Integrating Motivation Into Immersive Learning: An Experimental Approach to Enhance Virtual Reality's Effectiveness in Science Education

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Joseph Ferdinand

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1. Betreuer:	Prof. Dr. Ulrich Trautwein
2. Betreuer:	Prof. Dr. Richard Göllner

Tag der mündlichen Prüfung:	16.11.2023
Dekan:	Prof. Dr. Ansgar Thiel

Vorsitzender der Prüfungskommission:	Prof. Dr. Andreas Lachner
1. Gutachter:	Prof. Dr. Richard Göllner
2. Gutachter:	Prof. Dr. Benjamin Fauth

Dedication

In memoriam of my beloved siblings, Michael, Deslourdes, and Ronald Ferdinand

«Nou nan kè m pou tout tan.»

[You will forever be in my heart.]

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I vividly recall the day when I received the invitation for a job interview at the Hector Research Institute of Education Sciences and Psychology. I was on vacation in the enchanting town of my homeland, Haiti. Little did I know that this invitation would mark the beginning of an extraordinary and transformative journey. I am profoundly grateful and honored to have had the opportunity to contribute to this groundbreaking research on the integration of technology in education, pushing the boundaries of knowledge. Although it is impossible to name everyone who played a role in this endeavor, there are certain people to whom I would like to extend special thanks.

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I hope that readers will find enjoyment in reading this thesis and, more importantly, that it ignites meaningful discussions on the use of technology, particularly immersive virtual reality, in science education.

Joseph Ferdinand

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ABSTRACT

This dissertation aims to integrate motivational support into immersive virtual reality (VR) to enhance its effectiveness in science education. VR is considered a unique multimedia learning tool that affords students the possibility to experience and interact with the learning content in a unique way. From a hedonic perspective, the embedded visual representations and images, narrations, and interactive elements in VR can foster students' motivation (e.g., interest, enjoyment, and engagement), which can positively affect their learning outcomes. From a utilitarian perspective, VR offers unique affordances that traditional classroom teaching cannot and places students at the center of the learning process, thus facilitating the learning of complex concepts that can otherwise be too abstract or difficult to learn. However, despite its unique character, VR's effectiveness as a learning tool has not yet been established. In this regard, a growing number of empirical studies suggest that VR positively affects students' interest, motivation, and presence in the virtual learning environment but does not necessarily lead to better academic achievement. One of the reasons often presented to explain these mixed results is that the embedded hedonic elements in virtual learning simulations—which are supposed to enhance students' motivation—can also distract students, cause overstimulation, and increase cognitive load. Moreover, many currently available virtual learning simulations fail to incorporate instructional and motivational support.

According to the cognitive theory of multimedia learning (CTML), students' motivation plays a fundamental role in learning with multimedia; it fosters generative processing, which is the processing capacity required for students to make sense of the lesson content. At the same time, it has been shown that embedded motivational features (interactions, vivid simulations, and visual representations) and seductive details in VR (interesting elements that are irrelevant for the learning objectives) can take students' attention away from their learning goals and thus impede effective learning in VR. Hence, the fundamental question is how to keep students focused on their learning goals and engaged in effective processing of the learning content—consequently mitigating the possible negative effects of the hedonic elements on their learning performance. It has been argued that the integration of motivational support into the instructional design of virtual learning simulations (hereafter referred to as the integrative approach) can facilitate appropriate cognitive processing of the learning content. This is because motivation and cognition are directly or indirectly linked, and motivation is an important driving force behind students' behaviors (e.g., actions and interactions) and mental

processes (e.g., attention, selection, organization, and integration of relevant learning content into prior knowledge).

On the basis of the CTML and the integrative approach, this dissertation proposes that VR's effectiveness can be enhanced when motivational cues are integrated into immersive learning environments. The concept of motivation in this dissertation is grounded in two other theoretical perspectives: the technology acceptance model (TAM) and the expectancy-value theory (EVT). Both theoretical perspectives foreground the role of motivation in learning and have practical implications for both the traditional classroom and multimedia learning tools. The TAM is the most parsimonious and widely used model to study and predict students' attitudes towards multimedia learning tools. The TAM stipulates that students' perceived usefulness of a given multimedia learning tool such as VR is the most important predictor of its acceptance—in terms of intention to use the learning tool—which constitutes a fundamental prerequisite for its effectiveness. In the classroom setting, EVT also highlights the role of students' perceived usefulness of the learning activities for their learning performance. Notably, empirical research based on EVT has shown that classical usefulness interventions help to stimulate achievement-related behavior and improve learning outcomes. Most importantly, a large body of research on EVT provides clear and parsimonious methods on how to affect students' motivation positively.

Following this rationale, this dissertation pursues the following three main objectives: The first objective is to test whether integrating classical usefulness interventions (a learning usefulness or a daily-life usefulness intervention) into a virtual learning environment could also enhance VR's effectiveness. The second is to investigate whether students' acceptance of VR as a learning tool can be increased through motivational interventions and whether acceptance subsequently fosters students' learning experience in VR (e.g., perceived presence in VR) and enhances their affective and cognitive learning outcomes. The third is to examine to what extent such usefulness interventions affect students' visual attention and cognitive processing of the lesson content. To address these objectives, this dissertation applies an experimental approach in three studies and uses multimodal methods (e.g., self-report paper-pencil tests, integrated questionnaires in VR, knowledge tests, and eye-tracking analysis). The data ($N = 196$) used in these studies were collected from 10 different German high schools (academic track).

This dissertation's original contribution to the field is threefold: First, it considers the use of VR in education from a hedonic and utilitarian perspective and shows that the integration of motivational support into learning instruction in VR can help increase VR's effectiveness.

By using a classical motivational approach (usefulness interventions) to operationalize motivation, it also demonstrates that such parsimonious interventions can also be applied in the context of learning with VR. Second, contrary to almost all studies on TAM, this dissertation uses an experimental approach to test the assumptions of this model. Correspondently, it shows that a learning usefulness intervention can, in fact, increase students' acceptance of VR as a learning tool, which subsequently affects their learning experience in VR. Third, using an eye-tracking-based approach, it shows that integrating motivation support into the virtual learning simulation positively affects how students process the learning content in VR: The usefulness interventions have a positive effect on students' visual attention and cognitive processing of the lesson content in VR.

From a theoretical perspective, this dissertation supports the integrative approach, according to which the integration of motivation into multimedia learning is fundamental for effective processing of the learning content and provides some evidence concerning the role of motivational support in students' learning performance in VR. From a practical and educational perspective, this dissertation shows how a parsimonious usefulness intervention can be integrated effectively into virtual simulations and how students' perception of VR—perceived usefulness and acceptance of VR as a learning tool—can be promoted. This dissertation also provides educators with valuable insights regarding the need for students to be pedagogically prepared and aware of the usefulness of educational tools before using them for learning and teaching purposes. Thereby, this dissertation contributes to our understanding regarding the importance of students' motivation in learning with VR and how it can enhance VR's effectiveness in science education.

ZUSAMMENFASSUNG

Diese Dissertation untersucht, in wie weit die Lerneffektivität immersiver virtueller Realität (VR) in der naturwissenschaftlichen Bildung durch die Integration motivationsunterstützender Elemente erhöht werden kann. VR gilt als eine einzigartige multimediale Bildungstechnologie, die den Lernenden die Möglichkeit bietet, den Lerninhalt auf einzigartige Weise zu erleben und mit ihrer Lernumgebung zu interagieren. Aus hedonistischer Sicht können die in VR eingebetteten visuellen Darstellungen und Bilder, Erzählungen und interaktiven Elemente die Motivation der Lernenden fördern (z. B. Interesse, Spaß und Engagement), was sich positiv auf ihre Lernergebnisse auswirken kann. Aus einer utilitaristischen Perspektive erweitert VR den Möglichkeitsraum des traditionellen Unterrichts im Klassenzimmer in einzigartiger Weise: Es stellt die Lernenden in den Mittelpunkt des Lernprozesses, wodurch das Erlernen komplexer und abstrakter Inhalte erleichtert wird. Trotz ihrer Einzigartigkeit ist die Lerneffektivität von VR als Lerninstrument noch nicht erwiesen. Eine wachsende Zahl empirischer Studien deutet darauf hin, dass sich VR positiv auf das Interesse, die Motivation und die Präsenz der Lernenden in der virtuellen Lernumgebung auswirkt, aber nicht unbedingt zu besseren akademischen Leistungen führt. Einer der häufig angeführten Gründe für diese gemischten Ergebnisse ist, dass die eingebetteten hedonistischen Elemente in virtuellen Lernsimulationen – die die Motivation der Lernenden steigern sollen – die der Lernenden auch ablenken, eine Überstimulation verursachen und die kognitive Belastung erhöhen können. Außerdem bieten viele der derzeit verfügbaren virtuellen Lernsimulationen keine hinreichende didaktische und motivierende Unterstützung.

Nach der kognitiven Theorie des multimedialen Lernens (CTML) spielt die Motivation der Lernenden eine grundlegende Rolle beim Lernen mit Multimedien; sie fördert die generative Verarbeitung, d. h. die Verarbeitungskapazität, die die Lernenden benötigen, um den Lerninhalt zu verstehen. Gleichzeitig hat sich gezeigt, dass eingebettete Elemente (Interaktivität, Simulationen und visuelle Darstellungen) und verführerische Details in VR (interessante Elemente, die für die Lernziele irrelevant sind) die Aufmerksamkeit der Lernenden von ihren Lernzielen ablenken und somit ein effektives Lernen in VR behindern können. Die grundsätzliche Frage ist daher, wie man die Aufmerksamkeit der Lernenden auf ihre Lernziele lenken und sie dazu bringen kann, die Lerninhalte effektiv zu verarbeiten - und damit die möglichen negativen Auswirkungen der hedonistischen Elemente auf ihre Lernleistung abzumildern. Eine Möglichkeit stellt die Integration motivationsunterstützender Elemente in das didaktische Design virtueller Lernsimulationen dar (im Folgenden als

integrativer Ansatz bezeichnet), was zu einer effektiven kognitiven Verarbeitung der Lerninhalte beitragen kann. Dies liegt daran, dass Motivation und Kognition sowohl direkt als auch indirekt miteinander verknüpft sind und die Motivation eine wichtige treibende Kraft für das Verhalten der Lernenden (z. B. Handlungen und Interaktionen) und die mentalen Prozesse (z. B. Aufmerksamkeit, Auswahl, Organisation und Integration relevanter Lerninhalte in das Vorwissen) ist.

Auf der Grundlage der CTML und des integrativen Ansatzes wird in dieser Dissertation untersucht, in wie weit die Effektivität von VR durch die Integration motivationsunterstützender Elemente in die immersive Lernumgebungen gesteigert werden kann. Das Konzept der Motivation in dieser Dissertation basiert auf zwei theoretischen Perspektiven: dem Technologieakzeptanzmodell (TAM) und der Erwartungswerttheorie (EVT). Beide theoretischen Perspektiven stellen die Rolle der Motivation beim Lernen in den Vordergrund und haben praktische Implikationen, sowohl für den traditionellen Unterricht im Klassenzimmer als auch für die multimediale Bildungstechnologie. Das TAM ist das aussagekräftigste und am weitesten verbreitete Modell zur Untersuchung und Vorhersage der Einstellung von Lernenden zu multimedialen Lernmitteln. Das TAM besagt, dass die von den Lernenden wahrgenommene Nützlichkeit eines bestimmten multimedialen Lerninstruments wie z. B. VR, der wichtigste Prädiktor für seine Akzeptanz ist, d. h. für die Absicht, das Lerninstrument tatsächlich zu nutzen, was eine grundlegende Voraussetzung für seine Effektivität darstellt. Im Klassenzimmer unterstreicht die EVT auch die Rolle der von den Lernenden wahrgenommenen Nützlichkeit der Lernaktivitäten für ihre Lernleistung. Empirische Untersuchungen auf der Grundlage der EVT haben gezeigt, dass klassische Nützlichkeitsinterventionen dazu beitragen, leistungsbezogenes Verhalten zu fördern und die Lernergebnisse zu verbessern. Ebenso bedeutsam ist, dass ein großer Teil der Forschung zur EVT klare und einfache Methoden liefert, wie man die Motivation der Lernenden positiv beeinflussen kann.

