lead to cognitive overload, diminishing the learning benefits of immersion. They argue that VR should not replace traditional instructional methods but rather serve as a complementary tool, particularly when combined with explicit teaching strategies, scaffolding mechanisms, and guided reflection moments. This perspective is highly relevant to fraction learning, as it suggests that students benefit most when interactive experiences are supported by instructional scaffolding that directs their focus towards meaningful conceptual understanding [24].

2.4.3 VR-Based Applications for Fraction Learning

Beyond theoretical discussions and comparative studies, various VR applications have been developed specifically for teaching fractions. These projects provide practical insights into how immersive environments support mathematical learning by combining interactive engagement with structured instructional design.

The MathVR project, developed at Stanford University, provides an interactive learning platform where students visually manipulate fractions by merging and partitioning virtual shapes. A study on MathVR involving 75 elementary students found that those who engaged in hands-on fraction activities within VR scored 30 percent higher on fraction assessments compared to those using traditional paper-based exercises. Researchers attributed this improvement to the interactive, multisensory nature of the VR experience [58].

Another prominent application is Fraction Quest, a gamified VR learning tool designed to improve students' mathematical proficiency. This program integrates fraction exercises into an interactive, competitive learning environment, where users earn points for correctly solving fraction problems. Research findings indicate that students using Fraction Quest showed a 40 percent increase in engagement levels compared to non-gamified VR learning approaches. The study found that gamification elements, such as real-time feedback, goal-setting, and competitive leaderboards, significantly increased student motivation while reducing anxiety about mathematics [59].

A separate case study investigating VR-based fraction learning among middle school students found that learners using immersive fraction simulations achieved 35 percent higher test scores compared to their peers using traditional fraction exercises. Additionally, the VR learners exhibited greater enthusiasm for mathematics as a subject, with 80 percent of participants expressing a preference for VR-based lessons over conventional teaching methods [60].

Another approach is Stepping into Virtual Reality, which employs VR to teach fractions by enabling students to physically manipulate objects. For example, a virtual pie can be divided into halves, thirds, or quarters, allowing students to visualize equivalence, addition, and subtraction of fractions in an interactive way. This hands-on learning method enhances conceptual understanding by grounding abstract mathematical ideas in sensorimotor interactions [61].

Similarly, Virtual Fraction Blocks allows students to manipulate three-dimensional virtual blocks to understand how fractional parts combine to form wholes. Studies on this system demonstrated that interactive VR improved students' ability to perform fraction addition and subtraction, particularly for visual and kinesthetic learners. These projects illustrate how VR can enhance mathematics education by providing real-time, interactive feedback that is difficult to achieve with traditional teaching methods [62].

By integrating interactive, gamified, and embodied learning principles, these VR-based fraction applications demonstrate the potential of immersive learning environments to support conceptual understanding, engagement, and long-term retention of mathematical concepts.

3 METHODOLOGY AND DESIGN

This thesis encompasses two primary design objectives: transitioning the original Virtual Playground from its obsolete technology to a modern platform and uncovering the reflective processes it facilitates. Both objectives presented significant challenges, requiring careful decision-making to ensure the usability of the updated game while maintaining an appropriate balance between interaction and reflection within the virtual environment.

Section 3.1 revisits the original Virtual Playground, explaining the rules of the game, the objects and models included, and providing game flows as examples for better comprehension. Lastly, it summarizes the results of previous experiments conducted with children.

Section 3.2 sets out the reasons that make this work important, explaining the necessity of hardware migration and the design considerations of the new version of the game. It outlines the challenges faced and the solutions implemented, both in terms of game design and technical execution.

Section 3.3 introduces the integration of structured reflection into the Virtual Playground. The design of the original game presented a critical tension between interactivity and conceptual reflection, with prior studies indicating that high interactivity often hindered moments of deep learning. To address this, the updated game incorporates new reflection-driven mechanisms designed to prompt players to engage more thoughtfully with mathematical concepts. Two primary modes—Didactic Mode and Self-Reflection Mode—were developed to encourage structured reflection. Didactic Mode provides guided instructional support through a virtual tutor, offering scaffolding prompts when players struggle with a problem. Self-Reflection Mode allows players to pause and reconsider their answers before moving forward, fostering greater cognitive engagement.

Section 3.4 details the technical implementation of the updated game, describing the transition to a modern game engine, improvements in hardware compatibility, and modifications made to enhance usability. Additionally, it discusses new features such as interactive menus and an enhanced panoramic view that were included to support player interaction and reflection.

Finally, Section 3.5 presents the evaluation methodology used to assess the effectiveness of the redesigned Virtual Playground. It outlines the framework for expert reviews, usability testing, and learning outcome measurements, setting the foundation for the experimental results presented in Chapter 4.

3.1 Revisiting the Virtual Playground

The Virtual Playground was developed in 2005 to investigate how interactivity in VR could influence children's understanding of abstract mathematical concepts, particularly fractions. The learning task was embedded within a playground-themed environment featuring six interactive elements: swings, monkey bars, a slide, a merry-go-round, a crawl tunnel, and a sandbox. These elements were color-coded and represented by blocks that needed to be correctly sized through fractional calculations. For instance, the task required learners to adjust the area of the playground elements by adding or removing blocks onto the playground tiles. To complete the task, they had to compare fractions (e.g., deciding whether 1/3 or 1/4 represented a larger amount) and apply their understanding to solve the problem. The VE provided intrinsic feedback, such as visual and audio cues, and employed a virtual owl and other agents to present rules and goals (Fig.2)

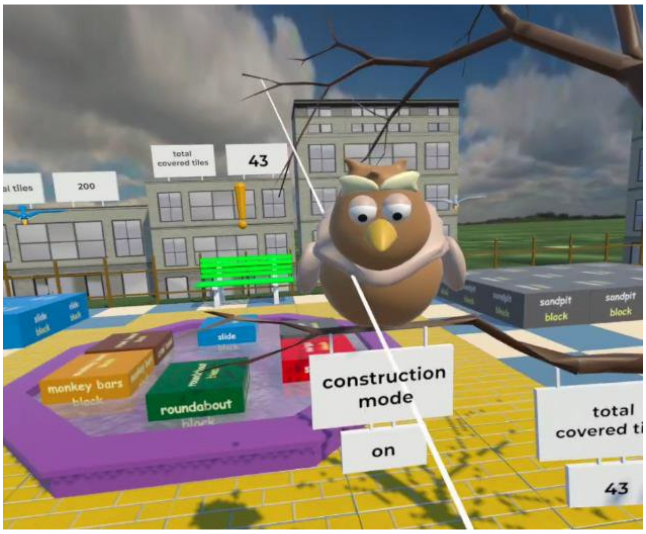

Figure 2 The virtual Owl presents the rules and guides the users.

Three experimental scenarios were tested with elementary school children, ages 8-11: interactive VR, passive VR, and a non-VR scenario using physical Legos. The interactive VR scenario allowed participants to manipulate virtual objects using a wireless wand in a fully immersive environment. The passive VR scenario involved observing a pre-recorded sequence where a virtual robot performed the tasks, encouraging participants to predict and explain its actions. The non-VR scenario used tangible Legos to replicate the tasks without digital mediation.

The findings revealed that while interactivity fostered engagement and problem-solving, it did not guarantee learning. In contrast, the passive VR scenario showed potential for promoting reflection, as participants observed and verbalized the robot's actions, engaging in reflective observation. This suggested that combining interactivity with guided prompts and reflective elements could enhance both engagement and understanding. Furthermore, it was found that the presence of a teacher positively influenced students' comprehension, with passive interaction yielding surprisingly better results than active engagement. The insights from the original Virtual Playground experiments serve as a foundation for this paper's investigation into modernizing the VE by incorporating structured reflection moments.

3.2 Reviving and Redesigning the Virtual Playground

The original Virtual Playground was designed for high-end virtual reality systems, specifically CAVEs, which were powered by SGI Onyx2 Supercomputers and utilized standard CAVE application development software along with open-source APIs such as OpenGL Performer. However, with the rapid evolution of technology, both the hardware and software became obsolete, particularly after SGI ceased operations in 2009. Consequently, reviving and extending this early work required a significant transition from projection-based VR systems to modern headset-based VR. Technological limitations at the time curtailed further development of the Virtual Playground, as the system relied on high-end, now-obsolete

CAVE-based hardware. Recent advancements in VR technology, particularly the proliferation of affordable head-mounted displays (HMDs) and accessible development platforms like Unity™, have revived interest in revisiting this line of research.

A fortunate aspect of the original development was that all 3D models were preserved in .obj format, enabling straightforward import into Unity. This allowed us to rebuild the environment by reprogramming the behavior of all virtual elements using Unity. Additionally, the interaction design had to be reimagined to fit the Meta Quest controllers, necessitating a complete remapping of control inputs (Fig. 3).

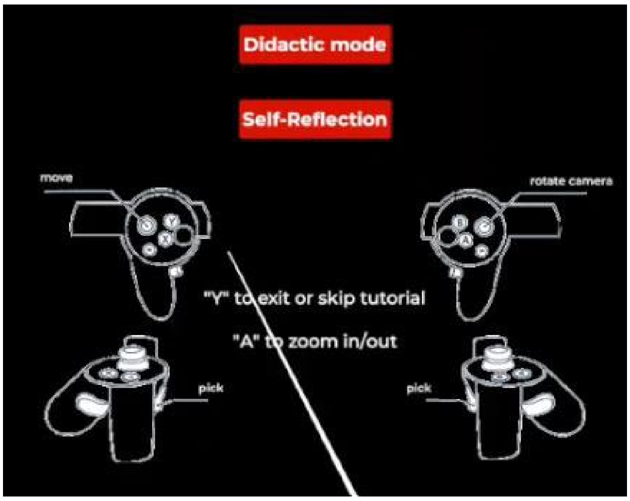

Figure 3 Interaction had to be remapped onto the HMD's controllers.

Another key challenge was recreating the audio elements. In the original version, virtual characters' voices were recorded with actors in a studio, as reliable text-to-speech technology was not available at the time. For the updated version, we leveraged modern text-to-speech systems to generate the characters' voices, but we also kept some of the original audio samples (e.g., the birds' conveying the rules, see Fig. 4), as well as various environmental sound effects.

Figure 4 Interaction with virtual characters, such as the birds, had to be reprogrammed

Additionally, the introductory scenario narrated by the owl was revised and made more succinct, acknowledging that younger users have limited attention spans and may struggle with lengthy instructions. The owl now welcomes players with a concise opening line:

"Welcome to the playground! Look around — things are a bit messy, with everything in odd sizes and places. Can you help us fix this? I'm here to guide you, so listen carefully!" before continuing with the rest of the scenario:

"First, click on me to switch to construction mode.

Now you're in construction mode! This view shows colored blocks representing each area on the playground. You'll use blocks to change size. You can click on me anytime to switch back and see your progress.

See that pool in the center? It's full of colored blocks you can use.

To make an area bigger, add blocks; to make it smaller, remove them. To pick a block, point to it in the pool and click the trigger. Move it to where you want to place it, then release the trigger to set it down. Each block is one tile, so remember, this is your unit.

In construction mode, you can also view the playground from above. Click on the 'A' button to try it and again to return to ground view.

Move close to each bird to learn what changes are needed. Only areas with a bird can be changed.

Switch to playground mode when you're ready to see if you sized things correctly. I'll check your work and give feedback if needed.

You can make changes in any order but remember: the total covered area must not exceed a quarter of the playground. Check the signs to see how many tiles you've covered.

Ready? Get set, go!"

3.2.1 Adapting Interaction Mechanics: From Desktop to VR

All the aforementioned modifications constitute the set of changes made in comparison to the original Virtual Playground. As previously mentioned, the reconstruction was based on a Unity 3D version of the project. In this version, several of the original features had to be modified to accommodate the different input system used in a desktop application (keyboard and mouse). Consequently, these desktop-oriented features needed to be re-adapted for VR interaction. Among the aspects of this transition were continuous locomotion, interactions with the birds, the owl and the cubes. Additionally, numerous technical issues arose during the migration from the older Unity engine used in the desktop application to the newer version supporting VR technology. In particular, shader compatibility and graphical rendering issues posed significant challenges, as certain visual elements did not function correctly. These were among the first technical obstacles encountered, requiring creative problem-solving to ensure a smooth transition and successful implementation of VR functionality.

In the desktop application, interaction with the playground objects could not rely on the original magic wand raycasting method. Instead, an alternative approach was implemented incorporating hand-integration and the use of a crosshair (Fig 5 & 6).