Diesem Grundgedanken folgend, verfolgt diese Dissertation die folgenden drei Hauptziele: Erstens soll geprüft werden, in wie weit die Integration klassischer Nützlichkeitsinterventionen (VR als ein nützliches Lerninstrument oder VR als ein alltägliches Instrument) in eine virtuelle Lernumgebung die Effektivität von VR erhöhen kann. Zweitens soll untersucht werden, ob die Akzeptanz der Lernenden für VR als Lerninstrument durch die Nützlichkeitsinterventionen erhöht werden kann und ob die Akzeptanz wiederum die Lernerfahrung der Studierenden in VR (z.B. wahrgenommene Präsenz in VR) fördert und ihre affektiven und kognitiven Lernergebnisse verbessert. Drittens soll untersucht werden, inwieweit solche Nützlichkeitsinterventionen die visuelle Aufmerksamkeit und die kognitive Verarbeitung des Lerninhalts durch die Lernenden beeinflussen. Um diese Ziele zu erreichen, wendet diese Dissertation in drei Studien einen experimentellen Ansatz an und nutzt multimodale Methoden (z. B. Selbstauskunft in Papier-Bleistift-Tests, integrierte Fragebögen in VR, Wissenstests und Eye-Tracking-Analyse). Die in diesen Studien verwendeten Daten (N = 196) wurden an 10 verschiedenen deutschen Gymnasien in der 10. Klasse erhoben.

Diese Dissertation leistet einen dreifachen Beitrag zum Einsatz immersiver VR in der naturwissenschaftlichen Bildung: Erstens betrachtet sie den Einsatz von VR in der Bildung aus einer hedonistischen und einer utilitaristischen Perspektive und zeigt, dass die Integration von motivationsunterstützenden Elementen in die VR-Lernumgebung die Effektivität von VR erhöhen kann. Durch die Verwendung eines klassischen Motivationsansatzes (Nützlichkeitsinterventionen) zur Operationalisierung von Motivation wird zudem gezeigt, dass solche sparsamen Interventionen auch im Kontext des Lernens mit VR angewendet werden können. Zweitens werden in dieser Dissertation, im Gegensatz zu fast allen Studien zum TAM, die Annahmen des Modells mit einem experimentellen Ansatz überprüft. Dementsprechend zeigt sie, dass eine Intervention zur Erhöhung der wahrgenommenen Nützlichkeit von VR als Lerninstrument tatsächlich die Akzeptanz der Lernenden für VR als Lerninstrument erhöhen kann, was sich wiederum auf ihre Lernerfahrung in VR auswirkt. Drittens wird mit Hilfe eines Eye-Tracking-Ansatzes gezeigt, dass die Integration von motivationsunterstützenden Elementen in die virtuelle Lernsimulation einen positiven Einfluss darauf hat, wie Lernende die Lerninhalte in der virtuellen Lernumgebung verarbeiten: Die Nützlichkeitsinterventionen haben einen positiven Effekt auf die visuelle Aufmerksamkeit und die kognitive Verarbeitung der Lerninhalte in der VR.

Aus theoretischer Sicht unterstützt diese Dissertation den integrativen Ansatz, demzufolge die Integration von motivationsunterstützenden Elementen in multimediales Lernen grundlegend für eine effektive Verarbeitung der Lerninhalte ist, und liefert einige Belege für die Rolle der Lernmotivation hinsichtlich der Lerneffektivität immersiver VR. Aus praktischer und pädagogischer Sicht zeigt diese Dissertation, wie eine einfache Nützlichkeitsintervention effektiv in virtuelle Simulationen integriert werden kann und wie die Wahrnehmung von VR durch die Lernende (wahrgenommene Nützlichkeit und Akzeptanz von VR als Lerninstrument) gefördert werden kann. Diese Dissertation bietet zudem praktische Implikationen für den Einsatz in der naturwissenschaftlichen Bildung: Es wird gezeigt, dass Lernende pädagogisch auf das Lernen mit VR vorbereitet werden und sich der Nützlichkeit von Bildungstechnologien bewusst sein müssen, bevor sie diese zu Lern- und Lehrzwecken einsetzen. Darüber hinaus trägt diese Dissertation zu einem besseren Verständnis der Bedeutung der Motivation beim Lernen mit VR bei und liefert wichtige Hinweise darauf, wie sie die Effektivität von VR in der naturwissenschaftlichen Bildung verbessert werden kann.

CONTENTS

1

INTRODUCTION AND THEORETICAL BACKGROUND

1 Introduction and Theoretical Background

The development of information technology has fundamentally altered the teaching and learning process. This process of digitalizing the education landscape has been accelerated by the COVID-19 pandemic, which inadvertently highlighted the usefulness of educational technologies. Educational technologies enable educators to explain and demonstrate lesson content more clearly and teach on a larger scale; they can also allow students to access the lesson materials remotely and collaborate with fellow students from different geographic locations. Immersive virtual reality (VR) is one of these technologies that are radically transforming education; it is particularly suitable for learning and teaching complex topics within science education (Honey & Hilton, 2011), as it offers students the possibility to actively engage in the learning processes, interact with the lesson content, and even conduct science experiments. VR is not actually a new technology per se; however, recent advancements in the field have made it more affordable and accessible. As a result, there has been an increased use of VR in educational domains, fulfilling the long-held prediction that VR would revolutionize science education (Fernandez, 2017; Karutz & Bailenson, 2015; Salzman et al., 1999a; Salzman et al., 1997).

Most definitions of immersive VR entail three fundamental characteristics: immersion, presence—the illusion of being physically present in the virtual environment (Held & Durlach, 1992; IJsselsteijn & Riva, 2003; Minsky, 1980a), and interactivity—the VR's ability to react almost instantly to users' actions with and within the environment (Cipresso et al., 2018). From an educational and psychological perspective, immersive VR can be described as an interactive multimedia technology that enables learners to access and experience a 360-degree virtual learning environment through computer-generated simulations (Bailenson et al., 2008; Okechukwu & Udoka, 2011). Using additional electronic equipment (such as head-mounted displays, controllers, and haptic gloves), learners can interact with elements of the virtual environment and *experience* the learning process more vividly. These characteristics allow students to participate actively in the learning process: first, VR limits sensory input from the outside world (e.g., noise and non-relevant interactions), allowing the learners to be present and engage almost exclusively with the virtual learning environment. Second, the interaction within the learning environment is experienced from a first-person perspective; VR uses tracking technology to track the learners' position and automatically updates and renders, in real-time, the virtual learning environment according to the learners' positions, movements, and actions (Bailenson et al., 2008).

According to this definition, VR allows students to actively explore the learning environment, which automatically responds to their actions (Georgiou et al., 2007; Roussou, 2004). These reciprocal interactions and the immersive aspect increase learners' motivation (Allcoat & von Muhlenen, 2018) and willingness to engage with the learning content (Georgiou et al., 2007; Karutz & Bailenson, 2015). Although VR is cost-effective in the long run, its use in education still requires time, effort, and financial resources (acquisition of VR headsets and programming of virtual learning simulations). Therefore, it is important to establish how effective VR is for teaching and learning. In this regard, Cromley et al. (2023) discuss two perspectives regarding the effectiveness of VR in education: the achievement-focused and the equity-focused perspective. According to the achievement-focus perspective, VR should be recommended only if it leads to better learning outcomes over other conventional learning tools or methods (PowerPoint presentations, lectures, online learning, etc.). In contrast, the equity-focused perspective supports the use of VR for teaching and learning based solely on its characteristics and affordances, even if it is only equally effective as other methods (Cromley et al., 2023).

Current empirical research on VR's effectiveness indicates that the mere use of VR in science education increases students' motivation but does not automatically result in improved learning performance (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019). In this regard, a few research studies have shown mixed results (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2018) or a slight advantage of VR compared to other methods (Luo et al., 2021; Wu et al., 2020). The current literature also provides some insight as to why VR may not be as effective as expected. First, it has been shown that the immersive aspect of VR can also place a burden on students' cognitive capacity (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2020): seductive details—elements that are interesting and flashy, but do not contribute to learning—can distract students from their learning goals and increase their cognitive load (Makransky & Petersen, 2021; Makransky, Terkildsen, et al., 2019; Meyer et al., 2019; Moreno & Mayer, 2002). Second, most of the current learning simulations were not designed in accordance with concrete, evidence-based pedagogical and instructional approaches (Fowler, 2015). Finally, VR is still not yet established as a learning instrument, and most students associate VR with gaming rather than learning (Baxter & Hainey, 2019). Such an attitude could negatively affect students' acceptance of VR as a learning tool and shift their attention more toward the entertaining aspect of it rather than learning.

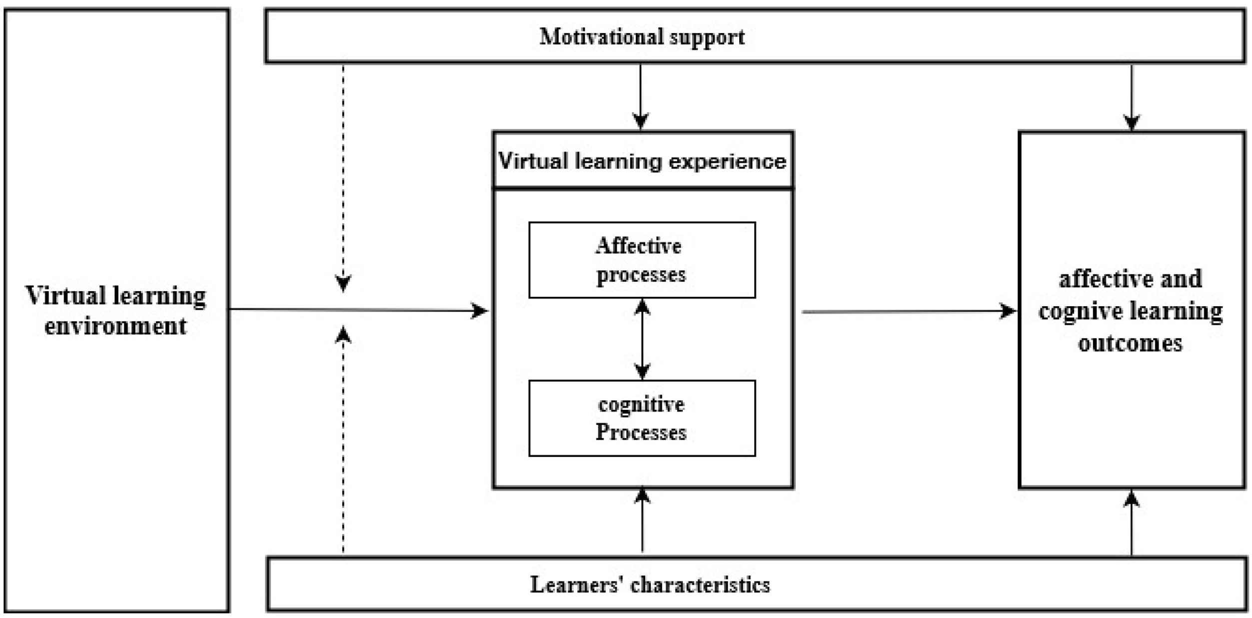
Given VR's lack of effectiveness despite its unique affordances and embedded motivational and hedonic features, this dissertation addresses the question of how the effectiveness of immersive virtual reality (VR) in science education can be enhanced. So far, there have been a few successful approaches aimed at enhancing VR's effectiveness in science education (Makransky et al., 2021; Meyer et al., 2019; Parong & Mayer, 2018). Notably, a recent meta-analysis on the effectiveness of VR in Science, Technology, Engineering, and Mathematics (STEM) suggests that VR has a positive effect on learning, especially when different instructional prompts are added to the virtual simulations (Cromley et al., 2023). However, implementing different prompts can be tedious, as it often requires specific prompts to be developed for a specific lesson or interrupts students' immersion, for example, to have them write a summary. At the same time, educators might be interested in a more general and parsimonious approach. Therefore, this dissertation investigates whether a brief intervention—integrating motivational support into a virtual learning simulation—enhances VR's effectiveness in science education.