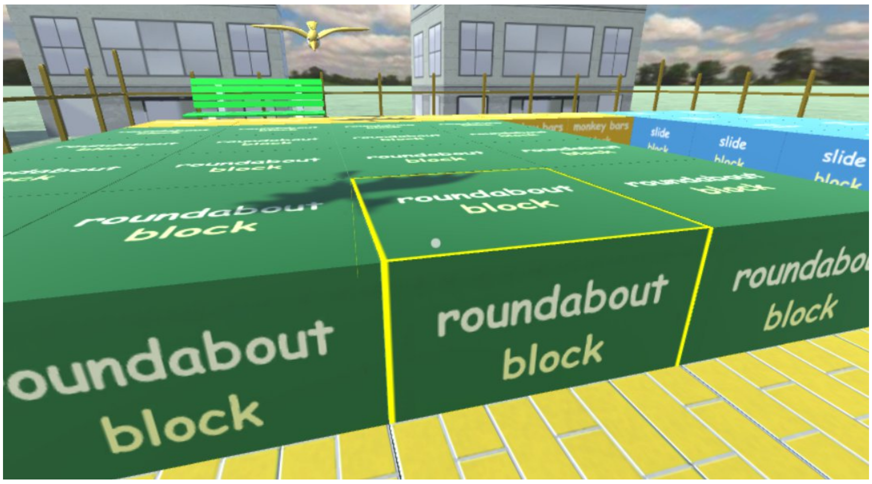

Figure 5 Interaction with virtual characters and objects though a crosshair.

Figure 6 Player picks a block with its integrated arms.

The crosshair enabled the player to focus on the object of interaction, effectively adapting the raycasting concept while ensuring a functional interaction system for a non-VR environment. Although this solution successfully fulfilled its purpose, transitioning to VR required a new interaction system that leveraged the immersive experience offered by virtual reality. To address this, we came up with the original idea of the player's interacting raycasting system. Since raycasting was no longer available in the desktop version, a new method was introduced that involved a crosshair and hand integration. Instead of using the magic wand to pick up a cube, as in the original VR version, the player in the desktop adaptation would aim at the cube using the crosshair and press the left mouse button to select it. Upon selection, virtual arms would appear, creating the illusion that the player was physically holding the cube. Pressing the same button again would release the cube onto the designated square tile in front of the player. The original bouncing animation of the cube, which continued until it settled onto the tile, was retained.

However, this integrated arms solution had to be abandoned, requiring a return to the original magic wand-based interaction. The previous implementation functioned by destroying the cube as soon as the player interacted with it, replacing it with a smaller cube inside the player's arms. During the landing phase, these temporary objects were destroyed, and a new cube was generated at a predefined height, following the landing animation sequence. Ultimately, this process would result in the cube appearing in its final position at its original size.

In the new VR version, the interaction system was reworked entirely. The player now raycasts the cube, allowing it to be held in the air at any height and in any direction as long as the Oculus Touch trigger button is pressed. The cube lands upon releasing the button and remains intact until the landing animation concludes. At this stage, a new cube is generated at a predefined height and size, completing the placement process. This transition introduced significant technical challenges, requiring the raycasting system, object manipulation mechanics, and landing animation to be completely redesigned and reprogrammed. Each stage of the interaction workflow had to be carefully restructured to ensure a seamless and intuitive experience within the VR environment.

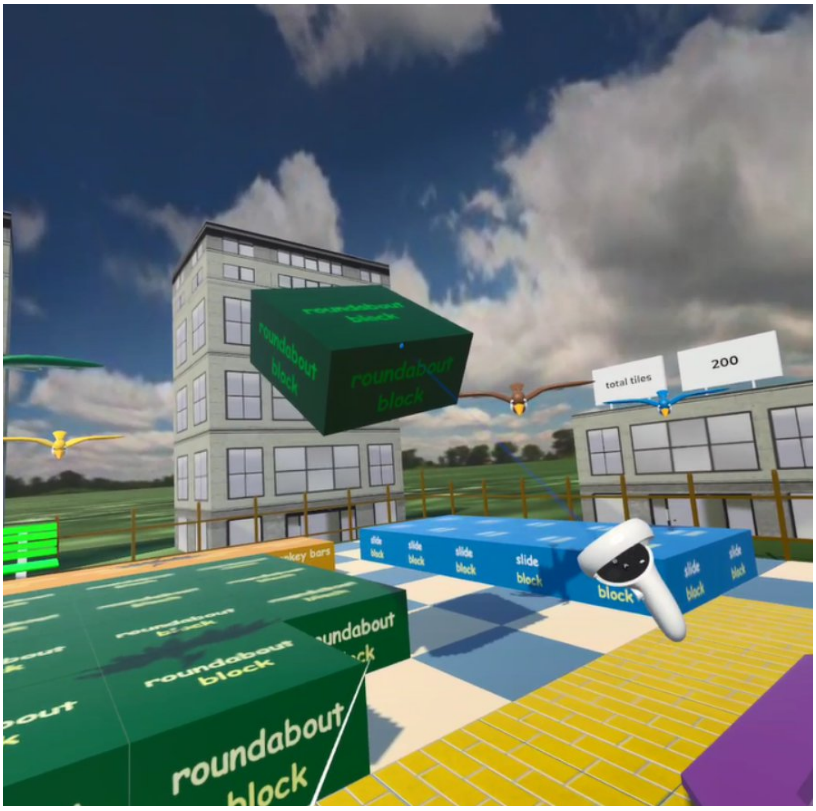

Figure 7 Player picks a block with raycasting.

The migration to the VR environment required a fundamental transformation at the code level. The Oculus integration library had to be incorporated to enable essential VR functionalities such as raycasting and object grabbing. Simultaneously, significant portions of the existing codebase were refactored to ensure compatibility with the new application. Any functionality that previously relied on keyboard inputs or mouse clicks had to be replaced with corresponding Oculus-specific functions. This process involved a meticulous review of the entire codebase, systematically replacing outdated input methods while ensuring that all game functionalities remained intact. Extensive testing followed to validate the integrity and stability of the upgraded system.

3.3 Embedding Reflection

The advent of immersive VR (iVR) has opened new possibilities for experiential and conceptual learning. Immersive VR environments provide learners with high levels of presence and engagement, which are critical for fostering motivation and sustained interaction. However, research indicates that these benefits do not automatically translate to deeper conceptual understanding.

Roussou et al. [24, 25] provide contributions to understanding the role of interactivity in VR learning environments through their development of the Virtual Playground, a VR application designed to teach abstract mathematical concepts. Their findings highlighted a crucial tension: while interactivity enhanced learner engagement, it often hindered reflection, which is essential for deep conceptual change. This tension forms the primary motivation for the present study, which aims to address this balance by integrating reflective moments into interactive VR experiences.

The need to resolve this tension served as the primary motivation for developing a game that incorporates structured reflection processes to overcome the challenges identified in previous research. This effort represents the second focus of this thesis, aiming to integrate reflective moments within an interactive VR environment to foster deeper conceptual understanding.

3.3.1 Research questions guiding our approach

In attempting to incorporate reflection in the revived version of the Virtual Playground, we came up with the following research questions that span the design, integration within iVR (balancing with interaction), and evaluation of reflection in terms of its effectiveness:

RQ1: How can opportunities for reflection be effectively embedded in interactive VR environments?

RQ2: What are the design tensions and challenges in balancing interaction and reflection in VR learning games?

RQ3: How do learners respond to reflection moments within an interactive VR game, and what impact does this have on their conceptual learning?

In the original Virtual Playground, the primary objective of the game was to solve mathematical puzzles related to fractions. In the interactive mode, the student would ask the bird for a mathematical problem and begin manipulating the space occupied by the colored cubes, adding or removing them to form an answer. The solution was then verified by pressing a button on the magic wand. However, the results of these experiments indicated that, although immersion and high interactivity were successfully achieved, children did not experience reflective moments to a satisfactory degree. In many cases, puzzles were solved by chance or through trial and error, while some students with prior video game experience found ways to bypass the scripted procedure without fully engaging with the mathematical concepts.

On the other hand, the results were more favorable in the passive mode. In this version, a robot solved all the mathematical puzzles while the student observed, resulting in a less interactive experience. This reduction in interactivity allowed children more time to process the robot’s answers and compare them with their own. Additionally, the physical presence of an elementary school teacher, who provided feedback and scaffolding prompts, further supported this process. As a result, children could recall and reconsider the solutions they had just observed, fostering reflection and leading to a deeper understanding of mathematical fractions.

Our expansion of the game needed to incorporate features that facilitate moments of reflection, provide scaffolding prompts, and promote a deeper conceptual understanding of fractions. At this point of the design process, we have incorporated opportunities for reflection in the virtual reality game (RQ1) and have begun exploring RQ2. The next subsection describes the extensions we have implemented.

3.3.2 Guided instructions and self-reflection integrated into the game.

Two modes were added to the original gameplay: Didactic Mode and Self-Reflection Mode.

Didactic Mode follows a guided instructional approach. The player interacts with the game as originally designed. However, after attempting to complete each task and seeing that it doesn't work, the option to get instructions is given by clicking on the virtual owl. An example of Didactic Mode follows: "Hmm.. I am afraid that your answer is wrong but don't worry. I am here to help you understand this. Would you like that?"

A panel then appears with three buttons: 'Try Again', 'Help Me' & 'Solve It.'

- if 'Try Again' is selected, nothing happens. The player can try to solve the puzzle again.
- If 'Help Me' is selected, a sequence of steps resembling a class lesson is conveyed to the user.
- If 'Solve It' is selected, the system switches to the correct result without providing further explanations.

Self-Reflection Mode aims to leverage the motivational power of interactivity to engage learners in action while embedding support for reflection. This dual prompting—action and reflection prompts—can be integrated into various forms, such as audio-visual feedback, through intelligent agents, and storytelling mechanisms that facilitate vicarious action. We plan to explore all these options in further application development.

We have just implemented "pauses" after carrying out each task, whether the execution of the task is correct or not. Following each task, the system asks the user "Do you want to see the answer or get time to think?" A panel appears with two buttons: 'Show Answer', 'I Need Time' (Fig. 8).

- If 'Show Answer' is selected, the user's answer is checked, and the mode is changed to reflect the result.
- If 'I Need Time' is selected, nothing happens, and the system responds: "Ok! Take your time to think about it."

If the response is incorrect, the system provides feedback, such as:

"I am sorry, but your answer is wrong. Don't give up and try again!" or "Oops, not quite right! Don't worry; keep trying, you're getting closer!"

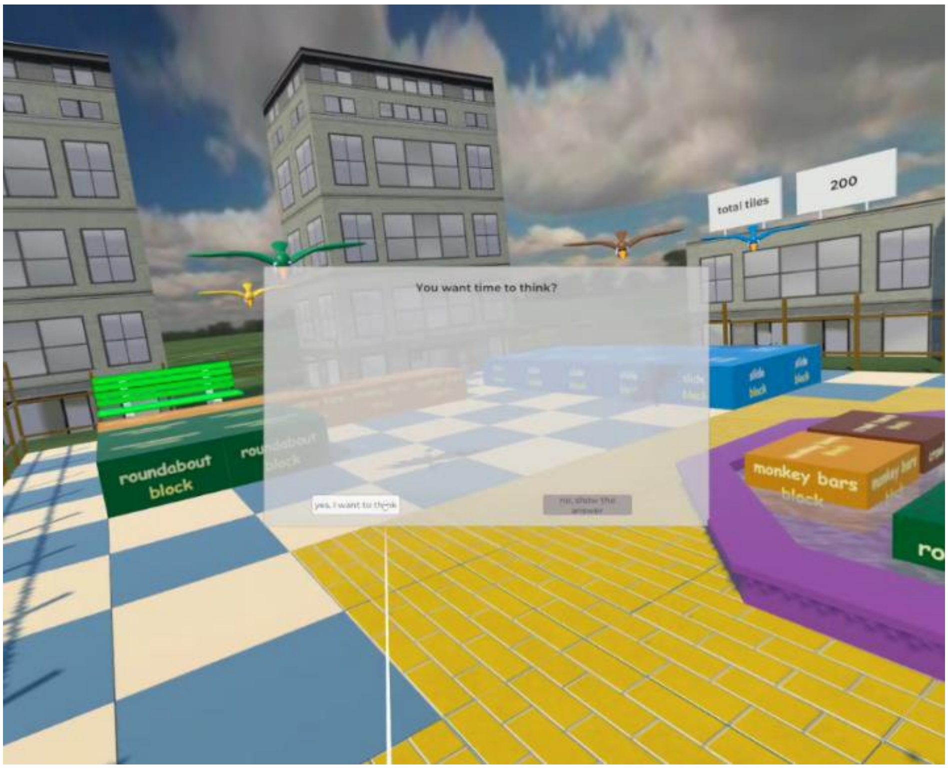

Figure 8 A user interface panel in self-reflection mode prompting the user to take time to think.

3.3.3 Guided instructions in didactic mode

Designing and developing the didactic mode was the most challenging aspect of this thesis, both from a technical and a design perspective. This mode introduces new features that extend the original gameplay by incorporating a virtual guide into the experience. The primary role of this virtual guide is to support learners in internalizing their experiences and fostering a deeper understanding through scaffolding prompts and guided debriefing.

The core objective of the playground remains unchained: the student must solve all the mathematical fraction puzzles to reveal the real playground objects and create a *“nice virtual playground to play”* as it is suggested in the beginning of the game. The guide intervenes only when the student requests assistance with solving the puzzle. Upon receiving an answer, the guide evaluates its validity. If the response is correct the owl provides positive reinforcement through an encouraging audio message. However, if the answer is incorrect, the didactic process begins.

At this stage, a user interface panel appears with three options: ‘Try Again’, ‘Solve it’ and ‘Help me’ as previously described (Fig 9). This system offers multiple choices, allowing the player to engage with the instructional process, skip it, or receive the correct answer immediately. The implementation of these options was designed to prevent potential negative emotions such as frustration, fatigue, or boredom, which could otherwise disrupt the interaction and diminish immersion in the game.

Figure 9 A user interface panel in didactic mode. The start of the sequence

Each instructional sequence begins by rephrasing the puzzle question. The owl then provides a series of explanatory steps, supplemented by visual aids displayed on the user interface panel (Fig 10, 11). For example, in the case of the red sequence:

“The red birdie asked you to select the answer that gives the larger number of blocks.

We have twelve red blocks in the playground. So, let’s see what is “one third” of the total twelve.

That is “one third” of twelve. That means that three of them make a total of twelve.

Great! Let’s see now what is “one fourth” of the total twelve.

That is “one fourth”! So, four of these make a total of twelve!”

Figure 10 A user interface panel in didactic mode. Explaining the mathematical problem (a).

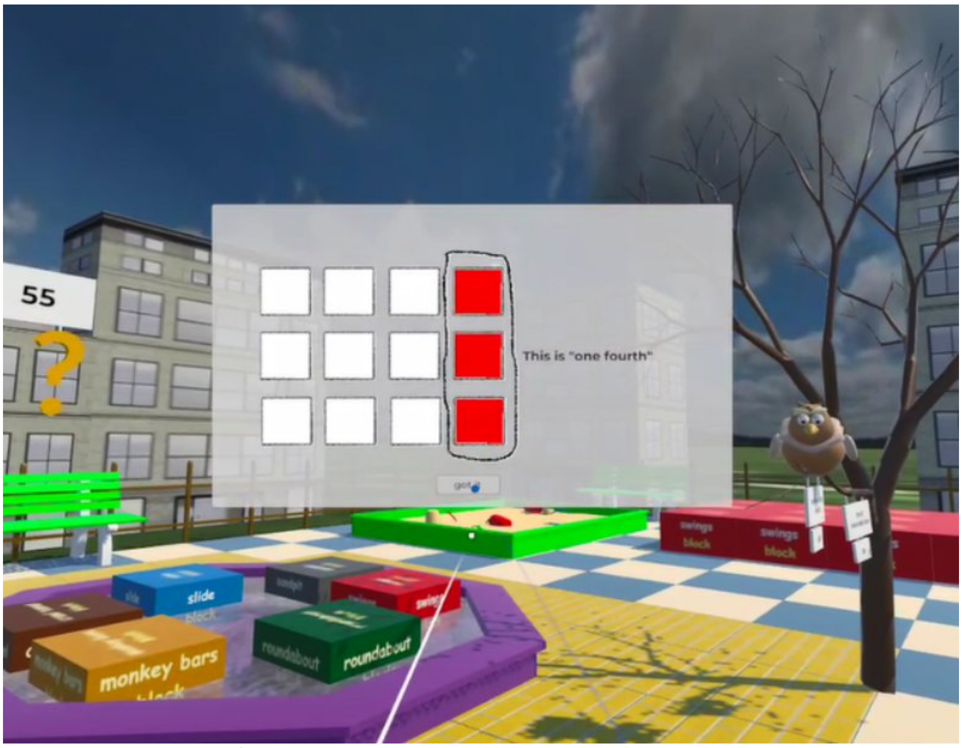

Figure 11 A user interface panel in didactic mode. Explaining the mathematical problem (b)

Up to this point, the owl delivers a sequence of explanations accompanied by corresponding images, allowing the player a few seconds to absorb and familiarize themselves with the new information. In certain instances, the owl grants the student control over the learning process by introducing the "Got it" button in the user interface panel (Fig 12). At this stage, the owl prompts the student to make a decision based on the knowledge acquired (Fig 13):

“Therefore, which of the two is larger? “

“Yes! You answered correctly! Now let me see you put these blocks on the playground and fix the swings.”

or

“Unfortunately, your answer is wrong again! Do you want to try again?”

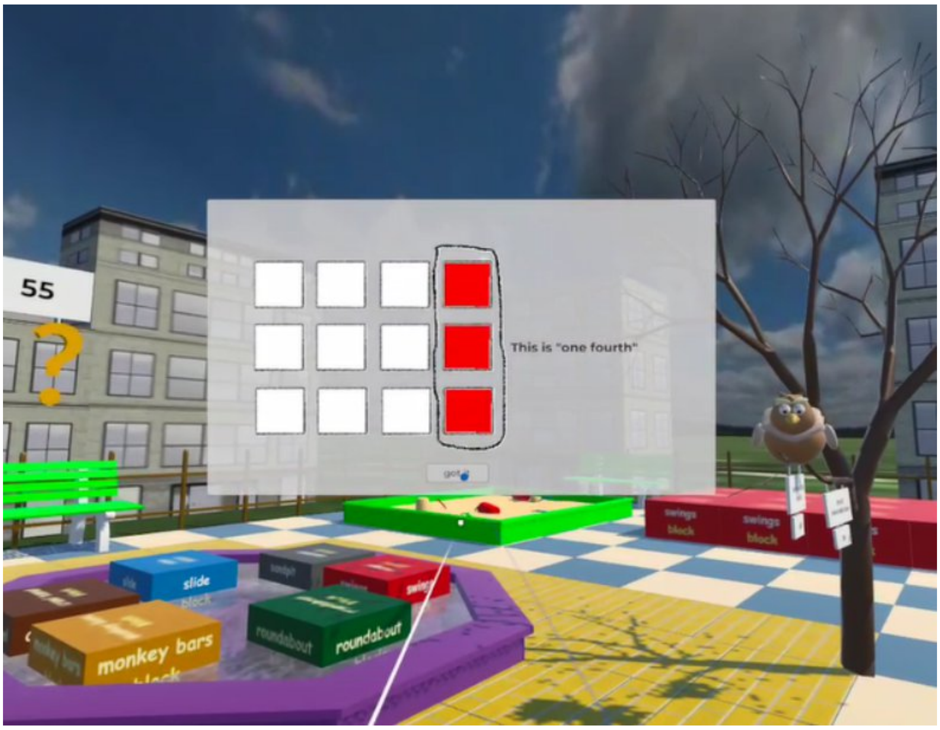

Figure 12 A user interface panel in didactic mode. ‘Got it’ button.

Figure 13 A user interface panel in didactic mode. Students must select an answer

.

The first message indicates that the student has made the correct choice, prompting the owl to conclude the sequence and encourage the student to place the correct number of cubes in the designated area. This assumes that the didactic sequence has effectively conveyed the necessary knowledge in easily comprehensible segments. Conversely, if the student provides an incorrect response to the owl's question, a different panel appears, displaying two options: the student can either attempt to solve the puzzle independently or request the virtual tutor to provide the correct answer. Both choices bring the sequence to an end with a final audio message corresponding to the selected option. In the latter case, the owl solves the puzzle, and the playground object is revealed on the field:

“*There you go! You truly want to fix this playground! I believe you can do it and I'll be here to check your answer after you finish your work!*

The correct answer is “one third” which means 4 blocks. It's ok you didn't find the answer this time. Let me place the blocks for you, so you focus on the next one! “

This strategy introduces the concept of scaffolding reflection in the virtual playground, based on the proposition that guided reflection can bridge the gap between surface-level engagement and deep conceptual understanding. This perspective highlights the role of the owl as an educator in facilitating reflective practices, ensuring that learners not only engage with content but also internalize and apply it effectively.

3.3.4 Prompt for reflection in self-reflection mode

This game mode grants the user complete control over the application. Designed as a more simplified version of the game, it aims to enhance reflective thinking by providing students with additional time to reconsider their answers.

Unlike the didactic mode, where the owl initiates a tutoring sequence, in self-reflection mode, the owl allows the student to manage the sequence leading to the solution of the puzzle. This process begins when the user interacts with the guide to verify their answer. At this point, a user interface panel appears with two options: “Show Answer” and “I Want to Think” (Fig. 8).

- Selecting “Show Answer” prompts the owl to immediately solve the problem, revealing the correct object in the playground. If the student's answer was incorrect, the virtual guide provides an audio response, allowing the user time to process and reflect on the outcome.
- Choosing “I Want to Think” results in no immediate action. Instead, the owl responds with an audio message, informing the student that they are free to take their time and return whenever they feel ready to attempt the puzzle again. Notably, in this case, the correctness of the answer remains unknown to the user.

This mode's simplicity is intentional. By transferring full control of the sequence to the player, it also assigns them full responsibility for the flow of the game. This approach serves as an experiment in leveraging interactivity within a virtual reality environment to encourage deeper engagement. The objective is to immerse students in the experience in a way that naturally fosters reflection and deeper cognitive processing.

3.3.4 Other features in Virtual Playground

In the previous sections, the gameplay mechanics of both the didactic and self-reflection modes were presented in detail. However, the Virtual Playground also includes several additional features and functionalities designed to enhance immersion and provide a more cohesive user experience. This subsection outlines these common elements present in both game modes, explaining their role and functionality within the application.

Exit menu

During the design phase of the new version of the Virtual Playground, it was unanimously decided to implement a user interface that serves a dual purpose: providing an option to exit the play mode, switch between game modes, or restart the current session, while also offering guidance on the functions of the touch controller buttons used in the application (Fig. 14). To ensure accessibility, a 3D exclamation mark object (Fig. 15) was placed in a visible location within the environment, encouraging users to interact with it for navigation and assistance.

This approach was chosen over assigning an additional button function to the controllers to prevent unnecessary complexity and reduce the risk of confusing users. Implementing a 3D object as an interactive element was considered a more intuitive and practical solution, ensuring ease of access without overloading the controllers with extra functionalities.

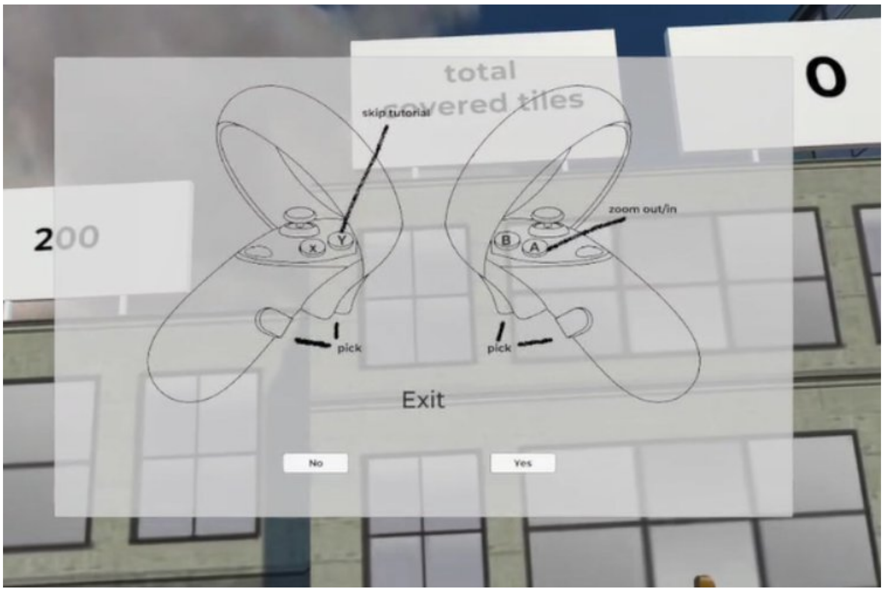

Figure 14 The exit panel. There is also guidance on the functions of the controllers.