Previous attempts to increase VR's effectiveness (e.g., pre-training, summary prompts, or enactment) are rooted in cognitive theories (CLT; Sweller et al. (2011); CMTL; Mayer (2009a) and tend to prioritize techniques to either minimize cognitive load or enhance effective processing, but often overlook the role of motivation in effective learning in multimedia (Astleitner et al., 2006; Astleitner & Wiesner, 2004). Actually, there is a large body of empirical research showing how different motivational approaches foster students' learning both in traditional classrooms (Brisson et al., 2017; Eccles et al., 1983; Eccles & Wigfield, 2020) and with multimedia (Ali et al., 2018; W. Huang et al., 2022; Lin et al., 2017). These motivational approaches fit well with the cognitive theory of multimedia learning (CTML; R. E. Mayer, 2014; Mayer, 2022) that now also explicitly specifies the role of motivation in effective cognitive processing: students' motivation plays a fundamental role in how they select, organize, and process learning content in learning with multimedia. Furthermore, several educational psychologists have advocated for the integration of motivation into cognitive theories related to multimedia learning, as motivation can enhance or hinder the effective processing of learning content in multimedia learning (Astleitner et al., 2006; Astleitner & Wiesner, 2004; Moreno & Mayer, 2007; Wiesner, 2008). An example of how motivation can impair learning is the fact that VR also causes distraction and overstimulation, which negatively affects effective processing in VR (Makransky, Terkildsen, et al., 2019; Mayer et al., 2022).

To test the motivational assumption of CTML and the integrative approach, I rely on the technology acceptance model (TAM; Davis, 1989) and the expectancy-value theory (EVT; Eccles et al., 1983), which not only foreground the role of motivation in learning but also provide clear methods to operationalize motivation and conduct interventions involving students' motivation in the learning context. In learning with technology, as a motivational factor, students' perceived usefulness of a given technological learning tool holds significant importance. According to the TAM, students' perception of the usefulness of a particular technology is the primary factor influencing their acceptance of such a learning tool, which is considered a crucial prerequisite for the effectiveness of VR in educational settings (Davis, 2011; Merchant et al., 2014). In the classroom setting, students' perceived usefulness of the learning activities, according to the EVT, also plays an essential role in their learning performance. In fact, empirical research based on EVT has shown that classical usefulness interventions help to stimulate achievement-related behavior and improve learning outcomes both in the short and long terms (Anderman et al., 2001; Brisson et al., 2017; Eccles et al., 1983; Gaspard et al., 2015). Considering that such interventions are parsimonious, easy to implement, and effective, this dissertation proposes that VR's effectiveness can be enhanced by integrating into immersive learning environments motivational clues that foster goal-oriented behavior and highlight the relevance of VR for learning or daily life. The mechanism underlying this expectation is depicted in Figure 1.

Figure 1

Theoretical model showing how the integration of motivational support into a virtual learning environment enhances its effectiveness



Note. The central part of this theoretical model shows how a virtual learning environment (with its utilitarian and hedonic features) affects students' learning experience in VR (affective and cognitive processes), which subsequently affects their learning outcomes. Affective processes include students' perceived usefulness of VR, acceptance of VR as a learning tool, and presence in VR. Cognitive processes refer to the selection, (mental) representation, and integration of relevant learning content into prior knowledge. The top part shows how integrating motivational support in the virtual learning environment influences the learning experience in VR (affective and cognitive processes) and students' learning outcomes. The bottom part indicates how students' characteristics (e.g., prior experience with VR, academic self-concept, and domain-specific interest) can affect learning in VR. The dotted lines represent putative relationships that would not be tested.

Based on this theoretical framework, this dissertation aims to address three overarching objectives: The first is to investigate whether a typical EVT-based classroom priming intervention will also improve VR's effectiveness in science education. More specifically, this dissertation investigates the role of students' awareness of VR's usefulness for learning or daily life in their learning outcomes. The second is to determine whether such a priming intervention can increase students' acceptance of VR as a learning tool and to assess whether acceptance—referred to as behavioral intention— in turn facilitates students' learning experience in VR and enhances their learning performance. To do so, this dissertation uses an experimental approach to test the core assumptions of the TAM in the context of learning with VR. The third objective is to assess how integrating a motivational intervention into an immersive learning simulation affects students' visual attention and cognitive processing of the lesson content. In other words, this dissertation investigates how students' motivation helps them to focus more on the learning content in VR and less on the seductive elements included in such an environment that can distract them from their learning goals.

The present dissertation is structured as follows: in Chapter 1, I establish the context of learning with VR and present the theoretical background of this dissertation. To do so, I present a hedonic and a utilitarian perspective on the use of VR as a learning tool (Section 1.1). Accordingly, from the hedonic perspective, I explain how immersion, interaction, and embedded visual elements can facilitate learning. From the utilitarian perspective, I describe different affordances of VR for learning. Finally, I discuss the current empirical evidence regarding VR's effectiveness, challenges as a learning tool, and different approaches to enhance its effectiveness (Section 1.2). Then, I highlight the role of motivation in learning, especially in learning with multimedia from the perspective of the cognitive theory of multimedia learning (CTML): I summarize the tenets of CTML and discuss the role of motivation in effective processing of the learning content in VR (Section 1.3). Finally, I present the integrative approach, according to which the integration of motivational support into the virtual learning simulation can enhance VR's effectiveness. Accordingly, I discuss different common motivational interventions to improve learning both in traditional classrooms and with multimedia, as they also provide a clear way to manipulate students' motivation to learn. Notably, I discuss interventions from the technology acceptance model, the expectancy-value theory, and the effects of priming interventions on goal-directed behavior, which can help students mitigate the negative effects of seductive details in VR (Section 1.4).

Based on this theoretical framework, I formulate the dissertation's overall aims and research questions (Chapter 2), which are addressed in the three empirical studies included in this dissertation. Subsequently, I present the three empirical studies in Chapters 3 to 5; they constitute the core of this dissertation. Finally, I discuss in Chapter 6 the findings of these studies with regard to their empirical (Section 6.1), theoretical (Section 6.2), and practical and educational contributions (Section 6. 3). I also discuss the dissertation's overall strengths and limitations (Section 6.4) and implications for future research (Section 6.5), before presenting a general conclusion (Section 6.6).

1.1 The use of immersive virtual reality in science education

Immersive virtual reality is considered a powerful multimedia learning tool that can revolutionize how students learn science by allowing them to experience the lesson content more vividly and participate more actively in the learning process (Karutz & Bailenson, 2015; Won et al., 2019). Several characteristics of VR have been put forward to explain why and how VR might positively affect science education (Makransky & Petersen, 2021; Petersen et al., 2022). The following two technical features of VR constitute a foundation that allows different affordances of VR (Bailenson et al., 2008), such as immersion and presence to emerge: first, VR can track learners' movements and interactions within the virtual learning environment. Second, VR is able to render and adjust the learning environment in real-time according to learners' actions and behavior. These features place the learner at the center of the learning experience in the immersive learning environment. Immersion and interactivity are among the most important and fundamental features of VR, underlying the unique affordances of VR that can facilitate effective learning in VR (Bailenson et al., 2008; Johnson-Glenberg, 2018). In this regard, the Cognitive Affective Model of Immersive Learning (CAMIL; Makransky & Petersen, 2021; Petersen et al., 2022) posits that immersion and interactivity can influence via presence and agency different affective and cognitive factors (e.g., interest, motivation, cognitive load, self-regulation), which subsequently can enhance or impede VR's effectiveness.

In addition to the affordances of VR that can facilitate learning, VR also provides students with the unique opportunity to experience learning content in an enjoyable and engaging manner (Makransky & Lilleholt, 2018; Mayer et al., 2022; Mikropoulos & Natsis, 2011). Empirical evidence suggests that students enjoy learning with virtual reality and report high levels of satisfaction and perceived learning (Makransky & Lilleholt, 2018; Makransky & Petersen, 2021; Vrellis et al., 2016). Considering that traditional classroom teaching has difficulty keeping students motivated and engaged with the learning content (Hu-Au & Lee, 2017; Kohn, 1999), it has been found that virtual reality (VR) enables educators to present and demonstrate complex concepts visually while simultaneously stimulating students' interest in the lesson (Adžgauskaitė et al., 2020; Kontogeorgiou et al., 2008; Mora et al., 2017). Accordingly, it can be argued that besides providing unique affordances for learning complex subjects (utilitarian factors), VR also contains features that foster motivation, enjoyment, and satisfaction (hedonic elements). Thus, understanding how VR's hedonic and utilitarian factors affect students' motivation to learn and interactions within the virtual learning environment and how these factors can facilitate or impede their learning performance are fundamental steps in effectively using VR in science education.

According to van der Heijden (2004), utilitarian elements of multimedia learning tools provide values and affordances that can improve performance (e.g., enhancing students' understanding of complex concepts). In contrast, hedonic elements aim to provide self-fulfilling value and emphasize the fun aspect of the process (e.g., increasing students’ enjoyment of and satisfaction with the learning materials) more than the instrumental value (e.g., improving learning). Edutainment combines both utilitarian and hedonic aspects of technology. Edutainment is defined as the integration of education and entertainment (Pan & Chen, 2008; Virvou et al., 2006); that is, multimedia learning tools that incorporate entertainment and gamification elements into the educational process to promote engagement and learning. In this sense, learning with immersive VR can be considered edutainment because the majority of virtual learning simulations include game elements and vivid images and tend to present the learning content in an engaging way (Chang et al., 2011; Pan & Chen, 2008; Virvou et al., 2006; Young Mi et al., 2016).

The distinction between the objectives of the utilitarian and hedonic components of technology learning tools suggests that students' engagement in virtual environments may vary depending on the purpose of such environments (Goh & Yoon, 2011) and which aspect has been highlighted. Accordingly, it can be argued that if the hedonic aspect is emphasized, students may primarily try to enjoy the learning experience in VR, whereas if the utilitarian aspect is emphasized, students may prioritize their learning performance in VR. Even though VR includes both hedonic and utilitarian elements, the primary objective of most virtual learning simulations is to facilitate learning. Therefore, it appears that students' attitudes and motivation to engage in the learning environment in the first place may influence how they interact with and process the learning content in VR. However, there is a paucity of research on the influence of hedonic and utilitarian aspects of immersive VR on students’ learning performance that accounts for their motivation. Therefore, an analysis of VR's utilitarian and hedonic aspects should shed light on the relationship between these distinctive aspects of VR and students' motivation and learning outcomes.

1.1.1 The utilitarian perspective: Affordances of immersive virtual reality for learning

To understand the extent of VR’s affordances for learning, it is important to consider not only its inherent properties but also students’ characteristics (e.g., prior knowledge, attitude, motivation, and goals), the subject to be learned, and the type of knowledge (e.g., procedural, factual or transfer). From an ecological psychology perspective, affordance is defined as the relationship between abilities and environments (Gibson, 1986). Markus and Silver (2008) describe affordances in terms of the functionality of a given technology in relation to the users' ability and goals and use the concept of functional affordances, which is derived directly from the ecological psychology perspective. Functional affordances represent "a type of relationship between a technical object and a specified user (or user group) that identifies what the user may be able to do with the object, given the user's capabilities and goals. More formally, functional affordances are defined as the possibilities for goal-oriented action afforded to specified user groups by technical objects" (Markus & Silver, 2008, p. 622). The following fictitious example will help to illustrate the concept of affordances from this perspective: A group of researchers from a German university use gamification in a brand new and pedagogically well-designed computer application that should help students master the fundamentals of mathematics. Despite the great properties this application may have, it would probably not help students to learn mathematics better if the students have not mastered the German language or are not, in the first place, particularly interested in learning mathematics but just want to enjoy the gaming aspect of it. This example illustrates that the properties of a given technology alone do not guarantee its effectiveness; instead, students' characteristics, perceptions, and goals are important aspects in determining its affordances and ultimately its effectiveness.

Based on this perspective, VR affordances for learning describe a set of possibilities that learners can achieve with VR depending on their characteristics and goals. Therefore, learners who are aware of VR's characteristics and enter a virtual learning environment with a greater motivation to learn will explore the learning environment accordingly and perform goal-oriented actions. In other words, their ability to focus on the learning-relevant aspects and ignore the seductive details of the virtual learning environment (interesting but irrelevant elements for the instructional objectives) could be enhanced, which ultimately could help them take advantage of the learning materials presented in VR and process the learning content more effectively.