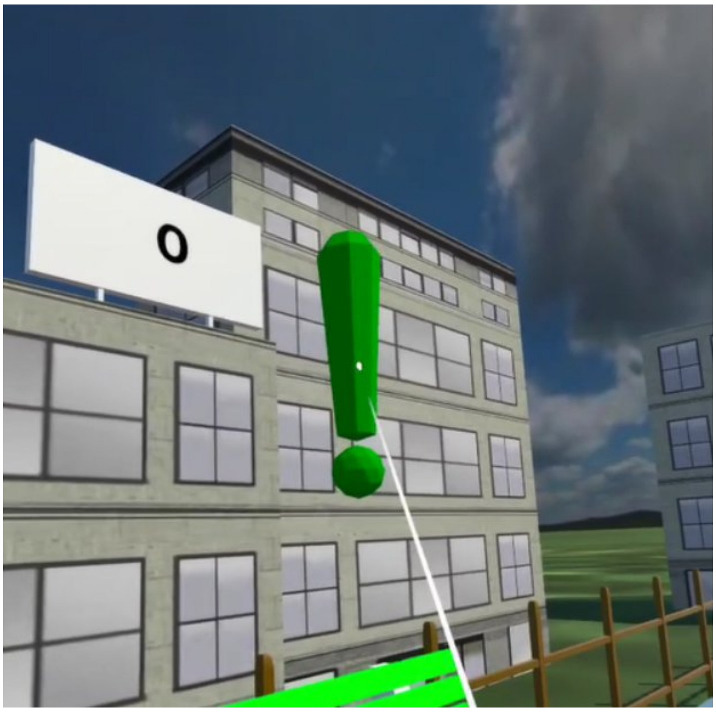

Figure 15 The exit panel. There is a UI that provides basic

Fly to the top (Panoramic view)

This feature was directly extracted and integrated from the original Virtual Playground application, allowing users to leave their current position with the press of a button and move to an elevated point above the playground for a panoramic view. As shown in Figure 16, the surrounding environment disappears during this transition to maintain the user's focus on the primary purpose of this feature: observing and evaluating the spatial arrangement of cubes.

While this functionality may not be among the most critical aspects of the game, it serves as a potentially valuable tool for certain users, as it is expected to contribute positively to the successful completion of the puzzles. For this reason, it was retained and incorporated into the new version of the application.

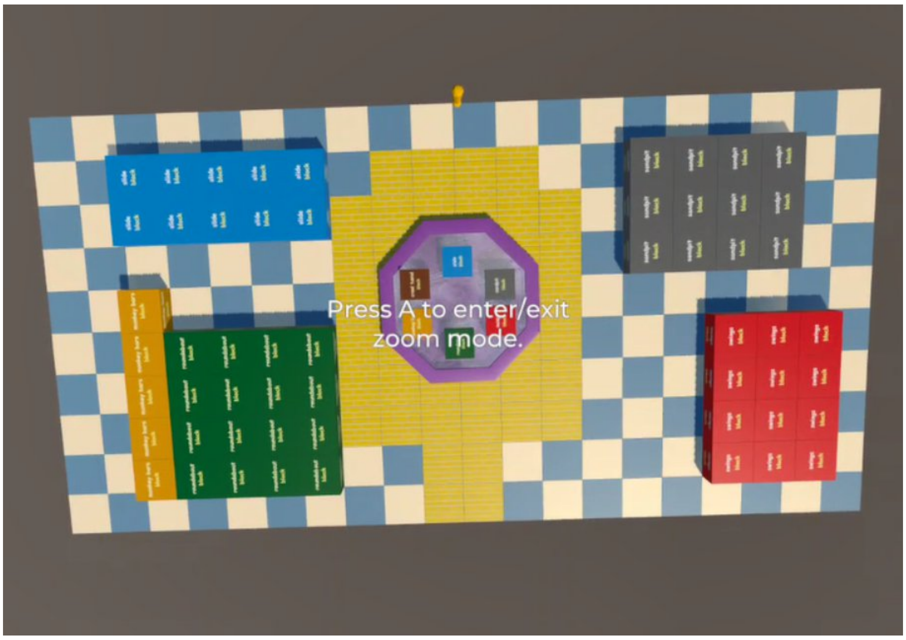

Figure 16 Panoramic view of the playground.

4 MAIN STUDY AND RESULTS OF THE QUALITATIVE ANALYSIS

As previously discussed in this thesis, the primary objective of this research is to develop an updated version of the Virtual Playground for the Quest headset, incorporating structured reflection moments into the interactive experience to address the long-standing tension between interaction and reflection. This updated version is intended to serve as a learning tool that educational experts can utilize and implement in primary school classrooms in the future. The technological limitations of the original game have been overcome through the use of the Oculus Quest 2, a modern head-mounted display, and the Unity development platform, which has revitalized interest in exploring this research direction.

Following the completion of the development phase, the game was delivered to VR and education experts for usability evaluation. Their detailed qualitative feedback was collected to inform future design and development improvements. To gain deeper insights into both the design and technical aspects of the application, structured interviews were conducted, during which experts provided their observations while interacting with the game. These recorded interviews highlighted both the strengths and areas for improvement, based on the participants' expertise in design and education. Finally, the collected feedback was analyzed and categorized based on the prioritization of the identified issues, ensuring a structured
approach to addressing the most critical concerns raised by the experts.

4.1 Experimental Conditions and participants in the Analysis

The study was conducted with a single group of participants, consisting of three VR experts and two elementary school teachers. The sole criterion for their selection was their field of expertise, as the study aimed to evaluate both the technical aspects of the VR application and its educational potential in teaching mathematical fractions.

Before interacting with the game, participants received a brief introduction to the purpose of the study and the background of the original Virtual Playground. It was explained that, although children did not face difficulties in navigating and interacting within the virtual environment, those who lacked a deeper understanding of mathematical fractions did not show significant improvement in their conceptual grasp of the subject. The main reason identified was the absence of opportunities for reflection, as the original game did not encourage students to reconsider or analyze their answers critically.

Following this introduction, participants were invited to engage with the updated version of the game, which was specifically designed to address this limitation by integrating structured moments of reflection. Each participant played through both game modes, experiencing the new mechanics and features firsthand. They were asked to evaluate the game from their respective professional perspectives—VR experts focusing on the technical implementation and usability, while teachers assessed its educational effectiveness and potential application in a classroom setting.

Every experiment conducted individually with no group collaboration or discussion between them. They had no objectives given to them, just the interview and the tutorial from the virtual guide, so they could explore freely. The participants were encouraged to verbalize their thoughts while playing, in order to record them and use this material as feedback. Each session lasted about thirty minutes. The teachers had no prior experience in VR technologies and applications, but they seem to adapt and get familiar with it quite easily.

After completing the gameplay session, participants provided detailed feedback through structured interviews, sharing their insights on both the strengths and areas for improvement of the game. Their observations were recorded and later analyzed, categorizing feedback based on the prioritization of identified issues. This approach ensured a comprehensive evaluation, balancing the technical and pedagogical aspects of the Virtual Playground's updated version.

Due to the easy portability of the equipment—an Oculus Quest device along with its touch controllers—the experiments were conducted in various locations, making participation more convenient. Each session was recorded directly from the Oculus Quest device, utilizing the embedded microphone to capture additional insights and comments made by participants throughout the gameplay. This approach eliminated a significant limitation of the original experiment, where the reliance on bulky and non-transferable CAVE-based hardware posed logistical challenges. As a result, this phase of the thesis was carried out more efficiently and on a larger scale.

4.2 Approach to Qualitative Analysis

Due to the small size of the participants we decided to conduct a qualitative analysis instead of analyzing numerical data which would not be meaningful either way. Our research focuses on descriptive, non-numerical insights gathered from expert feedback, interviews and observations. Qualitative analysis focuses on understanding experiences, opinions and interpretations rather than measuring variables with numbers. In our case, the five experiments (gameplay sessions + expert feedback) provide insights into the usability, effectiveness, and learning potential of our game.

Additionally, our study is qualitative because participants describe their experience, interaction and perception of the game rather than giving measurable data like scores or completion times. The exploratory nature of the game is also another significant factor of our choice, as our goal is to explore design improvements, usability challenges, and educational effectiveness, not to confirm a hypothesis with statistics. Lastly, we are using interviews, observations, and verbal feedback which are all qualitative research methods.

Since our data consists of opinions, comments, and observations, we conducted a thematic analysis using a dual categorization approach. First, issues were prioritized based on their impact on the overall experience and classified into three levels: high, medium, or low priority.

High-priority issues refer to critical problems that significantly affect usability, engagement, or learning and should be addressed in the next version. An example of such an issue is the failure of the game to recognize certain hand gestures properly, leading to frustrating interactions.

Medium-priority issues are important but do not severely hinder gameplay. While they should be improved, they are not urgent. For instance, making the owl’s voice clearer for younger students would enhance the experience but does not prevent users from progressing in the game.

Low-priority issues are minor or cosmetic concerns that can be refined over time. These include elements such as adding background music to create a more immersive atmosphere.

Second, we identified recurring themes in the feedback and categorized them into four key areas: usability & interaction, learning effectiveness, and technical improvements. This thematic analysis allowed us to highlight patterns in the participants' experiences and provide structured recommendations for future development.

Usability refers to the ease with which participants can navigate and interact with the game environment. This category includes feedback related to movement mechanics, interface clarity, accessibility, and overall user experience. If users struggle to control the game effectively, their engagement and learning experience may be negatively impacted. Interaction issues focus on how players engage with the virtual environment, objects, and game mechanics. This includes problems related to object manipulation, responsiveness of interactive elements, and the intuitiveness of control schemes. Interaction plays a crucial role in maintaining immersion and ensuring smooth gameplay.

Learning effectiveness evaluates the extent to which the game successfully supports conceptual understanding and reflective learning. It includes insights from educators regarding how well the structured reflection moments contribute to the learning process. Effective learning design should ensure that students are not only engaged but also able to internalize and apply the concepts presented in the game.

Technical improvements category addresses feedback related to the game's technical performance, visual clarity and hardware compatibility. While not directly affecting gameplay mechanics or learning outcomes, technical aspects contribute to overall immersion and user satisfaction.

By structuring the feedback according to these categories, we were able to prioritize key areas for improvement while maintaining a clear distinction between usability, interaction, learning effectiveness, and technical performance. The following section presents the participant feedback, categorized by priority and theme, along with suggested improvements for each issue.

4.3 Expert Insights and Prioritized Issues

Following the qualitative analysis methodology described in the previous section, this chapter presents the feedback collected from the five participants—three VR experts and two elementary school teachers—who evaluated the Virtual Playground. Their insights were gathered through direct interaction with the game, structured interviews, and recorded observations during gameplay.

The feedback was analyzed and categorized into three priority levels: high, medium, and low priority issues, based on their significance for improving future iterations of the game. High-priority issues include critical problems affecting usability, engagement, or learning effectiveness that require immediate attention. Medium-priority issues represent important but non-critical aspects that should be addressed to enhance the overall experience. Low-priority issues include minor design or aesthetic improvements that could be considered in future updates but do not significantly impact gameplay or educational outcomes.

The following sections present the categorized feedback, providing a structured overview of the most relevant usability, technical, and educational aspects identified by the participants. Each category includes direct participant observations and suggested improvements for future development.

4.3.1 High-Priority Issues

Transition from continuous locomotion to teleportation (Usability Issue)

The first and the second expert reviewer highlighted the need to transition from continuous locomotion to teleportation to mitigate motion sickness. This concern arises due to the possibility of nausea induced by continuous movement in VR for many people. The two teachers had little experience in VR applications and experienced severe nausea, which nearly prevented them from completing the experiment. As a result, they rushed to finish the game, avoiding the owl's feedback after solving each puzzle. For the last expert, R5, continuous locomotion caused such severe motion sickness that they were unable to complete the gameplay.

"Continuous movement can be disorienting for some users. A teleportation option should be considered to improve accessibility." – Expert R1

Suggested improvement: Implement a teleportation-based locomotion option as an alternative to continuous movement, allowing users to choose their preferred navigation style.

Marking in the field to outline the initial space of each cube color (Usability Issue)

The second expert and reviewer highlighted the need for an outline in the field to indicate the initial space occupied by each color. This observation arose when the expert attempted to solve the green puzzle and started removing cubes without first listening to the bird's instructions. As a result, he lost track of the original area covered by the green cubes, making it difficult to complete the division correctly. Expert R5 made the very same observation.

Suggested improvement: As both R2 and R5 experts suggested, an outline could be drawn around the initial area of each color island to provide a visual reference for players. This addition could also help guide users to place cubes in their designated areas, reducing the likelihood of misplacement or overlap with other colors. Implementing this feature would improve spatial awareness and assist players in maintaining accuracy throughout the puzzle-solving process.

Clarifying the Owl's Role in the Didactic Mode (Learning Effectiveness Issue)

During the didactic mode gameplay, the second expert followed an unintended approach to solving the puzzles. Instead of interacting with the owl to check their answers, they instinctively turned to the birdies for confirmation, regardless of whether his solution was correct or incorrect. As a result, they continued solving puzzles without ever switching to presentation mode or revealing the real objects in the playground. It was only when they reached the final puzzle that they considered interacting with the owl, as it was the last element they had not engaged with since completing the tutorial. At this point, they started to understand the intended gameplay flow.