Steffen et al. (2019) proposed a framework that considers VR's affordances in general in comparison to the physical world in order to highlight the advantages that VR brings and to better understand the motives that would bring users to adopt VR. Building on that work and the current literature, I highlight the main possibilities that VR provides in the context of learning and how learners can benefit from these in science education in VR:

a) Making the impossible possible

In addition to being immersive, VR gives schools and teachers the ability to convey lesson material in ways that are impossible in the real world. For instance, students can examine human cells or work with chemical elements as if they have been "shrunk" to microscopic level and could interact naturally with these elements. Similarly, students can study planets in our galaxy or black holes at the macroscopic level. Even more fascinatingly, students can travel back in time to study historical events as if they were eyewitnesses and even participate in the unfolding dynamics. Using VR, abstract concepts can become more accessible through visual representations that students can manipulate and dissect. For instance, Salzman et al. (1999b) used VR to help students better understand complex, abstract concepts such as electric field and electric potential. Such electrostatic concepts are difficult to master and have few observable real-life examples (Salzman et al., 1999b). Similarly, VR allows students to visualize and manipulate different molecular representations (Salvadori et al., 2016; Salzman et al., 1999b). More recent studies use VR to allow students to study the cells in the human body (Meyer et al., 2019; Parong & Mayer, 2018) and the structure of DNA (Safadel & White, 2020). This affordance is unique to VR and has the potential to motivate students and increase their interest in and comprehension of the subject being studied.

b) Conducting science experiments with zero risk of accidents

One of the advantages of VR is that it enables students to observe and study phenomena, events, and substances that are difficult and dangerous to manipulate in the real world. For instance, students can conduct their own physics and chemistry experiments without risk of accident or injury (Bogusevschi et al., 2020; Rahman et al., 2022; Zulma, 2019). Students can safely study nuclear fusion by visiting a nuclear power plant—in Fukushima or Chornobyl—to observe the aftermath of a nuclear accident. In this sense, VR is limitless because it provides a safe environment for teaching, learning, and training. For example, Lu et al. (2021) developed a virtual simulation to improve the scientific literacy of high school students and the general public regarding theoretical and experimental chemistry. This simulation enables users to experiment with chemical toxins and dangerous reagents while preventing all potential accidents that could occur during such experimental manipulations. In addition, students with disabilities or limited mobility who are interested in chemistry have the opportunity to conduct their own experiments using this simulation (Lu et al., 2021). This is especially relevant for labs in educational institutions that are not yet adapted to the needs of students with disabilities.

Overall, the opportunity to conduct science experiments on their own is highly motivating and encourages students to be more engaged in the construction of knowledge and to acquire a deeper understanding of complex concepts and phenomena (Georgiou et al., 2007). All this can be achieved under the guidance of the teacher in a safe learning environment.

c) Reproducing the world as it is

VR can be used to recreate the world or specific aspects of reality to enable students to analyze and study certain phenomena in detail or to train them in a particular field. This feature has been utilized for decades in the military and, more recently, in chemistry, physics, and biology (Cipresso et al., 2018; Howard, 2017; Y. Huang et al., 2021; Jensen & Konradsen, 2017). In the medical field, virtual reality is used to allow nursing students to experience certain situations and learn how to appropriately treat patients in those situations (Plotzky et al., 2021; Pottle, 2019; Woon et al., 2021). Similarly, medical students can practice surgery using VR (Hasan et al., 2021; H.-M. Huang et al., 2013; McKnight et al., 2020), with encouraging results showing that the skills obtained through VR are similar to those obtained through dry laboratory simulation (Bric et al., 2016). This provides students with the best opportunity to experience and become familiar with situations they are likely to encounter in real life without experiencing the stress and burden of the situation or involving patients.

Simultaneously, educators can use VR to reproduce locations where students from different parts of the world can meet without having to travel. Although these virtual learning environments do not replace reality, they do allow students to manipulate the elements without long-term negative effects on humans (as patients), animals, or the environment. For instance, if students are studying the impact of deforestation on climate change, they do not need to cut down trees; instead, they can use virtual simulations to test how different levels of deforestation impact the environment and make informed projections for the future. More interestingly, it seems that using VR to promote environmental consciousness could be effective. In this regard, Ahn et al. (2014) showed that experiencing the process of cutting a virtual tree led to higher environmental consciousness than just reading about it. VR's ability to replicate and manipulate reality and evaluate the results makes virtual reality a powerful learning tool, as students can explore different facets of a phenomenon and immediately experience the consequences of a given action.

d) Creating an imaginary world

VR also enables the creation of situations or environments beyond what exists in the real world. This makes virtual reality a very fertile environment for creativity, allowing students and teachers to generate new ideas and test alternative explanations. Virtual learning environments can be based on imaginary possibilities that captivate and motivate students to engage with particular subjects and hypothetical realities. This feature is not unique to VR, as films and television have long portrayed fictive realities that induce strong emotions, reflections, and debates about important subjects in societies. However, in the case of VR, students experience such fictitious realities more vividly and from a first-person perspective, which might foster awareness or empathy, for example. In this regard, Roswell et al. (2020) created an alternative reality to teach empathy and care; using immersive VR, participants could experience racism from the perspective of a black person at three time points in her life (childhood, adolescence, and adulthood). The results show that VR could effectively promote awareness and empathy for racial minorities (Roswell et al., 2020). More importantly, Roswell et al. (2020) suggest that it can be used in the same fashion to deal with other forms of discrimination (e.g., sexism, ageism, and homophobia).

Similarly, this feature affords educators the opportunity to teach skills in the event of a life-threatening situation (pandemics, accidents, or natural catastrophes). This possibility can expand students' vision of the world and make them think through and create solutions for basic and complex problems more effectively. In addition, this feature allows the creation of simulations that transcend time and space: learning first-hand about the first migration of homo sapiens out of Africa or projecting how the world would look in 100 years if climate change is ignored would be possible in VR. Huang et al. (2020) took advantage of this feature by using ecological modeling, procedural modeling, and virtual reality to create an immersive simulation that allows the user to visualize and experience environmental changes in a forest in northern Wisconsin (USA) 50 years into the future under two climate scenarios.

1.1.2 The hedonic perspective: VR-based edutainment

The primary goal of technology-based edutainment is to facilitate learning by "tricking" students into engaging with the learning material; the assumption is that once students are hooked, they would be subtly *forced* to learn (Bugreeva, 2021; Zin & Zain, 2010). This is based on the premise that the interactive elements and immersive experience (in the case of VR) could help maintain students' interest in the learning content by stimulating their attention (Aksakal, 2015; Bugreeva, 2021; Corona et al., 2013). In addition, it is assumed that the embedded edutainment elements in multimedia can impact students’ motivation and facilitate the processing of the learning content (Chang et al., 2017; Chen, 2020; Plass & Kaplan, 2016); therefore, edutainment might improve the effectiveness of multimedia learning. Learning in VR is not an abstract process but rather an engaging one in which students' actions initiate automatic responses from the VR system, which renders and adapts the learning environment accordingly

(Bailenson et al., 2008). In this sense, the edutainment elements (hedonic and motivational features) make learning VR an active and stimulating experience (Anikina & Yakimenko, 2015; Buckingham & Scanlon, 2016). As such, learning with VR can be very enjoyable and satisfactory (Bulu, 2012; Makransky & Lilleholt, 2018; Makransky & Petersen, 2021; Vrellis et al., 2016).

Based on the self-determination theory (SDT; Deci & Ryan, 1985, 2008; Deci & Ryan, 2015) and hedonic theory, Huang et al. (2018) analyzed how the learning process in VR satisfies or impedes the satisfaction of students' psychological needs (e.g., autonomy, competence, and relatedness) and influences students' engagement and intent to continue using VR. Notably, learners' perceived autonomy has a positive effect on a variety of motivational and hedonic factors, including intrinsic motivation, positive emotions, emotional involvement, flow, etc. It has been proposed that learning with VR increases motivational and hedonic factors (e.g., satisfaction and enjoyment, engagement, intrinsic motivation, and interest), which can facilitate learning in the virtual learning environment (Allcoat & von Muhlenen, 2018; Chang et al., 2017; Di Natale et al., 2020; Makransky & Mayer, 2022; Makransky & Petersen, 2021). Reviewing the current literature with regard to how immersive VR affects students' satisfaction and enjoyment, engagement, intrinsic motivation, and interest and how these factors are related to learning may help to better assess the role of hedonic and motivational factors in effective learning with VR.

a) Enjoyment and positive emotions

Multimedia learning involves the combination of text and images (Mayer, 2009a). Multimedia learning tools, specifically immersive virtual reality, which is heavily based on graphic design and enables the visual representation of complex concepts in a 3D learning environment, can elicit positive emotions during the learning process (Harp & Mayer, 1997; Um et al., 2012; Um et al., 2007). For example, edutainment learning content can increase students' enjoyment, which can influence their intention to use educational tools (Merhi, 2015). In the same vein, a growing number of studies have shown that immersion has a positive effect on affective processing during learning in VR: higher levels of immersion enhance students' presence (Makransky & Lilleholt, 2018; Makransky & Mayer, 2022; Makransky, Terkildsen, et al., 2019), enjoyment (Makransky & Klingenberg, 2022; Makransky & Mayer, 2022), interest (Makransky et al., 2020; Meyer et al., 2019; Parong & Mayer, 2018), satisfaction (Bulu, 2012; Makransky & Lilleholt, 2018; Vrellis et al., 2016), and perceived learning (Makransky & Klingenberg, 2022; Makransky & Lilleholt, 2018).

The fundamental question is how hedonic factors such as positive emotions, enjoyment, and satisfaction affect learning (Um et al., 2012; Um et al., 2007). On the one hand, it has been shown that positive emotions influence motivational and cognitive processes that are relevant for learning (Erez & Isen, 2002; Isen et al., 1987; Isen & Reeve, 2006). For instance, edutainment learning content can facilitate learning by increasing students' engagement (Kang & Wu, 2022), persistence (Brubacher & Silinda, 2019; Simon et al., 2015), and intrinsic motivation (Makransky, Borre-Gude, et al., 2019; Pekrun, 2006). Even though enjoyment implies gratification (such as excitement, pleasure, positive emotions, and satisfaction), it has been argued that enjoyment is also related to interest in the learning content (Ainley & Hidi, 2014; Makransky & Mayer, 2022). Therefore, positive emotions elicited from multimedia learning can influence students' cognitive effort, motivation, learning performance, and satisfaction (Um et al., 2012; Um et al., 2007). On the other hand, it can be argued that positive emotions can also consume a significant amount of working memory capacity, thereby inhibiting effective learning (Fairfield et al., 2015; Harp & Mayer, 1998; Hou & Cai, 2022; Hur et al., 2017). For example, learning with VR can be overstimulating, leading to an increase in cognitive load and a decrease in learning performance (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2018, 2020). Moreover, previous findings suggest that immersion positively affects affective but not always cognitive learning outcomes. For instance, it has been shown that immersion led to more liking and presence but not learning (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019). However, a recent study reveals that immersive VR increased students' presence, which led to greater enjoyment; subsequently, enjoyment had a positive effect on students' learning performance on the immediate posttest but had no effect on the delayed posttest (Makransky & Mayer, 2022).

b) Engagement

Engagement refers to learners' active participation in the learning activities, which includes their reactions to and interactions with the learning content (Boekaerts, 2016; Wang et al., 2016). Several key characteristics of edutainment multimedia tools (e.g., interactivity, choice, novelty, and sensory engagement) are discussed as factors that can promote students' engagement in learning with multimedia (Liu et al., 2009). It has been shown that engagement is a fundamental element of learning in both traditional educational settings and multimedia environments (Lei et al., 2018; Martin & Bolliger, 2018; Wonglorsaichon et al., 2014). More concretely, students' engagement is associated with both cognitive and motivational processes (Astleitner, 2018; Aubteen Darabi et al., 2007); as such, engagement is a crucial factor in the effectiveness of multimedia learning (Keller & Suzuki, 2004; Keller, 1997). Learning in immersive virtual environments allows students to interact with and explore the learning materials, which can support students' focus and effort (Dalgarno & Lee, 2010; Dinis et al., 2017) as well as engagement (Allcoat & von Muhlenen, 2018; Mount et al., 2015).