Expert R3 exhibited the same behavior as R2, leading to a rapid sequence of puzzle-solving until the final challenge. At this point, there was a gap in the gameplay where the user became confused and began searching for a way to proceed until they eventually discovered the required interaction with the owl. R3 commented that this instruction was not clearly conveyed during the sequence. Even after understanding the mechanism, they only partially grasped how the owl verifies answers based on the last color the user interacted with. Specifically, R3 attempted to check the correctness of the red island of cubes they had created but, instead of selecting a red cube, they interacted with the red bird. This behavior was also observed with R2, indicating an intuitive but incorrect assumption made by multiple users.

Expert R5, due to severe motion sickness, was unable to spend enough time in the game to fully grasp the distinction between the two gameplay modes. As a result, they followed the same approach as the other experts, not engaging with the owl for assistance in didactic mode. This further supports the observation that users who experience discomfort in VR may prioritize rapid completion over engaging with the virtual tutor, which could impact the effectiveness of the learning process.

In contrast to the other experts, R4 quickly understood the functionality of the virtual tutor but deliberately chose to disregard it due to the motion sickness and nausea induced by the experience. Lastly, R4 instinctively relied on the birdies for confirmation, mirroring the behavior observed in R2 and R3.

Suggested improvement: This feedback was derived from our direct observations of expert R2's and R3's playthrough rather than explicit comments from them, but it raises a significant concern. If other users follow a similar pattern, it could lead to inconsistencies in gameplay data and interfere with research findings. Since players are expected to naturally recognize the owl as the primary interaction point for checking answers, this issue highlights a weakness in the current design and must be addressed as a priority.

One possible solution involves refining the tutorial sequence. As noted later in this analysis, expert R2 and R3 had difficulty following instructions due to missing some audio cues, which led them to suggest a replay mechanism or a log system for past instructions. Implementing such a feature could reinforce the owl's importance and prevent players from overlooking its role.

Another approach could be to enhance the owl's presence after the tutorial sequence. This could be achieved by displaying on-screen text reminders in the player's view or by having the birdies explicitly inform the player, after giving puzzle instructions, that the owl is responsible for verifying solutions. These measures would ensure that players recognize the owl as the key element in the game's didactic process.

Additionally, expert R2 expressed discontent with the automatic answer-checking mechanism of the owl, which provides immediate feedback based on the color of the last cube the user grabbed. This feature was originally intended to streamline interactions and reduce unnecessary steps between engaging with the owl and starting the didactic sequence. However, its implementation may need to be reconsidered to ensure that it aligns with user expectations and maintains a smooth, intuitive experience.

Stable user interface panels (Usability Issue)

The first expert reviewer suggested that the current implementation, where user interface panels follow the camera view with a slight delay, is outdated and may cause disorientation. In the current version of the game, all interface panels—both in the two gameplay modes and the main menu—follow the player's gaze.

Expert reviewer R2 made a similar observation, specifically regarding the main menu UI interface, noting that while the movement may help users keep track of the panel, it is not a suitable solution for interactive panels that contain UI buttons.

"User interface panels that follow the camera sight is an outdated and unnecessary approach. This could potentially cause dizziness and discomfort for users." – Expert R1

"The moving UI panel in the main scene is disorienting. I understand it helps the user keep track of it, but it is not a suitable solution when interaction with UI buttons is required." – Expert R2

Suggested improvement: Place user interface panels at fixed positions within the virtual environment instead of having them follow the player's gaze. This adjustment would help reduce dizziness and disorientation while also enhancing the overall aesthetics of the design.

Reducing Instructional Information in the Main Menu UI (Usability Issue)

The first expert reviewer reported confusion when encountering the instructional information displayed in the main menu panel. He noted that the amount of information regarding gameplay controls was excessive and possibly redundant, as the owl provides explanations later in the game modes. Additionally, the layout made it unclear what the primary objective was, leading to difficulties in associating the virtual buttons with their corresponding physical controls (Fig. 16).

"The main menu panel is too confusing. It was not clear what the objective was, and I had to remove the headset to match the buttons on the panel with the actual touch controllers." – Expert R1

Implemented improvement: Based on this feedback, we redesigned the main menu panel to provide a more concise and visually clear set of instructions, reducing unnecessary details. The updated version, shown in Figure 17, presents only essential information, ensuring that players can quickly grasp the controls without feeling overwhelmed. This adjustment minimizes potential confusion and improves overall user experience.

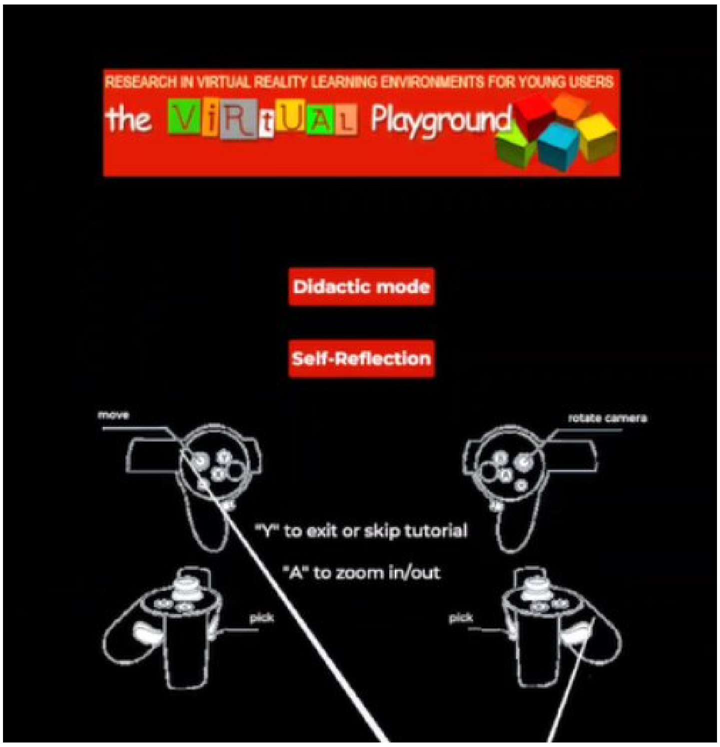

Figure 17 The updated version of the UI in the main menu.

Checking the solution with owl is not clear (Learning Effectiveness Issue)

Feedback from expert R1 confirms the assumption that there is a gap between submitting an answer and verifying its correctness. As suspected, this could cause a disruption in the flow of gameplay, as approaching the owl to check the answer is not an intuitive action for players. Expert R1 noted that, while he eventually figured it out, other users might not, making this a potential obstacle in the game.

"*I do not like the fact that I have to go and talk to the owl in order to confirm my answer. Some users may not think about it.*" – Expert R1

Suggested improvement: This issue was identified during the development phase, and several solutions were considered. One approach was implemented in the version tested by expert R1, where a grey fog effect was introduced to surround the virtual playground. This fog would appear and disappear based on the presence of cubes and the placement of playground objects. However, this solution was ultimately discarded, as it interfered with the aesthetics and overall design of the application. Expert R1 later confirmed this concern, expressing dissatisfaction with the visual impact of the fog effect. Future iterations of the game should explore alternative ways to make the solution-checking process more intuitive without compromising the design and user experience.

Comprehension of Audio Instructions (Learning Effectiveness Issue)

Expert R2 reported experiencing distractions that led to missing important audio messages. They specifically found the birds that follow the player's position to be disruptive, further diverting attention from the instructions. Additionally, they suggested implementing a way to replay the instructions, either by repeating the audio message or providing access to a log of past messages. They also mentioned that they did not notice the final audio cue at the end of the tutorial.

Expert R3 and R4 faced similar difficulties in the first stage of the game, as they did not fully comprehend the game's objective. This suggests that the tutorial sequence does not serve its intended purpose effectively. As currently implemented, it appears that users struggle to distinguish the key information conveyed through the audio sequence. While they understood that the first step was to speak to the owl, they became disoriented by the environment, causing them to miss critical instructions. We can reasonably assume that this issue may be even more pronounced for children.

"*I got distracted and lost the owl's audio message. Now I don't know what the instruction was.*" – Expert R2

Suggested improvement: To enhance instruction clarity and ensure that players do not miss important guidance, future iterations could include a message replay feature or a log of past instructions accessible at any time. Furthermore, adjustments to the visual and behavioral aspects of the birds may be necessary to minimize distractions and improve focus during tutorial sequences. A possible solution could involve making the birds static while the tutorial sequence is active, ensuring that players can concentrate fully on the instructions without unnecessary interruptions. This approach could also be applied to other interactive objects in the game to further reduce distractions and enhance the overall user experience.

4.3.2 Medium-Priority Issues

Disorientation in the "Fly to the Top" Feature (Usability & Interaction Issue)

Expert R2 found the "Fly to the Top" feature (Panoramic view) to be highly disorienting. He suggested an alternative approach where the player remains upright and grows while looking downward, rather than being positioned parallel to the ground. The current implementation felt unnatural and created an uncomfortable sense of spatial orientation.

"The fly-to-the-top function is very disorienting. I would prefer to become larger and look down rather than being positioned parallel to the ground. The sensation felt very strange." – Expert R2

Suggested improvement: To reduce disorientation, future iterations could consider modifying the transition effect so that the player maintains an upright position while gaining an elevated viewpoint. This adjustment may enhance spatial awareness and provide a more natural way to observe the playground from above. Testing different camera perspectives and scaling methods could help determine the most comfortable and intuitive solution.

Unnatural Cube Spawning in the Pool (Usability & Interaction Issue)

This observation was categorized as a medium-priority issue because it does not significantly affect the overall gameplay experience. However, for some users, it may disrupt the sense of immersion that the game aims to achieve, making it an important aspect to address in future development.

The issue identified involves a bouncing effect occurring when the player picks up a cube from the pool. Additionally, a new cube is immediately generated in the same location, which is necessary to ensure an unlimited supply of cubes throughout the gameplay. However, the immediate creation of the new cube can feel unnatural and slightly jarring to the user.

"When I pick up a cube from the pool, I notice a ‘bouncing’ effect that has no reason to happen. It would be more preferable to create the next cube with a little time delay." – Expert R1

Suggested improvement: Introduce a slight delay before spawning the next cube, as suggested by expert R1, to create a smoother interaction and prevent the immersion-breaking effect.

Incorrect Validation of Cube Placement (Technical Issue)

Expert R2 encountered a technical issue related to cube placement validation. Specifically, he moved the yellow cubes into an area that was intended for the brown ones. However, prior to this, he had already correctly placed both the brown and green cubes in their designated positions, which triggered the appearance of the corresponding playground objects.

Despite the correct placement of all cubes, the owl still issued the warning message that is intended to notify the user when cubes of different colors are placed in adjacent tiles, even if their total number is correct. In this case, however, the yellow cubes were not placed next to the green ones, meaning that the message was incorrectly triggered.

Suggested improvement: This issue suggests a coding error in the neighbor-checking mechanism, requiring further investigation and refinement. The system should only trigger the warning when cubes of different colors are actually placed in neighboring tiles, ensuring that the feedback remains accurate. Debugging and improving the placement validation logic will be essential to prevent misleading messages and maintain clarity in gameplay interactions.

Misinterpretation of Cube Arrangement (Medium-Priority Usability Issue)

Expert R2 encountered a misunderstanding when solving the blue puzzle. While they placed the correct number of cubes, they arranged them in an incorrect shape. Eventually, they made the connection on their own and realized that the cubes needed to form a continuous structure. Expert R4 faced a similar issue with both the blue and brown puzzles and noted the frustration caused by the placement restrictions on certain tiles. The inability to place cubes on fences, benches, and pavements created confusion and annoyance. R4 suggested that these restrictions might pose a greater challenge for children, who may have less patience than adults when experimenting within the game.

Suggested improvement: This issue does not prevent gameplay progression but may introduce unnecessary confusion for some players. Since the game does not explicitly indicate that cubes should be placed in a continuous shape (as in the case of the blue island), some users may struggle to recognize this requirement.

A possible improvement could involve introducing a subtle visual or verbal cue from the owl or another in-game element to reinforce the rule without making the solution too obvious. Additionally, a non-intrusive hint system or an optional example demonstration could provide guidance for players who do not immediately recognize the intended structure.

Furthermore, the restrictions preventing cube placement on certain tiles could be reconsidered. As R4 pointed out, these constraints do not appear to provide any educational benefits and may instead contribute to player frustration. Removing or modifying these limitations could improve the user experience while maintaining the intended learning objectives.