Puttawong et al. (2017) and Visoottiviseth et al. (2018) intended to capitalize on the edutainment aspects of immersive VR to enhance students' engagement and learning. For example, Puttawong et al. (2017) designed a virtual learning environment based on entertainment principles to teach computer science students about firewall security. The authors argued that edutainment is a valuable alternative to traditional lectures because it is more engaging, and the entertaining elements will keep students interested, as they have to come to firewall knowledge by themselves through their interaction with the virtual simulation. In addition, students' actions and interactions within the immersive virtual learning environment can foster their engagement in the learning materials (Calvert & Abadia, 2020; Johnson-Glenberg, 2018; Johnson-Glenberg et al., 2021). In this regard, a recent study found that students learning with VR reported a high level of engagement regardless of the level of immersion (W. Huang et al., 2021). However, another study (Parong & Mayer, 2020) using electro-encephalogram (EEG) measurements revealed that students learning with VR showed lower cognitive engagement compared to their counterparts learning with video. Moreover, students in the VR condition also reported higher emotional arousal and extraneous cognitive load, which negatively impacted their learning performance (Parong & Mayer, 2020).

c) Intrinsic motivation

Learning with multimedia can be highly intrinsically motivating if the learning content incorporates fantasies, is challenging, fosters curiosity, and gives students a great deal of control over the learning process (Malone & Lepper, 1987). Intrinsic motivation refers to engagement in activities for their own sake or activities that are intrinsically rewarding (Deci & Ryan, 2010; Malone & Lepper, 1987). In the SDT, autonomy is highlighted alongside competence and relatedness as one of the fundamental human needs that, when satisfied, can lead to intrinsic motivation. As the entire learning process in VR is learner-centered and the VR system renders and adapts the entire learning system based on the learners' actions (Bailenson et al., 2008), learning in virtual reality affords students a high degree of autonomy. Makransky and Petersen (2021) refer to this affordance of VR as agency; however, it describes the same opportunity for students to participate actively in the learning process. In this regard, virtual simulations may increase students' intrinsic motivation, since immersive learning involves vivid experience and the ability to manipulate and interact with learning content (Dalgarno & Lee, 2010; Makransky, Borre-Gude, et al., 2019; Makransky & Lilleholt, 2018).

There is a substantial body of empirical evidence demonstrating that motivation enhances learning in multimedia (Leutner, 2014; Wong & Adesope, 2021). Students' motivation affects their affective and cognitive processing, which enhances their learning performance (Moreno & Mayer, 2007; Pintrich, 2003). In the context of virtual reality learning, empirical studies have demonstrated that immersive VR results in higher intrinsic motivation than non-immersive learning tools (Makransky, Borre-Gude, et al., 2019; Makransky & Lilleholt, 2018; Olmos-Raya et al., 2018). According to Makransky and Petersen (2021), immersion and interactivity lead to greater presence and agency, which influence various cognitive and affective processes (e.g., higher intrinsic motivation and interest) in virtual learning environments; subsequently, these cognitive and affective processes improve students' learning performance. Petersen et al. (2022) tested these assumptions and revealed that both immersion and interactivity had a positive effect on presence, which subsequently fostered situational interest and intrinsic motivation. However, situational interest enhanced learning, but intrinsic motivation did not. Another recent study (W. Huang et al., 2021) indicates that students learning with moderate and high immersion reported consistent motivation across three VR learning sessions, whereas students who switched from medium immersion to high immersion in the third session reported increased motivation.

d) Interest

Edutainment content, such as virtual learning simulations, can pique students' interest in learning materials (Knogler & Lewalter, 2014; Makransky & Petersen, 2021; Park et al., 2014; Park, 2015; Petersen et al., 2022). In fact, empirical evidence indicates that VR stimulates students' interest— particularly situational interest (Makransky & Petersen, 2021; Parong & Mayer, 2018; Petersen et al., 2022). Interest describes a more or less stable relationship between a person and a particular domain, characterized by affective and cognitive processes and manifested in concrete actions and mental processes (Krapp, 2002). This relationship can be conceptualized as either situational or individual interest (Hidi, 1990; Hidi & Renninger, 2006). Individual interest refers to a more stable relationship characterized by the development of value beliefs regarding a particular domain (Renninger et al., 1992; Schiefele, 1998), whereas situational interest refers to an immediate affective response (often positive) to a specific object, context or environment (Hidi, 1990; Hidi & Renninger, 2006). For instance, students may express interest in learning chemistry during a VR learning session due to various hedonic elements in VR, such as immersion, positive emotions, and the ability to conduct their own experiments and virtualize the chemical reaction, and not because they have a particular affinity for chemistry. Students with an interest in chemistry (individual interest) have developed a positive relationship with this domain over time and will be motivated to study chemistry regardless of the addition of hedonic elements. Individual interest can, therefore, be viewed as an individual trait that has a positive effect on students' effort, and situational interest as an affective response provoked by the environment (Hidi & Renninger, 2006).

However, situational interest can help students develop an interest in science education by serving as a springboard. In this regard, situational interest can serve as a foundation for interest (Knogler et al., 2015; Krapp, 1999, 2002; Park, 2015), which can improve students' attention during the learning process and learning outcomes (Hidi & Anderson, 1992). This transformation (from situational interest to individual interest) is possible through the internalization process (Krapp et al., 1992). Furthermore, situational interest can motivate short-term achievement-related behavior, such as behavioral and cognitive engagement, interest, and self-efficacy, and is positively correlated with self-regulation (Sun & Rueda, 2012). In this regard, virtual reality learning can increase students' interest in particular subject areas by first arousing their situational interest through embedded gamification and hedonic elements (Y. Huang et al., 2022; Makransky et al., 2020; Renninger & Hidi, 2015). Makransky and Petersen (2021) propose that immersion and interactivity in VR can stimulate situational interest, which in turn enhances students' VR learning. During a VR learning session, presence can also boost situational interest in learning (Makransky & Petersen, 2021; Petersen et al., 2022). Recent empirical research has shown that immersion has a positive effect on situational interest, whereas interactivity does not (Petersen et al., 2022). Additionally, the authors reveal that presence has a positive influence on students' situational interest, which has a positive impact on their learning. However, comparing immersive VR to videos, Parong and Mayer (2021) found no effect of immersive VR on student interest in learning history.

1.2 Effectiveness of immersive virtual reality for learning and teaching

Whether it depicts a real or fictitious situation, a virtual learning environment provides unique affordances and entails hedonic and motivational elements that could facilitate more effective learning compared to more conventional instructional methods and learning tools. The perspective of a new learning tool that places students at the center of the learning process by allowing them to be more active and experience the learning content has prompted great interest in the use of VR in education. In response to the growing interest in learning with VR, numerous studies and meta-analyses have attempted to answer the question of the effectiveness of VR for learning (Cromley et al., 2023; Hamilton et al., 2020; Wu et al., 2020). Assessing VR's capacity to facilitate information acquisition and knowledge construction (Mayer & Fiorella, 2021) is essential for its establishment as an effective learning instrument. Parong and Mayer (2021) put it more bluntly: if learning with immersive VR is not more effective than learning with more conventional learning tools such as a computer monitor or video, then "there may not be sufficient reason to convert conventional lessons into IVR [immersive virtual reality] lessons (p. 1434)". However, proponents of the equity-focused perspective value VR merely because of its affordances as long as it is equally effective as other methods (Cromley et al., 2023).

When it comes to hedonic and motivational factors (e.g., enjoyment, satisfaction, and perceived learning), VR is much more effective than other conventional learning tools (Y. Huang et al., 2022; Makransky, Borre-Gude, et al., 2019; Makransky & Lilleholt, 2018). With regard to students' learning performance, however, the current evidence is inconclusive: some studies show a clear advantage for virtual reality (Alhalabi, 2016; Cromley et al., 2023; Hamilton et al., 2020; Woon et al., 2021), but others reveal mixed results or even a disadvantage in comparison to other learning methods and more conventional learning tools (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2018; Radianti et al., 2020; Wu et al., 2020). In order to better assess the effectiveness of VR, this dissertation reviews the current empirical results from media comparison studies and according to the types of knowledge considered.

Media comparison studies: immersive virtual reality and other conventional learning tools and methods

Most of the research on VR's effectiveness tends to compare VR with other well-known and established learning tools or methods (desktop VR, video, slideshows, etc.). A review of thirteen media comparison studies, for instance, found that immersive VR is not necessarily more effective than more traditional media, such as a computer monitor, video, or PowerPoint (Mayer et al., 2022). For example, in two separate studies, Parong and Mayer (2018, 2020) showed that students learning about the cells in the human body with a slideshow performed significantly better than those learning the same content in VR. Comparing students learning from a science simulation via a desktop display or a head-mounted display, Makransky, Terkildsen, et al. (2019) found similar results.

In a meta-analysis, Jensen and Konradsen (2017) showed that immersive VR is not more effective than other non-immersive pedagogical tools and can even be counterproductive in some cases. However, the authors did find that VR is more effective when it comes to cognitive skills related to the acquisition and understanding of spatial and visual information, psychomotor skills, and affective skills related to emotional responses. Other meta-analyses came to different results. For example, Wu et al. (2020) found that VR is slightly more effective than non-immersive learning tools and VR can facilitate both knowledge and skill development, but also showed that one-third of the studies reported no effect or even a negative effect of VR on students' learning performance. However, Hamilton et al. (2020) reported a more pronounced advantage of VR over other learning tools. Hamilton et al. (2020) revealed that most studies considered showed that VR led to better learning performance than traditional learning tools, whereas a small number of studies showed no difference in learning gains. VR is especially advantageous when learning activities involve abstract and complex concepts that require visualization and experiential learning (Hamilton et al., 2020). In this sense, these meta-analyses (Hamilton et al., 2020; Jensen & Konradsen, 2017; Wu et al., 2020) are similar, as VR is unique in its capacity to visually represent complex concepts and make them more accessible for active interactions, manipulation, and understanding.

Although these meta-analyses provided significant insight regarding the effectiveness of VR in comparison to non-immersive learning tools, they also revealed many issues related to the studies considered. First, most studies did not present clear pedagogical and theoretical considerations that could drive the effects of immersive VR on students' learning (Hamilton et al., 2020). It seems that educators and teachers simply use whatever virtual learning applications are currently on the market; however, most of these applications were not developed based on proven learning theories (Fowler, 2015; Hamilton et al., 2020; Radianti et al., 2020).

Second, many studies primarily evaluated the usability of these applications instead of learning effectiveness (Radianti et al., 2020). In addition, Hamilton et al. (2020) argued that the validity of the instruments used to assess learning constitutes the greatest weakness of the studies included in their meta-analysis. This suggests that more empirical studies with valid instruments that do not simply examine usability but also learning performance are needed to accurately assess VR's effectiveness for learning.

Third, empirical results from the media-comparison studies, in general, must be interpreted in light of the everlasting debate related to the question of whether or not media influences learning (Artino & Durning, 2012; Clark, 1983; Clark, 1994). Kozma (1994) argued that media facilitates certain instructional methods more than others do and that the most important question is not to answer whether media influences learning but to explain the relationship between specific media and particular learning outcomes. In this regard, the relationship between media and learning outcomes should be examined in terms of how media characteristics influence the cognitive representation and processing of learning content (Salomon, 1979). For instance, one could assess how particular VR affordances affect how students process the lesson content. This is an important factor to consider when comparing VR to other conventional learning tools, as VR enables students to interact with the lesson from a first-person perspective and experience the content more vividly. In this regard, Parong and Mayer (2018) argued that such comparisons can help understand how particular features of multimedia affect learning, especially if the learning content presented in both media is very similar. Meyer et al. (2019) made a similar claim and found an interaction between learning methods (i.e., pre-training) and media (VR), indicating that some methods performed better with certain media than others.

Effectiveness of VR in relationship to the type of knowledge considered

VR's effectiveness also seems to vary depending on the type of knowledge (e.g., factual, conceptual, or procedural) considered (Howard, 2018; Jensen & Konradsen, 2017). Numerous taxonomies are used to refer to different types of knowledge (e.g., Zack, 1999). Among those, Anderson et al. (2001) propose a taxonomy with four different types of knowledge: a) *Factual knowledge*, which refers to the ability to recall facts and events; that is, the basic knowledge or factual information acquired in a particular subject. b) *Conceptual knowledge* is knowledge about classifications or principles in a particular domain; it can be considered as the understanding of the interrelationships among the elements within a structure or a system. c) *Procedural knowledge* is "know-how", knowledge of the method required to master a specific skill or a procedure. d) *Metacognitive Knowledge* refers to the awareness and knowledge of one's own cognition. Although metacognitive knowledge is not typically assessed in the context of learning with VR, it may be a fundamental aspect in learning in an immersive virtual learning environment that is very stimulating, as it can help students to remain aware of their leaning objectives (Klingenberg et al., 2020; Zhao et al., 2023).