Representing the UI panel with the correct answer in last tutoring step (Learning Effectiveness Issue)

Expert R3 provided a valuable observation from an educational perspective during the didactic sequence of the brown puzzle. In some puzzles, the didactic sequence includes UI panels displaying a number of cubes grouped into sets, aiming to visualize the mathematical problem and facilitate comprehension.

In the case of the brown puzzle, the birdie asks for one-third of twelve. As part of the instructional sequence, the owl presents a UI panel showing twelve blocks grouped into three sets of four cubes each, prompting the student to evaluate whether the grouping is correct (Fig. 18). The student is given two options to respond. If they select the wrong answer, the panel disappears, and the owl provides an explanation. Expert R3 suggested that the UI panel with the correct grouping should remain visible during the owl's audio explanation, arguing that this would reinforce understanding and improve the learning experience.

Suggested improvement: From a technical standpoint, implementing this change is straightforward, yet it holds significant educational value, as highlighted by the education expert. It is strongly recommended that future development iterations incorporate this modification in the next version of the Virtual Playground.

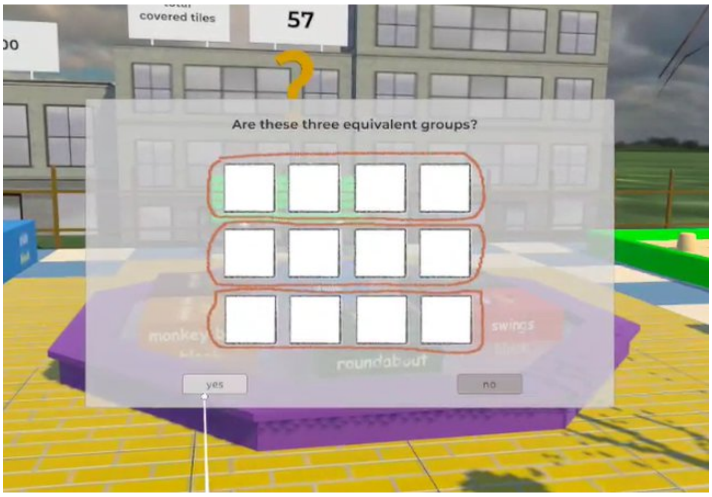

Figure 18 UI panel form brown didactic sequence

Unnatural Height of the player (Usability & Interaction Issue)

Expert R2 noticed an abnormality with his position in the field, specifically mentioning a disorienting sense of height in the playground and a feeling that his feet were "inside the floor." The Oculus Quest device is capable of tracking the user's physical height and adjusting it accordingly in the virtual world. However, this can result in unintended scaling issues, where taller users may exceed the desired height scope, creating an unwanted sense of being a "giant" in the virtual environment.

To prevent this, we manually shortened the virtual height of the player. However, this adjustment led to unforeseen consequences, including the perception of feet sinking into the floor and a general misalignment between the player's physical and virtual presence.

Despite expert R2 considering this a minor issue, we categorize it as a medium-priority concern for future development, as it could negatively impact immersion and user engagement.

"I feel my feet inside the floor. The player's physical height should be aligned with the virtual one." – Expert R2

Suggested improvement: This issue could be mitigated by implementing a function that limits height scaling within a predefined range, ensuring that all users experience a consistent perspective. If the detected height falls outside the defined scope, an automatic adjustment could be applied to prevent extreme variations. Given the technical complexity of this adjustment, we recommend thorough testing and calibration in future development phases
to ensure a smooth and immersive experience.

Inability to perform continuous raycasting for cube interaction (Usability & Interaction Issue)

This issue concerns the inability of the user to pick up cubes in a continuous manner due to the temporary deactivation of raycasting after dropping a cube. The current implementation prevents immediate interaction because the raycasting function disappears for a few seconds before reactivating. This delay was originally introduced as a technical workaround to avoid a major issue that disrupted the overall functionality of the game. Without this countermeasure, cube positioning could become unstable, causing dropped cubes to be placed in random locations on the field.

Both expert reviewers found this delay problematic. Expert R1 noted the interruption in gameplay flow, while expert R2 found that after extended gameplay (approximately 25 minutes), the delay became frustrating and negatively impacted the user experience.

"*When I pick up and drop a cube, I cannot pick up the next one immediately, as the raycast bar disappears for a while. Let the raycast bar reappear more quickly.*" – Expert R1

Suggested improvement: While the current delay serves a technical purpose, it requires further refinement to balance usability and stability. The exact cause of the issue remains unclear and requires deeper technical investigation. A potential solution could involve optimizing the cube interaction system to eliminate the need for an artificial delay or reducing the duration of raycasting deactivation to minimize disruption without reintroducing previous technical issues. If continuous cube interaction is to be implemented in future versions, the development team would need to explore a more robust solution to ensure smooth and uninterrupted object manipulation.

Inability to perform raycasting for cube interaction (Usability & Interaction Issue)

Expert R3 reported occasional difficulties when interacting with the cubes, noting that they sometimes had to attempt picking up a cube multiple times before succeeding. While this issue did not completely hinder the gameplay experience, the fact that it was noticed and commented on suggests that it warrants further attention. Similarly, Expert R4 experienced a more pronounced challenge, becoming stuck for several minutes due to an inability to interact with the cubes. It was only after some trial and error that they realized the issue stemmed from the short length of the raycasting beam. Lastly, Expert R5 also noted the issue with the raycasting beam length, emphasizing that users were required to walk long distances to interact with cubes, despite having them within their line of sight.

Suggested improvement: The likely cause of this issue is the length of the raycast beam. In the case of Expert R3, the beam was probably too short relative to the distance they maintained between themselves and the cubes, making interaction more difficult. While the current beam length appears to be within an appropriate range for most users, individual differences in player height and arm length may affect its effectiveness. Conducting further experiments with a diverse set of users will help determine the optimal raycasting distance to ensure and consistent interaction.

Malfunction of cube drop functionality (Usability & Interaction Issue)

This issue is closely related to the previously mentioned concerns regarding cube interaction. Expert R1 observed that some cubes, when placed in restricted areas, were sent back to their original position, while others overlapped or merged with existing cubes.

The first observation is an intended feature, designed as a safeguard to prevent cubes from being placed in forbidden locations such as pavement tiles or near the fence. In these cases, the game triggers an audio response from the owl and automatically repositions the misplaced cube to its original location. This behavior is an enhancement of a pre-existing feature from the original Virtual Playground, ensuring that game logic is maintained.

The second issue, however, was previously undetected during development. Despite extensive testing, the problem of cubes occasionally merging with others was not observed.

"*When some cubes were placed incorrectly, they were either sent back to their original position or remained inside other cubes.*" – Expert R1

Suggested improvement: The cause of the overlapping cube issue remains unknown and requires further technical investigation. Since this problem was not identified during the development phase, future updates should focus on resolving it to prevent unintended interactions. Despite its importance, this issue does not significantly impact gameplay progression and does not constitute a barrier to the game's completion.

Immediacy in didactic mode sequence (Learning Effectiveness Issue)

Expert R1 expressed frustration regarding the timing and pacing of interactions in the didactic mode sequence, particularly the delay between interacting with the owl and receiving an answer. He suggested that the owl should only engage in tutoring when the user explicitly requests help, while allowing an immediate answer option for those who do not need assistance. Additionally, the delay between the first audio prompt and the appearance of the selection panel (where the player chooses between tutoring, showing the answer, or trying again) was perceived as unnecessarily long, leading to frustration.

"In case you ask the owl for the answer, you have to wait in front of an empty panel for a few seconds and listen to an audio sample. It needs a shorter sequence. I suggest asking the owl for help only in case you need help. The player should skip this part if he wants a fast answer." – Expert R1

Implemented improvement: This issue was identified during the development phase, emphasizing the need for a more flexible and efficient way for users to receive answers. It was determined that players should not only have the ability to get an immediate answer but also be able to skip the tutoring sequence entirely if they do not need guidance.

To address this, we redesigned the first user interface panel to present the option of immediately receiving the correct answer at the beginning of the owl interaction. Additionally, a "skip" button was introduced to allow players to bypass the tutoring sequence entirely. This revised implementation, visible in the first panel of the tutoring sequence (Fig. 9), reduces unnecessary interaction time, minimizing fatigue and frustration for the user.

Expert R1's feedback showed that this solution was not fully adequate and suggested a more immediate method that the current design does not support. Future design and development teams should reconsider the structure of the didactic sequence's beginning to improve responsiveness while preserving its instructional value. One potential solution could be optimizing the audio clip to reduce waiting time while ensuring that the message remains clear and effective. Additionally, integrating an older implementation of checking the answer through a button press could offer an immediate response to the user. However, this approach would need to be carefully designed to maintain the didactic nature of the mode. Specifically, replacing the current raycasting interaction with a button press could streamline the process while keeping the guidance aspect intact.

Remove the exclamation mark from the playground (Learning Effectiveness Issue)

Expert R1 pointed out that the exclamation mark object in the playground lacks clear meaning and does not effectively indicate its function. The object was originally placed in a visible location to allow users to interact with it via raycasting and access the exit menu. However, the expert noted that its purpose was not immediately apparent and suggested moving its functionality to the owl instead.

Expert R1 and R2's opinions converge in some aspects, as the second expert also questioned the necessity of this object. Expert R2 suggested that a button press would be a more intuitive solution rather than interacting with an actual 3D object. Additionally, he noted that the UI interface message was ambiguous, as it was unclear whether the "Exit" label referred to exiting the application or merely closing the panel.

"*The exclamation mark above the bench does not imply what it can be used for. I suggest moving the panel functions to the owl.*" – Expert R1

“The panel says ‘Exit’, but does it mean exiting the application or just closing the panel?” – Expert R2

Suggested improvement: The exclamation mark was initially implemented to simplify interaction by avoiding the need for an additional button on the touch controllers. Expert R1 suggested removing the object and integrating the exit menu function into the owl. However, this solution presents a design challenge, as adding this functionality to the owl may overcomplicate interactions. An alternative approach could involve replacing the exclamation mark with a more intuitive object, such as a small whiteboard placed next to the owl, allowing users to interact with it in the same way while improving clarity and usability.

Regarding expert R2's observation, this part of the application was deliberately designed to avoid reliance on button presses, making interaction more immersive. However, the ambiguity in the UI message wording suggests that clearer labeling or additional instructions may be required. Further feedback from future users may help resolve this issue and determine the most effective solution.

Frame Rate Performance and Potential FPS Drops (Technical Improvement)

Expert R1 raised a concern regarding the game's performance, specifically questioning whether the frame rate stability was consistent throughout the gameplay experience. He suggested verifying whether the application experiences frame drops that could affect the overall smoothness and responsiveness of the VR environment.

"Should you check the FPS? It might be dropping frames." – Expert R1

Suggested response: The frame rate performance was not a focus during the development of this version, and no systematic FPS monitoring or optimization was conducted. Given the importance of maintaining a smooth VR experience, future iterations of the game should include performance profiling and frame rate analysis to determine whether frame drops occur and under what conditions. If FPS instability is detected, optimization strategies such as adjusting rendering settings, or optimizing shaders should be considered to enhance performance. Additionally, testing on different VR hardware configurations could help identify potential performance bottlenecks and ensure a consistently smooth experience.

Unexpected Behavior When Dropping Two Cubes Simultaneously (Technical Issue)

Expert R2 encountered a technical issue when attempting to pick up and drop two cubes simultaneously using both hands. While the game is not designed to support this interaction, it still allowed him to do so. However, upon releasing the cubes into the pool, only the first cube disappeared as expected, while the second remained visible instead of being removed.

Suggested improvement: This issue does not break core gameplay functionality but creates an inconsistency in the interaction system, which could confuse users who attempt to interact with multiple cubes at once. Since the game is not intended to support dual-hand cube manipulation, the system should either completely prevent users from grabbing two cubes simultaneously or properly handle both cubes when they are dropped.

Overlooking the skip button (Usability & Interaction Issue)

During the experiments with experts R2 and R3, it was observed that they did not make use of the skip button, despite its introduction in the first tutorial step. Additionally, the visual ray and accompanying text, which indicate the presence of the skip button when the player's gaze focuses on their hands, did not effectively draw their attention to this functionality (Fig. 19).

The skip button serves a practical purpose throughout the game, allowing users to bypass the owl's visual and audio sequences when necessary. However, its consistent neglect by the experts suggests that its presence is either unclear or unintuitive. While this is not a critical issue, it could lead to unnecessary fatigue and frustration, which are undesirable for the user experience. The current implementation of the visual ray and instructional text was expected to provide sufficient guidance, yet the findings do not support this assumption.

One possible explanation is that both R2 and R3 were right-handed and primarily interacted using their right hand, while their left hand—where the skip button was located—remained outside their field of view for most of the gameplay. This led to them overlooking the visual cue indicating the button's function. A potential solution could involve switching button functionalities between controllers to accommodate right-handed users, but this would merely shift the issue to the other hand rather than resolve it.

Presenting the skip button's functionality in the help menu (accessible via the exclamation mark object) and in the game's starting menu also did not seem to increase awareness. These observations highlight a persistent usability issue for which a clear solution is not yet apparent. Further user testing and alternative design approaches may be necessary to ensure that players can easily recognize and utilize the skip button when needed.

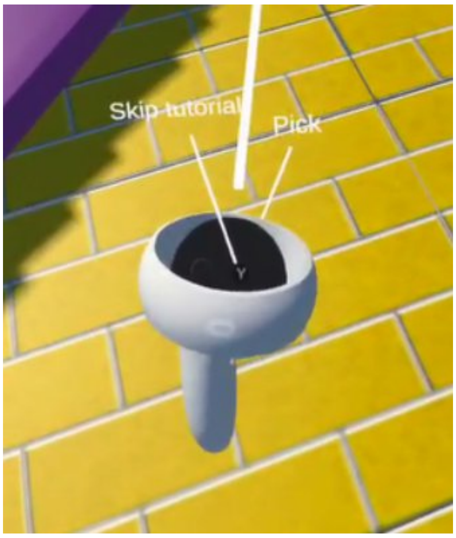

Figure 19 UI line and text indicating touch

4.3.3 Low-Priority Issues

Replacing the Didactic Moving UI Interface with a Blackboard (Learning Effectiveness Issue)

Expert R1's feedback suggests that the current moving UI interface used for tutoring should be replaced with a fixed blackboard and chalk, creating a more structured and visually coherent learning environment. This change would remove the outdated moving interface and instead establish a stable element that reinforces the didactic nature of this mode.

"*It would be more preferable for the white interface with the explanation to be fixed next to the owl instead of moving around. A blackboard with a chalk taking its place would be a nice idea*." – Expert R1

Suggested improvement: This suggestion has been categorized as a low-priority issue, as it is primarily a cosmetic enhancement rather than a functional necessity. However, it presents an opportunity to improve the educational atmosphere of the game and enhance the clarity of instructional content. Future development efforts could explore this modification as a way to refine the tutoring experience while maintaining the intended educational objectives of the Virtual Playground.

Moving instruction text closer to the camera (Usability Issue)

Expert R2 observed that the instructional text displayed in front of the player occasionally conflicts with objects in the playground, resulting in parts of the text becoming obscured during certain tutorial steps. To address this, he suggested moving the text closer to the camera while slightly reducing the font size to maintain its current proportions and readability.

"The text is hiding behind the objects in the playground. Probably you can solve this issue by presenting the text closer to the camera and enlarging the size of the text." – Expert R2

Suggested improvement: The proposed solution offers a practical and non-intrusive way to resolve this issue with minimal modifications to the existing code. By positioning the text closer to the camera, future developers can prevent visual conflicts between UI elements and 3D objects, ensuring clear and uninterrupted visibility of instructional content.

Disappearance of Raycasting Beams After Game Completion (Technical Issue)

Expert R2 encountered a technical issue where the raycasting beams disappeared after completing the game. As a result, he was unable to interact with objects normally. To restore functionality, he had to manually press the Y button on the controller, which reactivated the rays and allowed him to open the exit panel.

Suggested improvement: This issue indicates a bug in the interaction system, where the raycasting functionality is unintentionally disabled at the end of the game. Future development should include a thorough review of the event handling logic to ensure that raycasting remains active unless intentionally deactivated. A possible solution would be to automatically re-enable the rays once the game reaches completion, preventing players from having to use a workaround to regain control. Testing different game completion scenarios could help identify the exact cause of the issue and ensure smooth interaction flow.

Refurbishing the graphics and 3D objects (Learning Effectiveness Issue)

Expert R1 categorized this proposal as a very low-priority improvement but emphasized the need to enhance the visual quality of the application. Specifically, he suggested upgrading the 3D models used in the game, such as trees and birds, as well as improving shaders and shadows. Additionally, he recommended introducing movement to these objects to create a more dynamic and visually engaging environment, as the current playground appears too static.

"It is mandatory to upgrade the 3D objects, the shaders, and shadows. Adding movement to them would be nice because now everything is very static." – Expert R1

Suggested improvement: This feedback is highly relevant for future iterations of the game. The development focus of this version was primarily on improving the learning experience and reflection processes by integrating new features and ensuring their functionality. As a result, visual enhancements, including improvements to objects and graphics, were not prioritized. However, it is acknowledged that a more visually appealing and dynamic environment would significantly contribute to the game's overall engagement and immersion, especially for younger players. Future development efforts should consider upgrading textures, lighting, and animations to create a more immersive and stimulating virtual playground while maintaining the core educational objectives.

Inefficient Cube Removal and Placement Mechanism (Usability & Interaction Issue)

Expert R5 expressed concerns regarding the functionality of the central fountain, questioning its necessity and overall efficiency in cube manipulation. They noted that the current method of removing cubes—requiring the user to physically transport them to the fountain—felt cumbersome and unintuitive. Similarly, the process of placing new cubes by retrieving them from the fountain added unnecessary steps, making the gameplay less fluid. This issue may result in frustration and disrupt the overall learning experience, as players must repeatedly walk back and forth instead of focusing on problem-solving.

Suggested improvement: To enhance usability, R5 proposed a more streamlined approach for both cube removal and placement. Instead of requiring players to transport cubes to the fountain, an alternative mechanism could allow users to remove cubes by simply aiming at them for an extended period. Likewise, rather than retrieving new cubes from the fountain, players could generate a new cube directly on an empty tile by aiming at the desired location and pressing the trigger. This would allow the newly placed cube to adopt the color of its nearest neighbor, maintaining the intended mathematical relationships while improving efficiency and user experience. Integrating these changes would minimize unnecessary movement, making interactions more intuitive and reducing potential frustration for players.

4.4 Expert Insights from Educational Aspect

Even though the previous section outlines in detail the learning effectiveness issues identified by experts during the experiments in the playground application, this section is dedicated to presenting the insights of educational experts separately. By doing so, we shift the focus away from the technical aspects of the game and examine its educational potential more extensively. This discussion centers on the feedback provided by the two teachers who participated in the evaluation.

Both teachers had limited experience with VR technology and applications, and it is likely that this was their first direct interaction with a VR-based educational tool. They were encouraged to provide feedback on both technical and educational aspects, with particular emphasis on their pedagogical perspectives. While some of their observations pointed to areas for improvement in usability and technical implementation, their insights into learning effectiveness were particularly valuable. The suggestions they made for enhancing the educational experience were documented and discussed in the previous section. However, they also emphasized several positive aspects of the game's educational design.

The virtual playground consists of five mathematical puzzles focused on fractions. The virtual assistant in the didactic mode provides both visual and audio feedback for each puzzle, following a structured approach designed to ensure consistency in guidance. This approach was developed based on discussions with education professionals, who highlighted the importance of maintaining a uniform problem-solving framework. According to their experience in classroom settings, presenting multiple methods for solving a problem can lead to confusion among students, whereas adhering to a single structured approach helps maintain focus and comprehension.

Each puzzle follows a consistent instructional sequence: first, the bird provides instructions, followed by an explanation of the fraction concept. The problem is then visualized, prompting the student to make a selection among groups of cubes while receiving step-by-step guidance to develop a comprehensive understanding of the puzzle. Finally, if the student is unable to find the correct solution independently, a guided resolution is offered. This structured design supports scaffolding, gradually assisting students until they can complete the tasks without additional guidance.

Expert R3 strongly endorsed this approach, noting during the experiment that the virtual assistance provided was well-structured and highly beneficial for students. Drawing from their experience as a primary school teacher, they emphasized that the game's instructional design aligns with effective educational practices, reinforcing students' understanding of fractions in a clear and engaging manner.

Expert R3 emphasized the importance of the gray island as a stable reference point in the game. Its fixed nature provides students with a consistent anchor for their calculations, aligning with pedagogical strategies that utilize reference points in learning. In mathematics, having a fixed reference helps students develop a concrete understanding of relative quantities, particularly in fractions, where comparisons play a crucial role. This structured approach minimizes confusion and enhances students' ability to grasp proportion and scale more effectively.

Additionally, the teacher highlighted that each puzzle introduces a distinct mathematical operation—some require increasing the number of cubes, others involve reducing them, and some rely on comparisons with the gray island. This variety exposes students to different fraction concepts in a structured manner, reinforcing their understanding from multiple perspectives. By preventing repetition and maintaining cognitive engagement, this design fosters deeper comprehension and sustained interest in mathematical problem-solving.

According to experts R3 and R4, the placement of the red cube island on the ground, combined with the question *"Which is bigger: one-third or one-fourth?"*, serves as an effective method for understanding this mathematical concept. The red cubes are arranged in three rows of four, as shown in Figure 20, allowing students to visually compare the size of each fraction. This spatial organization makes it evident that one-third occupies a larger area than one-fourth, reinforcing the concept through direct visual perception.

Figure 20 Panoramic view of the red

Upon completing the experiment, we engaged in a highly insightful discussion with expert R3, which uncovered additional valuable insights into the application's effectiveness. Like expert R2, expert R3 initially approached the puzzles independently, without seeking assistance from the virtual tutor. This led to an important realization: it is highly likely that many children will follow the same pattern, solving as many puzzles as possible before eventually seeking help. When they do consult the virtual tutor, the system will reveal all answers at once but provide feedback only for the last color they interacted with. This design element was seen as beneficial, as it aligns with children's natural tendency to complete tasks rapidly and then review their mistakes. By observing which playground objects appear and which do not, they can quickly identify their correct and incorrect answers, allowing them to focus on their mistakes. This process has the potential to optimize gameplay duration, preventing fatigue or loss of interest due to prolonged playtime.

Expert R3 further noted that this behavior stems from the inherent nature of video games. Children perceive the virtual playground primarily as a game rather than an educational tool. Their instinct is to explore, interact with objects, and have fun, often overlooking the learning aspects. At this point, R3 suggested the presence of a physical teacher to guide the gameplay experience. This aligned with findings from the original Virtual Playground experiments, which also emphasized the role of an instructor. However, this insight was somewhat unexpected, as the enhanced owl character was specifically designed to replace the need for a physical teacher. This observation appears to challenge the realistic learning theory, which suggests that active engagement leads to better learning outcomes compared to passive observation. The contradiction suggests that the nature of video games may play a role in shaping children's interaction patterns.

Considering these reflections, we propose that the previously identified issue of clarifying the owl's role in didactic mode may not be a barrier to the game's learning effectiveness. Ultimately, players do interact with the owl and receive feedback, even if their approach differs from the intended learning sequence.

Lastly, expert R3 highlighted the limited embodiment present in the current version of the application. They suggested that allowing players to grab the cubes with their hands, rather than relying on raycasting, would enhance embodiment and, in turn, promote reflection and more effective learning. Building on this observation, they proposed an alternative approach to presenting grouped cubes. Instead of displaying predefined UI panels that visually segment the cubes into groups, the owl could encourage children to create their own groupings using a virtual marker. This suggestion is particularly insightful, as it would require students to actively count and organize the cubes rather than passively recognizing patterns. Such an approach would be especially beneficial for children who have not yet fully developed their numerical sense, as it would challenge them to engage more deeply with the mathematical concepts.

As regards expert R4, the general feedback we received was very encouraging and positive. First, it was pointed out that the general environment of the playground is very colorful and interesting, which helps children keep their attention and interest in the game. A little practice is needed, and the user can navigate and interact in the game, without any technical bugs or performance issues that could disturb the gameplay experience.

Expert R4 emphasized that the use of English in the application supports an interdisciplinary approach to teaching mathematics. Integrating different subjects into the learning process aligns with the latest curriculum guidelines and methodological recommendations, which promote cross-disciplinary connections. For example, geography is often paired with history to enhance understanding, and similarly, English can be easily integrated with other subjects that are essential in everyday life. Additionally, beyond teaching fractions, the game introduces geometric concepts, such as the requirement for certain shapes, like the brown and green islands, to be square. This aspect can serve as a useful tool for reinforcing prior knowledge or verifying students' understanding of geometry. It allows educators to assess whether students can recall fraction concepts and integrate them with spatial reasoning, fostering a deeper understanding of mathematical relationships.

As mentioned in the previous section, expert R4 found the restrictions on cube placement in certain tiles to be disruptive, arguing that they offer no educational benefits and are likely to cause frustration and fatigue for children. Maybe a bigger playground would solve this issue.