In the Cognitive Affective Model of Immersive Learning (CAMIL), Makransky and Petersen (2021) include four types of knowledge that the affordances of VR can affect distinctively: factual knowledge, conceptual knowledge, procedural knowledge, and transfer of knowledge. Transfer is the capacity to apply the knowledge gained in novel situations (Singley

& Anderson, 1989). Makransky and Petersen (2021) argue that both procedural and conceptual knowledge can enhance knowledge transfer; that is, the capacity to apply a concept learned in one domain to a related domain. Specifically, virtual reality (VR) simulations that depict real-world performance situations can facilitate transfer to similar situations in the real world (Makransky et al., 2021; Makransky & Petersen, 2021).

Particularly, VR has been used to foster procedural knowledge (Huang et al., 2023), as VR has a distinct advantage over other multimedia for demonstrating and training specific skills; the immersive aspect of VR also has a positive effect on procedural learning (Jung & Ahn, 2018; Morélot et al., 2021). In this vein, Hamilton et al. (2020) revealed that VR is especially effective for teaching and acquiring procedural skills. For example, Bharathi and Tucker (2015) investigated whether immersive VR could enhance engineering students' performance on product functional analysis tasks. The results showed that students in the immersive VR condition were significantly faster than those in the non-immersive condition, indicating that VR's ability to systematically adapt to learners' actions and position is a major advantage driving the effect of VR on the development of procedural skills (Bharathi & Tucker, 2015). Not only can VR be more effective than other learning tools, it can also facilitate the transfer of the skills acquired in VR to the real world (Hejtmanek et al., 2020; Jung & Ahn, 2018). For instance, Sankaranarayanan et al. (2018) found that students who learned fire emergency response through a virtual simulation were better able to perform the correct procedure in the correct order compared to students who learned the same procedure through presentation and paper. Overall, it appears that VR could be effective for all types of knowledge, but procedural learning and training are particularly suited to VR (Hamilton et al., 2020; Wu et al., 2020).

1.2.1 Possible reasons for VR’s lack of effectiveness

The above review of VR’s effectiveness in different contexts has shown that VR offers unique affordances for learning, is highly motivating and partly effective for teaching and learning science. From an equity-focused perspective, this warrants the use of VR in education so that students can take advantage of these affordances. On the other hand, the review showed that VR can also be less effective in comparison to other methods (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2018). Therefore, it is important to understand the possible causes of VR’s lack of effectiveness and possible factors that can enhance its effectiveness in science education. In this dissertation, I examine the three most significant factors that can hinder the effectiveness of VR for teaching and learning: the poor instructional quality of many current virtual simulations, increased cognitive load during learning in VR, and lack of guidance and motivational support. Then, I discuss the role of presence in learning with VR, which can be both fostering and hindering.

Poor instructional quality of many current virtual simulations

The technological advancements in computer and graphics technology, as well as the decrease in the cost of VR devices, have made the technology more accessible and mainstream. With this VR hype comes a flurry of programming and development of virtual learning simulations intended to illustrate learning content and provide students with the opportunity for immersive learning. Nevertheless, many of the currently available virtual learning simulations were created by programmers with little input from educational psychologists or educators (Hamilton et al., 2020). In their meta-analysis, Hamilton et al. (2020) observed that educators are utilizing currently available simulations despite their possible instructional design flaws. Moreover, there are few guidelines and resources to help educators actually implement VR in the classroom effectively (Wu et al., 2019). This development is more technology-driven than pedagogy-driven, and consequently, many of the currently available learning simulations lack pedagogy (Chen et al., 2005; Fowler, 2015; Wu et al., 2019). Upon observing this situation, Fowler (2015) rhetorically asked: "Where is the pedagogy?”

According to two recent meta-analyses, the majority of studies on VR in education did not consider a distinct learning theory (Hamilton et al., 2020; Radianti et al., 2020). Moreover, most of the first studies on VR did not account for learning and focused solely on usability (Radianti et al., 2020). All this suggests that the lack of effectiveness of VR could also be the result of suboptimal instructional design based on established learning theories; therefore, more empirical studies applying evidence-based learning theories and approaches are needed to fully answer the question of the effectiveness of VR for learning. The significance of pedagogically sound instructional design in virtual reality for effective learning has been emphasized before and during the present wave of interest in VR in education (Chen, 2009; Chen et al., 2005; Johnson-Glenberg, 2018). In addition, numerous studies have shown that proper instructional design improves students' learning performance in multimedia (Wu et al., 2019).

Increased cognitive load in VR

Learning with VR is very motivating: It increases students enjoyment and satisfaction (Bulu, 2012; Makransky & Lilleholt, 2018) and can foster engagement (Georgiou et al., 2007; Karutz & Bailenson, 2015; Vrellis et al., 2016). However, VR as a highly interactive and immersive learning tool can also distract students from their learning goals (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2018, 2020). In order to make virtual learning simulations more appealing and motivating, visual and auditory details (hedonic elements) are incorporated. In some cases, these details are necessary and facilitate learning; in others, they constitute seductive details that can hinder effective learning (Lehman et al., 2007; Park et al., 2015). Visual and auditory instruction materials or elements in VR can be considered seductive details when they are both (a) interesting and (b) irrelevant to the instructional and learning goals (Lehman et al., 2007; Park et al., 2015). Seductive details have the potential to draw students' attention away and cause an increase in cognitive load (Moreno & Mayer, 2000; Richards & Taylor, 2015), which negatively affects students' learning performance (Rey, 2012).

It has been shown that adding seductive details to multimedia can hinder students' learning (Harp & Mayer, 1998; Mayer, 2017; Rey, 2012), especially for students with lower attention control (Rey, 2014). In four different studies, Harp and Mayer (1998) theorized how "seductive details do their damage" by proposing three mechanisms by which seductive details impair learning: diversion, disruption of the learning process, and distraction from the learning goals. There is further evidence supporting this assumption (Lehman et al., 2007; Rowland et al., 2008; Sanchez & Wiley, 2006), which boils down to the distraction and cognitive overload hypothesis. Therefore, virtual learning simulations that are not carefully designed can hurt rather than foster learning (Bedwell et al., 2012; Howard, 2017).

Consequently, one of the main reasons for the lack of effectiveness of VR is due to the increased cognitive load in an immersive virtual learning environment (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019; Moreno & Mayer, 2000; Parong & Mayer, 2018). Parong and Mayer (2018) argued that perceptual realism in the 3D virtual learning environment might have caused a higher cognitive load during the lesson, which could have impaired students' learning performance. Because human cognitive processing capacity is limited, any cognitive overload will reduce students' capacity to process the learning content effectively (Mayer, 2009a; R. E. Mayer, 2014; Mayer, 2022). Furthermore, it has been argued that learning with highly immersive and interactive multimedia such as VR may be overstimulating and cause an increase in cognitive load, which could impair learning (Makransky, Terkildsen, et al., 2019). Results of a recent study using EEG have shown that learning with VR leads to a significantly higher cognitive load than learning with a computer monitor, a video, or a PowerPoint presentation (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2020, 2021).

Lack of guidance and motivational support in learning with VR

Regardless of how great the technical features of a learning technology might be, if students lack awareness of these features and have negative attitudes toward them, a learning technology may not be as effective as it could be. In addition to evidence-based instructional design principles, students' attitudes and motivational support could constitute major contributing factors to VR's effectiveness in science education (R. E. Mayer, 2014; Mayer, 2022; Mayer & Fiorella, 2021; Mayer et al., 2022; Moreno & Mayer, 2007). For instance, Makransky and Lilleholt (2018) showed that students' perception of VR positively affected learning in VR through both an affective path and a cognitive path. The affective path showed how immersive VR enhanced students' perceived usefulness of VR, which in turn affected their presence in VR; subsequently, presence had positive effects on motivation and enjoyment. The cognitive path also revealed that immersive VR affected students' learning outcomes through their perceived usefulness of VR and perceived cognitive benefits and agency in VR. Similarly, it has been shown that students' perceived usefulness of a given technology plays a key role in implementing an effective virtual learning environment as it fosters acceptance—a central prerequisite that can facilitate actual use and enhance students' willingness to engage with the virtual learning environment (Davis, 2011; Martins & Kellermanns, 2004). However, despite its importance for learning in general, very little attention has been given to students' attitudes and motivation to learn as fundamental factors that can enhance VR effectiveness. Moreover, there are very few empirical studies examining how motivational support in learning with VR can foster learning (Shackelford et al., 2019). Without such an understanding, the design of effective virtual learning environments will remain a challenge (Shackelford et al., 2019).

Current evidence suggests that immersion and interaction alone do not help students process the learning content more effectively because VR can also be overstimulating (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2020, 2021). This is because enriched virtual learning environments with seductive details do not just stimulate students and enhance their learning experience; they also compete for students' attention and can cause overload (Rupp et al., 2016). Moreover, the lack of guidance and motivational support in VR is likely to contribute to its ineffectiveness (Cook et al., 2019; Shackelford et al., 2019; Wu et al., 2023). In order for students to profit from the affordances of VR, the whole learning process should be established in a way that supports students' goal-oriented behavior, which could help them avoid distractions and increase their learning performance. For instance, Chen et al. (2005) showed that students benefited from a virtual learning simulation that guided them through the learning session, regardless of their learning styles. In addition, their performance was substantially superior to that of unguided explorers. These results highlight the significance of instructional design and pedagogical support for the effectiveness of immersive VR (Chen et al., 2005).

Relationship between presence and learning in immersive virtual environments

As an affective and psychological variable, presence constitutes the essence of the learning experience in VR and appears to be essential for learning (Dengel & Mägdefrau, 2019; Makransky & Petersen, 2021; Petersen et al., 2022; Selzer et al., 2019). Immersive learning is a learner-centered experience in which the learner's perceptions of visual and auditory stimuli, actions, and interactions are crucial. Presence confers some authenticity to this process, as it implies that students perceive themselves to be "physically present" in the virtual learning environment (IJsselsteijn & Riva, 2003; Slater, 2009; Slater & Sanchez-Vives, 2016). In this regard, the current literature shows that learning with VR, as opposed to non-immersive learning tools, results in a greater sense of presence (Cummings & Bailenson, 2015; Makransky & Lilleholt, 2018; Makransky & Mayer, 2022; Yu, 2021). Nonetheless, the fundamental question remains: how does presence influence the learning performance of students in VR?

It has been proposed that presence may enhance learning performance, as higher presence in the virtual learning environment is positively associated with motivational factors, such as attention, involvement, interest, and engagement (W. Huang et al., 2021; Makransky & Petersen, 2021; Mikropoulos & Natsis, 2011; Petersen et al., 2022). Presence seems to foster learners' willingness to engage with the learning content (Vrellis et al., 2016) and is associated with learners' motivation (Makransky & Lilleholt, 2018). Makowski et al. (2017) argued that presence could improve memory encoding as a result of attentional engagement and willingness to participate in the virtual environment. Presence is also associated with learning enjoyment and satisfaction with the learning materials (Bulu, 2012; Choi & Noh, 2021; Makransky & Lilleholt, 2018; Vrellis et al., 2016).

Despite its potential and unique role, very few studies have examined the relationship between presence and learning performance (Krassmann et al., 2019; Ochs & Sonderegger, 2022). A recent systematic literature review revealed that nearly half of studies on this subject did not assess the relationship between presence and learning (Krassmann et al., 2019). Moreover, the majority of studies on VR concentrated on evaluating usability and neglected to assess learning outcomes in general, let alone examine the potential effect of presence on learning (Radianti et al., 2020). Consequently, the current literature is inconclusive, as empirical studies demonstrate contradictory effects of presence on student learning outcomes.

Some empirical research indicates that presence improves students' learning achievement (Kontogeorgiou et al., 2008; Mikropoulos, 2006; Schrader & Bastiaens, 2012; Selzer et al., 2019). According to CAMIL (Makransky & Petersen, 2021), presence can increase students' intrinsic motivation and situational interest in learning activities. Petersen et al. (2022) used structural equation modeling to test these hypotheses and showed that immersion and interactivity in VR led to greater perceived presence, which had a positive effect on intrinsic motivation, situational interest, and embodied learning. However, only situational interest had a positive influence on learning in the end. Another recent study supports the motivational role of presence in learning with VR (W. Huang et al., 2022). The authors found that presence had a positive effect on students' motivation, which increased their cognitive engagement with the learning materials; consequently, students' cognitive engagement increased their learning achievement (W. Huang et al., 2022).

Presence may be especially important for spatial knowledge-related learning activities, according to Parong et al. (2020). Correspondingly, the research results showed that presence was positively related to learning performance on route and survey knowledge and overall spatial knowledge. Moreover, presence significantly mediated only the effect of immersion on survey knowledge task performance (Parong et al., 2020). This led the authors to conclude that the role of presence in learning may vary across different types of spatial knowledge and domains. Such an assumption is in line with other research findings that suggest that the type of learning content and the learning context can affect the relationship between presence and learning (Jensen & Konradsen, 2017; Ochs & Sonderegger, 2022; Radianti et al., 2020).

Other empirical findings suggest that the level of presence may also impair learning (Bailey et al., 2012; Makransky, Terkildsen, et al., 2019; Moreno & Mayer, 2004). Ochs and Sonderegger (2022) recently examined the relationship between presence and learning and found that participants in the VR condition reported a higher level of presence but performed substantially worse on the memorization test compared to participants in the control condition. In addition, the authors found no correlation between presence and learning test performance (Ochs & Sonderegger, 2022). These results are similar to previous findings showing no significant relationship between presence and learning (Buttussi & Chittaro, 2018; Sutcliffe et al., 2005). Another recent study revealed that a higher level of presence negatively affected recall after a learning session in VR about the acidification of the ocean and the disruption of marine systems (Ahn et al., 2022).

Overall, presence seems to be essential for learning with VR, as it can increase student engagement and interest (W. Huang et al., 2022; W. Huang et al., 2021; Makransky et al., 2020; Petersen et al., 2022). Paradoxically, however, such engagement can hinder learning because highly immersive and interactive VR with embedded seductive details can distract students from their learning goals and consume mental resources that are no longer available to invest in meaningful learning (Ahn et al., 2022; Makransky, Terkildsen, et al., 2019; Ochs & Sonderegger, 2022). This conclusion parallels previous explanations indicating that learning with VR is a novel experience and that immersive VR can lead to cognitive overload, which inhibits effective learning (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019; Moreno & Mayer, 2004). Similarly, Ochs and Sonderegger (2022) argue that it is not possible to conclude categorically that presence has no effect on learning based on these findings. This is because it is also possible that distractions, cybersickness, increased cognitive burden, etc., significantly outweigh the potential positive effect of presence on learning. All of this suggests that additional research is needed in this field. However, this also emphasizes the need to provide students with adequate support and orientation in VR and to direct their engagement, actions, and interactions toward the instructional objectives.

1.2.2 Previous attempts to enhance VR's effectiveness in science education

A growing number of studies have shown that applying various learning prompts to immersive VR could help increase its effectiveness in science education (Cromley et al., 2023; Klingenberg et al., 2020; Mayer et al., 2022; Yang & Wang, 2021). This strategy, known as the value-added approach, entails adding or modifying a virtual learning stimulation's feature so that learners can better process the learning content (Mayer et al., 2022). A recent meta-analysis by Cromley et al. (2023) indicates that VR has a positive impact on learning in Science, Technology, Engineering, and Mathematics (STEM) from middle school through college. Notably, the added-value approach (what the authors referred to as redesign-VR) is particularly advantageous for student learning in VR (Cromley et al., 2023). The value-added approach is an umbrella term that encompasses a variety of learning strategies, including instructional design principles (such as the modality principle, pretraining, and segmentation), generative learning strategies (such as summary prompts and enactment), etc.

Instructional design principles comprise an ensemble of established guidelines for structuring multimedia learning content to avoid cognitive overload, facilitate effective processing, and consequently maximize students' learning (Mayer, 2021; Mayer & Moreno, 2003). Instructional principles such as segmentation (Klingenberg et al., 2022), pre-training (Meyer et al., 2019), and the modality principle (Moreno & Mayer, 2002) have been implemented to improve VR's effectiveness. According to the *modality principle*, students learn better with spoken words than with written words (Castro-Alonso & Sweller, 2021; Mayer, 2021). Based on this assumption, Moreno and Mayer (2002) showed through several separate experiments that participants in an environmental class learned more from narration than from printed text. *Pretraining* is based on the premise that students learn more effectively when they spend time familiarizing themselves beforehand with key concepts (e.g., names and characteristics) related to the topic under study(Mayer & Fiorella, 2022; Mayer, 2021; Mayer & Pilegard, 2014). Recent research has shown that pretraining increases the effectiveness of VR (Howard & Lee, 2019; Meyer et al., 2019). *Segmenting* is the process of presenting the learning content in segments—chunks of information that are believed to be more easily processed than the entire content presented all at once (Ahn et al., 2022; Mayer & Fiorella, 2022; Mayer & Pilegard, 2014). Recent studies on the effect of segmenting on student learning outcomes in VR have contradictory results: Ahn et al. (2022) showed that segmenting the learning content in VR did not improve students' learning performance, whereas Parong and Mayer (2018) and Klingenberg et al. (2022) found a positive effect of segmenting on students' learning performance.

The inconsistency in these findings regarding the effect of segmenting on VR's effectiveness can be partially explained by the fact that these studies are not completely similar. Students in the study by Parong and Mayer (2018), for instance, were required to summarize the lesson material after each segment. This indicates that students may have benefited from the compound effect of two learning strategies (segmenting and *summary prompt*). However, this assumption was not supported by a recent study (Klingenberg et al., 2022), which found that although both segmentation and summarization led to improved transfer, the combination of both learning strategies did not improve VR's effectiveness.

Generative learning strategies refer to those strategies aimed at prompting students to engage in effective processing of the lesson content (Fiorella & Mayer, 2022; Fiorella & Mayer, 2015b). For instance, a summary prompt was successfully used to enhance students' learning performance in a virtual learning simulation about the human body (Parong & Mayer, 2018). In this study, students had to pause the learning session after each of the six learning segments to write a summary of what they had learned. The results revealed that such a learning strategy had a positive effect on their learning performance in a posttest. Similarly, Makransky et al. (2021) used enactment to help students better process the learning content they had acquired through a virtual simulation about DNA. *Enactment* is the process of using physical objects to recreate the core of the previously learned lesson; enactment can activate the same cognitive processing as a summary prompt and answering questions (Fiorella & Mayer, 2022; Fiorella & Mayer, 2015a, 2015b).

In their meta-analysis, Cromley et al. (2023) noted that active learning is the method that generates the majority of the positive effects of the added-value approach on students' learning outcomes. For instance, students learn key concepts in pre-training before participating in the lesson (pretraining), they are prompted to recapitulate what they have learned after each segment (summary prompt), and they use physical objects to demonstrate their newly acquired knowledge (enactment). Despite the fact that these learning strategies can promote learning, they may have some disadvantages: Pretraining necessitates the development of specific materials for each lesson. A summary prompt requires students to stop the virtual learning simulation to compose a summary. Enactment requires learning materials (physical objects) that are related to the specific subject.

Moreover, it is not yet well known how multiple induced breaks in a learning session affect the immersive experience, notably students' presence in the learning environment. Ahn et al. (2022) showed that segmenting the VR content had a small but significant negative effect on presence. Enactment is an activity after the learning session in VR that allows students to review the lesson learned with physical objects. However, educators might be interested in practical and parsimonious learning techniques that are easy to implement and do not interrupt the flow of the learning content. Furthermore, the majority of strategies within the added-learning approach are based solely on how to better process the learning content from a cognitive perspective and do not take into account affective processes (motivations, attitudes, learning goals, etc.) in immersive virtual reality, which are assumed to be essential in the context of learning with a dynamic and interactive learning tool such as VR.

1.2.3 Fostering effective learning in immersive virtual reality

Although edutainment seems to be important for learning with multimedia because it has a powerful influence on students' motivation (Wong & Adesope, 2021), it has also been the subject of significant criticism. Okan (2003) presents a critical perspective on the notion that the use of vibrant visuals and interactive components in multimedia may greatly enhance students' learning experience. He further cautions against inadvertently creating unrealistic expectations amongst learners that knowledge may be acquired effortlessly without diligent effort and rigorous study. In a similar vein, Resnick (2004) criticized the portrayal of edutainment as a potential solution to the challenges associated with the educational process, sometimes characterized as a form of "suffering". The risk associated with such an approach is that students could develop a perception that learning is synonymous with pleasure and amusement, which might diminish their capacity to invest the time, energy, and concentration required to comprehend complex learning content (Okan, 2003).

Contrary to the predictions of the edutainment approach, the inclusion of hedonic and immersive elements and interactive components into the learning environment might have a detrimental effect on students' learning. Rather than facilitating learning, these elements can serve as distractions, leading to an increase in cognitive load and impairing learning performance (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019; Meyer et al., 2019; Parong & Mayer, 2018, 2020). Simultaneously, the affordances of VR seem to outweigh its hedonic characteristics. Hence, the main issue is how to support students during learning in the virtual learning environment so that they can avoid potential distractions (seductive details), remain focused on learning objectives, and, most significantly, benefit fully from these affordances.

According to Mayer et al. (2022), learning in VR can be considered active learning (Kirschner et al., 2006; Mayer, 2004) if learners are engaged in cognitive processing activities—active learning does not necessarily require a certain level of physical activity (Mayer, 2021, 2022). Moreover, effective learning is *constructed*: it involves the selection of relevant information, the (mental) organization of the selected information—building relations between different pieces of information—and the integration of the new information into prior knowledge (Mayer, 2022). For students to benefit from multimedia learning tools (e.g., virtual learning simulation designed according to VR affordances and including hedonic factors), they must apply appropriate processing strategies (Fiorella & Mayer, 2022; Mayer & Fiorella, 2022; Mayer et al., 2022; Moreno & Mayer, 2007). This also requires that students develop the mental capacity to be able to evaluate the presented information and distinguish between what is relevant, unimportant, and trivial (Gandz, 1997). This is critical in the context of learning with VR, especially because of the embedded seductive details—interesting elements but irrelevant to learning goals. Therefore, motivational support and guidance in immersive VR are fundamental so that students' experience in VR can be oriented toward learning. Such an approach constitutes a balancing act between the affordances of VR, the hedonic factors and students' motivation to learn.

Role of motivation in learning

Motivation is one of the most important factors in both traditional classroom and multimedia learning (Kriegbaum et al., 2018; Schunk & Zimmerman, 2008). Previous research has demonstrated that motivation is, next to intelligence, a strong predictor of student achievement (Kriegbaum et al., 2018; Steinmayr & Spinath, 2009); for instance, motivational factors such as self-efficacy, self-concept, interest, and learning goals predicted students' mathematical competence beyond intelligence and prior knowledge (Kriegbaum et al., 2015). In a more recent study, Lavrijsen et al. (2022) found that students' intelligence and personal preference to engage in cognitively demanding tasks were the strongest predictors of academic achievement; however, students' motivation also explains a substantial amount of variance. Even after controlling for intelligence and personality, several motivational processes (notably academic self-concept, achievement goals, achievement motivation, autonomous motivation, and effort beliefs) explained additional and unique shares of the variance in students' academic achievement (Lavrijsen et al., 2022).

Motivation is essential for effective learning with multimedia, as it enables students to actively engage with and invest effort in processing the learning materials (W. D. Huang et al., 2013; Lei et al., 2018; Leutner, 2014). It has been shown that several motivational factors significantly influence students' cognition, meta-cognition, and learning performance (Schunk & Zimmerman, 2008; Um et al., 2012; Um et al., 2007); these factors include but are not limited to: self-efficacy, intrinsic motivation, interest, perceived values, and goals orientation (Schunk & Zimmerman, 2008). However, many existing theoretical frameworks concerning effective multimedia learning have been criticized for failing to incorporate motivation and underspecifying how motivation can significantly affect the processing of learning content (Astleitner et al., 2006; Astleitner & Wiesner, 2004). In order to optimize students' use of multimedia learning technologies such as VR, it is essential for instructional design to include students' characteristics, such as attitudes, motivation, perception, and prior knowledge (Paas & Kester, 2006; Plass et al., 2009).

1.3 Effects of motivation on students' cognitive processing in VR through the lens of the cognitive theory of multimedia learning

According to the CTML (Mayer, 2009a; R. E. Mayer, 2014; Mayer, 2022), students' motivation can play a fundamental role in students' meaningful learning in VR—their engagement in effective processing. CTML, which is based on the cognitive load theory (CLT;

Chandler & Sweller, 1991; Sweller et al., 2011), provides the theoretical framework to understand how the hedonic variables in VR can enhance or hinder learning as well as how students' characteristics (prior knowledge and motivation) can facilitate adequate processing of the learning content in VR.