As far as the didactic sequences concerned, expert R4 was very positive and found the procedures very clear and accurate. The visualization of the separation in groups of the cubes is very helpful and all the didactic sequences follow a similar pattern. Specifically, the red sequence is considered even better as it visualizes the two choices of one-third or one-fourth of twelve, making it clear to understand the answer. R4 supports the approach of visualizing first a wrong group and then the correct one and believes that it will lead to deep comprehension of the concepts.

Expert R4 believes that the virtual playground has the potential to become a valuable tool in future classrooms but emphasizes the need for preliminary instruction before introducing the game. Children require guidance on what they will be doing and the purpose of the activity. While the tutorial is considered well-structured, R4 suggests that children may overlook parts of it due to distractions within the virtual environment. When asked whether children would be able to complete the game, R4 noted that those who have previously worked on similar exercises in school are more likely to succeed. To reinforce understanding before gameplay, R4 recommends engaging students in a hands-on activity using LEGO bricks or millimeter grid paper. These physical materials can help familiarize children with the 'adding and removing' cube-based process, making it easier for them to grasp the mathematical fraction concepts in the game.

5 DISCUSSION

5.1 Interpretation of results

The study revealed valuable insights not only about the limitations of our work but also about the potential of the Virtual Playground to foster deeper conceptual understanding of mathematical fractions in children. The qualitative feedback highlighted the strengths of the application while also identifying areas for refinement. Although expert suggestions point to necessary improvements for future iterations, their overall evaluation was positive, recognizing the effort invested and its potential to yield meaningful learning outcomes in children's experiments.

The findings of this study provide valuable insights into the integration of structured reflection within interactive VR learning environments and its impact on conceptual understanding of mathematical fractions. The expert evaluations revealed both the strengths of the Virtual Playground and areas that require refinement to optimize learning outcomes.

One of the key observations was the natural inclination of users to solve all puzzles at once before interacting with the virtual tutor. This behavior suggests that children may approach the Virtual Playground more as a game than as a structured learning experience, prioritizing immediate exploration and progression over reflection. While this tendency aligns with the motivational benefits of interactive VR, it also reinforces the importance of carefully designing intervention points that guide learners toward reflective thinking without disrupting engagement. The didactic mode attempted to address this by offering structured guidance, but its effectiveness varied depending on user behavior. Some users instinctively engaged with the owl for help, while others ignored it until the final puzzle, indicating that clearer instructional cues may be necessary to reinforce the tutor's role in the learning process. Additionally, expert feedback revealed that the movement system's continuous locomotion contributed significantly to this behavior. Experts R3 and R4 reported experiencing motion sickness and nausea, which led them to rush through the game rather than engaging with the owl for assistance.

Motion sickness was identified as a significant concern, particularly for users unfamiliar with VR. The transition from continuous locomotion to teleportation was implemented to mitigate this issue, yet one expert still reported severe nausea that impacted their ability to complete the experiment. This underscores the need for further refinement in movement mechanics and the potential inclusion of additional comfort settings to accommodate different levels of VR experience.

The results also highlight the significance of embodiment in the learning experience. Expert R3 noted that enabling students to manipulate objects directly with their hands, rather than relying on UI panels for fraction groupings, could enhance reflection and deepen conceptual understanding. This observation aligns with the principles of embodied cognition, which suggest that physically engaging with learning material fosters stronger cognitive connections. Future iterations of the Virtual Playground could integrate gesture-based interactions to allow students to physically group and compare fraction sets, further reinforcing mathematical concepts through embodied action.

Additionally, the study confirmed the benefits of providing a stable reference point, as seen in the use of the gray island. Experts emphasized that having a consistent spatial anchor for fraction-based comparisons helped learners develop a clearer understanding of relative quantities. This design choice aligns with established pedagogical strategies that emphasize anchoring points to facilitate numerical reasoning.

However, despite these strengths, several usability issues emerged that could impact learning effectiveness. For instance, some users encountered difficulties with the raycasting mechanism when selecting cubes, requiring multiple attempts to interact with objects. While this was not a critical issue, it introduced minor friction in the user experience. The findings suggest that optimizing raycasting length based on user variability—such as height and arm reach—could improve interaction consistency. Two of the experts faced real difficulties in placing the cubes in the non-forbidden areas. The relevant rules along with the small area of the playground created a lot of confusion and led to wrong choices about the spatial place of the cube islands.

The qualitative feedback also reinforced the ongoing debate about the role of human teachers in VR-based education. While the Virtual Playground was designed to replace the need for a physical instructor, expert insights suggested that direct teacher guidance remains a valuable component of the learning process. The presence of a teacher in previous iterations of the Virtual Playground provided real-time scaffolding, which some experts believed enhanced learning outcomes. This finding raises questions about whether VR applications should function as standalone educational tools or be integrated into blended learning environments where teachers facilitate reflective discussions alongside VR-based activities. Apart from teacher presence, educational expert R4 emphasized the importance of preliminary classroom activities related to the Virtual Playground. Hands-on exercises using LEGO bricks or millimeter grid paper to introduce fraction concepts could better prepare students for the gameplay experience, ensuring a smoother transition to the virtual environment.

A central contribution of this study is the integration of structured reflection within the Virtual Playground, designed to support varying levels of cognitive engagement and instructional guidance. The reflection mechanisms embedded in the game are grounded in scaffolding principles, ensuring that learners receive tailored support according to their individual needs. This approach recognizes that different students require different levels of instructional assistance, leading to the implementation of a multi-tiered reflection framework within the game.

The first level of reflection follows a structured instructional model, where the system provides explicit guidance through the virtual tutor. In this mode, learners receive step-by-step support as they progress through the problem-solving process. This approach aligns with traditional scaffolding methods, where learners are guided through challenges to develop a deeper conceptual understanding. Such structured assistance is particularly valuable for students who require external guidance to navigate mathematical concepts effectively.

The second level of reflection grants learners the ability to pause and reflect independently before confirming their answer. Rather than receiving immediate guidance, students are given the opportunity to engage in deliberate cognitive processing, allowing them to assess their reasoning before deciding. This approach accommodates learners who benefit from additional time to process information and fosters a more self-directed engagement with the educational material.

The final level offers immediate feedback by providing the correct answer upon request. This option allows learners to bypass reflection and proceed directly to the solution. While this approach caters to those who prefer immediate resolution, it also raises questions regarding the balance between interactivity and deep learning. Providing an option to skip reflective engagement acknowledges individual learning preferences but may limit opportunities for conceptual reinforcement.

The presence of these differentiated reflection mechanisms highlights a critical consideration in the design of VR-based educational applications: learning experiences must be adaptable to accommodate diverse cognitive needs. Not all students respond to instructional interventions in the same way, and an effective learning environment must account for variations in prior knowledge, problem-solving strategies, and engagement preferences. By incorporating multiple levels of reflection, the Virtual Playground is designed to address this heterogeneity, ensuring that learners who require structured assistance can access it while allowing more autonomous learners to engage with the material at their own pace.

This study underscores the importance of integrating flexible scaffolding mechanisms within immersive learning environments. When implementing reflection-based VR learning, it is crucial to consider the varying needs of students and the extent to which guided instruction enhances learning outcomes. The current design aims to achieve this adaptability, offering a framework that supports both structured guidance and independent exploration.

In summary, the results of this study highlight the potential of structured reflection in VR learning environments but also reveal challenges in balancing interactivity with deeper cognitive processing. The findings indicate that while immersive VR can successfully engage students in active exploration, careful instructional design is necessary to ensure that reflection is not overshadowed by the interactive elements. Addressing the usability and interaction challenges identified in this study will further refine the effectiveness of the Virtual Playground, contributing to the broader discussion of how immersive technologies can support conceptual learning in mathematics education.

During the oral defense of this thesis, members of the examination committee provided valuable feedback regarding the design and pedagogical implementation of the Virtual Playground. Two specific points were raised that warrant further reflection and may inform future iterations of the application.

One of the key observations made by the examination committee concerned the implementation of constructivist and scaffolding principles in the didactic mode of the Virtual Playground. Although the system is theoretically grounded in these learning theories, its current implementation appears to replicate traditional instructional methods. The virtual tutor largely delivers pre-defined explanations and visual demonstrations—much like a teacher using a blackboard—without fully leveraging the experiential and interactive potential of virtual reality. As a result, the learning process, although structured, risks becoming passive rather than participatory.

A more experiential approach, rooted in the affordances of VR, could significantly enhance the educational value of the didactic mode. For example, the feedback process could be made more active by involving learners directly through meaningful interactions with the environment. Instead of merely watching or listening to the tutor, users could manipulate objects, answer embedded challenges, or engage with interactive prompts during brief pauses in the instructional sequences. Such strategies would align more closely with the principles of constructivism and experiential learning, offering a more immersive and engaging educational experience.

A second point raised by the committee concerned the self-reflection mode. While the rationale behind offering learners' autonomy to reflect on their problem-solving process is pedagogically sound, it was noted that this mode may offer too much freedom without sufficient prompting or support. In its current form, users can complete entire puzzles without any built-in encouragement to pause and reflect, which may lead to missed opportunities for deeper cognitive engagement. In other words, the mode risks failing to produce actual moments of self-reflection if learners are not sufficiently guided or prompted to critically evaluate their actions.

This feedback suggests that future design iterations should consider introducing gentle scaffolding in didactic mode. Thought-provoking questions, minimal guidance, or embedded cues could be employed to support the emergence of reflective thinking without undermining user autonomy. The broader implication here is that while reflection is a critical component of deep learning, its successful integration into interactive systems requires thoughtful balancing between freedom and structured support.

Another observation made by the examination committee concerned the relationship between usability and learning effectiveness. Specifically, some of the learning effectiveness issues reported during the evaluation—such as the tendency of users to unintentionally ignore the virtual tutor and proceed to solve the puzzles without its guidance—were interpreted as usability issues rather than purely pedagogical ones. This overlap suggests that barriers to effective learning in immersive environments may stem from design-related limitations that hinder the learner's interaction with core instructional elements. As such, improving usability could directly enhance learning outcomes.

The committee also recommended that the educational effectiveness of the application be further investigated in future work. While expert observations provided valuable insights, a more systematic evaluation—potentially involving pre- and post-testing, learning analytics, or controlled user studies—could offer more concrete evidence regarding the application's impact on students' conceptual understanding.

5.2 Suggestions for Future Work

While the current version of the Virtual Playground has demonstrated its potential for fostering conceptual understanding of fractions through immersive VR experiences, several areas warrant further development and refinement. The insights gathered from expert evaluations and gameplay observations highlight opportunities to enhance both the technical aspects and the pedagogical design of the application.

One key direction for future work involves improving interaction mechanics to increase embodiment. As suggested by expert feedback, allowing students to directly manipulate cubes with their hands rather than relying solely on raycasting could enhance the learning experience. Introducing a virtual marker for users to draw their own groupings of cubes may further reinforce numerical comprehension by actively engaging learners in the problem-solving process.

Another area of improvement concerns the tutorial and instruction delivery. The feedback revealed that some users struggled to fully grasp the intended interaction flow, particularly regarding the role of the virtual guide in the didactic mode. Future iterations could explore alternative methods of onboarding, such as adaptive tutorials, real-time guidance, or clearer reinforcement mechanisms, to ensure that players understand how to engage with the tutor effectively.

Enhancing reflection mechanisms also presents a promising avenue for future development. While the integration of structured reflection moments has already been implemented, further research could explore different ways to encourage metacognition without disrupting engagement. For instance, incorporating delayed reflection prompts, where learners revisit their prior mistakes after completing the entire game, could provide additional reinforcement of key mathematical concepts.

From a technological perspective, refining the locomotion system remains an important consideration. Transitioning from continuous movement to teleportation successfully mitigated motion sickness for most users, but additional refinements could be explored to improve accessibility for players with varying levels of VR experience.

Furthermore, the role of the physical instructor in VR-based learning environments warrants deeper investigation. Although the virtual guide was designed to replace the need for a real-world teacher, expert feedback suggests that a hybrid approach—where the application works in conjunction with classroom instruction—could yield more effective learning outcomes. Future studies could assess whether an integrated teaching framework, combining both virtual and real-world scaffolding, enhances the overall educational impact.

Lastly, conducting large-scale user studies with children as the primary audience is essential. While expert evaluations provided critical insights, direct testing with students in real-world educational settings will offer a more comprehensive understanding of the game's effectiveness. This will help validate the design choices made so far and inform future iterations to better align with the needs and cognitive processes of young learners.

ABBREVIATIONS – ACRONYMS

CAVE	Cave Automatic Virtual Environment
AR	Augmented Reality
VR	Virtual Reality
HCI	Human-Computer Interaction
HMD	Head-Mounted Displays
STEM	Science, Technology, Engineering, and Mathematics
iVR	Immersive Virtual Reality

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