1.3.1 Tenets of the CTML

The cognitive theory of multimedia learning (Mayer, 2009a; R. E. Mayer, 2014; Mayer, 2022) is predicated on the following three main assumptions:

a) *The dual-channel assumption*: Working memory consists of two separate independent channels to process visual and auditory information (Mayer, 2022). Accordingly, visual simulations, pictures, animations, and other forms of visual information in VR are processed by the visual channel; narration and all other auditory information and sounds are processed by the auditory channel.

b) *The limited capacity assumption*: Working memory capacity is limited; that is, there is a limited amount of information that can be processed in each channel at any one time (Mayer, 2022). Based on this assumption, when students are learning with a virtual simulation that includes seductive details, they are forced to make decisions regarding which elements to pay attention to and which ones to ignore.

c) *Active processing assumption*: active learning requires the selection and organization of relevant information into coherent mental representation and the integration of this mental representation into prior knowledge (Mayer, 2022). This suggests that, in order for active learning to happen in VR, students need to be able to pay attention to the relevant information (selection), establish structural relations between the elements of the selected information (organization), and connect the new information with what they already know about the subject and other relevant prior knowledge (integration).

Based on these assumptions, the use of immersive virtual reality in education presents multiple challenges that can be summarized into three important questions: how to guide students in the virtual learning environment so that they can select the relevant learning content; how to design an engaging learning environment and at the same time not overload students' working memory; and how to encourage active and meaningful learning. In order to attempt to solve these challenges and increase VR's effectiveness, it is important to understand the cognitive demands placed upon learners' working memory during learning. According to CTML, there are three kinds of demands during information processing: extraneous processing, intrinsic processing, and generative processing. All three demands are similar, respectively, to extraneous cognitive load, intrinsic cognitive load, and germane cognitive load in CLT (Chandler & Sweller, 1991; Sweller et al., 2011).

Extraneous processing refers to cognitive processing that does not support the instructional objectives and does not help make sense of the learning content presented (Mayer, 2009a, 2022). Extraneous processing occurs due to suboptimal instructional design. In learning with VR, poor quality of instruction and seductive details can increase extraneous processing, thus negatively affecting students' learning performance (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2020, 2021). This is because extraneous processing constitutes a waste of cognitive capacity and does not contribute to any useful construction of knowledge (Mayer, 2022).

Essential processing is the processing that is required to mentally represent the learning content in working memory for a period (Mayer, 2009a, 2022). It is caused by the inherent complexity of the learning material; the more complex the learning content is, the higher the essential processing required to achieve the instructional objective. In the context of learning with VR, essential processing can facilitate learning as it involves selecting relevant information in the virtual learning environment and organizing it in working memory (Mayer, 2022; Mayer & Pilegard, 2014). However, when the learning materials are too unfamiliar and presented at a rapid rate, learners' cognitive capacity can be overloaded (essential overload; Mayer & Pilegard, 2014). Consequently, learners may not have fully understood the concepts presented (Mayer, 2009a; Mayer & Moreno, 2003).

Generative processing refers to the cognitive processing required to actually understand the learning material. It is crucial for the process of selecting, organizing, and integrating the new content into prior knowledge (Mayer, 2009a, 2022). Generative processing is strongly affected by learning motivation (R. E. Mayer, 2014; Mayer, 2022). Learning with immersive VR can lead to higher generative processing and subsequently enhance learning if the virtual learning simulations used manage to engage students in the active construction of knowledge. Otherwise, generative processing underutilization can occur; this refers to a situation in which learners have cognitive capacity available but are not motivated enough to engage in meaningful learning (Mayer, 2009b).

1.3.2 Adequate instructional design for effective learning in VR

Considering that learners' cognitive capacity for processing information in the virtual learning environment (oft embedded with seductive details) is limited, and the three demands on cognitive capacity are additive, any amount of working capacity that is used to meet one of the three demands would affect the others two negatively (Mayer, 2009a, 2022). For instance, if students get distracted by the seductive details in the virtual learning environment and are forced to spend a considerable amount of cognitive capacity on extraneous processing, they would not have sufficient capacity to invest in essential and generative processing, which are fundamental for adequate processing and knowledge construction (Mayer, 2022). In addition, individual differences in terms of cognitive capacity, prior knowledge, motivation, attitudes, meta-cognitive and self-regulative strategies may affect how students process the learning content in VR (Liu et al., 2022; Plass & Kaplan, 2016; Song et al., 2016; Wu et al., 2023). For instance, students with a higher level of prior knowledge may be more capable of handling the extraneous processing and optimizing the essential and generative processing (Fiorella & Mayer, 2021; Mayer & Pilegard, 2014). Similarly, students with a high motivation to learn may have less difficulty focusing on the relevant content and avoiding the seductive details in VR that could increase extraneous demands. Furthermore, students' motivation could help them to engage in generative processing, thus increasing their understanding of the learning content (R. E. Mayer, 2014; Mayer, 2022).

From the perspective of CTML (R. E. Mayer, 2014; Mayer, 2022), effective learning in immersive virtual reality requires the reduction of extraneous processing, the management of essential processing, and the fostering of generative processing.

Reducing extraneous processing in immersive virtual reality will require a change from technology-driven to a more pedagogy-driven development of virtual learning simulations. The development of such virtual learning simulations should take into account instructional design principles (Mayer, 2021) and proceed according to established learning theories (Mayer, 2021, 2022; Radianti et al., 2020). However, this aspect of VR's effectiveness is beyond the scope of the present dissertation.

Managing essential processing is fundamental to avoid essential overload and, more importantly, to facilitate knowledge construction (Mayer & Pilegard, 2014). A few instructional strategies have been used to successfully increase VR's effectiveness in science education. For instance, pre-training (Howard & Lee, 2019; Meyer et al., 2019) and summary prompts (Parong & Mayer, 2018), which lead to enhanced learning performance, are not only generative learning strategies (Fiorella & Mayer, 2015a, 2015b)— strategies that aim at facilitating students' appropriate cognitive processing—but also a technique to manage essential processing. Pre-training enables students to familiarize themselves with key concepts before learning with VR, which could help them avoid essential overload. Similarly, as previously discussed, the summary prompts used by Parong and Mayer (2018) allowed students to engage with the learning content by writing a summary after each section. However, the fact that the lesson itself was segmented constitutes a technique that can also help students manage their essential processing capacity.

Fostering generative processing involves encouraging students to actively engage with the lesson. Since generative processing is caused by motivation, researchers and educators have great latitude to apply a variety of techniques to promote generative processing of the learning content (Fiorella & Mayer, 2015b; Mayer, 2009b). For instance, the *multimedia principle*, according to which students learn better with words and pictures than with words alone (Mayer, 2009a, 2021), is itself an instructional technique to foster generative processing. This technique is the cornerstone of most edutainment learning materials (including immersive VR). A few other examples of techniques (Mayer, 2009b) that can foster students' generative processing are the *emotional design principle* (adding elements to multimedia learning tools that induce positive emotions), *guided discovery* (providing hints and feedback during learning sessions), and *generative learning strategies* (providing prompts for effective learning).

Even if a virtual learning environment were designed so that instruction could support the learning goal and minimize extraneous demands, educators would still have to use techniques to help students manage essential processing and foster generative processing. From a hedonic perspective, it can be argued that the incorporation of hedonic elements in VR (e.g., emotional and multimedia design principles; embodiment principle) can enhance engagement and thus foster generative processing and learning (Moreno & Mayer, 2007). The opposite argument can also be made: the embedded hedonic elements in VR can also constitute seductive details that can increase students' extraneous processing, thus impeding learning. Current empirical evidence, although inconclusive, tends to support the latter argument (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2020) and suggests that adding generative learning strategies can foster learning (Meyer et al., 2019; Parong & Mayer, 2018). The present dissertation focuses on the role of motivational support for VR's effectiveness; that is, whether motivational support can foster effective processing in VR (focusing on relevant information and engaging in meaningful learning) and facilitate learning.

1.4 The integrative approach: how integrating motivation into instructional design facilitates learning

Almost since the beginning, there have been educational psychologists and researchers arguing for the integration of motivation into various cognitive theories of learning with multimedia (Astleitner et al., 2006; Astleitner & Wiesner, 2004; Keller, 1997; Lee & Boling, 1999). In this regard, the cognitive-affective theory of learning with media (CATLM; Moreno, 2005, 2007; Moreno & Mayer, 2007), which is very similar to the CMTL, can be considered an answer to some critiques (e.g., Astleitner & Wiesner, 2004) of the underspecification of the role of motivation in various cognitive theories of learning (e.g., CLT and CTML). CATLM includes both motivational and metacognitive factors that can enhance students' learning with multimedia such as VR (Moreno, 2007; Moreno & Mayer, 2007). Currently, CTML (Mayer, 2022) also explicitly refers to motivation and highlights how motivation plays a fundamental role in learning and, more specifically, in effective processing of the learning content (i.e., generative processing). Moreno and Mayer (2007) posit that students' motivation can influence learning by increasing or decreasing cognitive engagement. Such a perspective underscores that motivation has a direct and indirect impact on cognitive processing—it can either hurt or foster effective processing. For instance, learning in a virtual learning environment with embedded seductive details might cause overstimulation, thus impairing learning achievement (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019). Similarly, Scheiter and Gerjets (2007) argue that interactive and motivational elements in multimedia could distract students and impose high demands on their cognitive capacity, thus hindering effective learning.

Astleitner and Wiesner (2004) argue that such integration is fundamental for effective learning with multimedia because motivational processes also require working memory capacity and are linked with various cognitive processes such as attention, engagement, and goal-oriented behavior. Based on the assumption that mental capacity is limited, Astleitner and Wiesner (2004) further argued that effective learning requires the management of mental resources; mental management is linked to attention, engagement, and monitoring during the processing of information in multimedia environments. *Attention* affects the capacity of working memory, which is devoted to a specific task for a given period of time. *Engagement* relates to mental activities in relation to a specific task within a given time period. *Monitoring* determines the level of focus and dedication to a specific task at a specific time by evaluating the success of mental activities. The monitoring function is similar to the current understanding of the role of self-regulation in learning with multimedia (Boekaerts, 2010; Scheiter et al., 2018; Zhao et al., 2023). Effective mental management of working memory capacity is contingent upon students' motivational processes, such as goal setting and action control (Astleitner & Wiesner, 2004).

Applying this concept of mental management (Astleitner & Wiesner, 2004) to learning with VR, it appears that motivational support can assist students in focusing on their learning objectives (avoiding distractions), engaging in learning activities (active learning and generative processing) and self-regulating their own action and interaction with the virtual learning environment. For students to be able to engage in effective processing (selection, organization, and integration) and avoid distractions, students must be sufficiently motivated to invest effort in the learning materials (Scheiter & Gerjets, 2007). In the same vein, R. E. Mayer (2014) suggests that incorporating motivational elements into multimedia could facilitate learning as long as these elements do not overload students' cognitive processing capacity. When integrating features to prime students' motivation into virtual learning simulations, it is important to ensure that those features do not inadvertently cause unnecessary cognitive load.

Motivational support in virtual learning environments

Despite its potential role in enhancing students' effective cognitive processing in VR, so far, motivational support in immersive virtual learning environments has received very little attention. Shackelford et al. (2019) argued that such a lack of understanding of motivational support in immersive learning makes it even harder to design learning simulations that increase students' perceived motivational support and foster their effective cognitive processing of the lesson content. Using the Attention, Relevance, Confidence, and Satisfaction (ARCS; Keller, 1987a, 1987c) Model, Shackelford et al. (2019) assessed the relationship between features in a virtual learning situation in archeology and students' perceived motivational support. In the ARCS Model, attention is related to students' interest in the learning content, and relevance refers to students' perceived usefulness of the applications for present and future outcomes (Keller, 1987a, 1987b). Previous studies showed that students' perceived motivational support is associated with affective (e.g., satisfaction) and cognitive processing (e.g., cognitive investment) during learning (W. D. Huang et al., 2013; Huang et al., 2006). In their VR study, Shackelford et al. (2019) revealed that although students learning archeology with VR reported overall high motivational support, they perceived relatively lower relevance. This highlights the need to ensure that students are aware of the affordances of the learning tools used.

Considering students' difficulty in selecting the relevant information (avoiding distractions) in order to learn effectively in VR, Vogt et al. (2021) used annotations to guide students' attention to relevant learning content. The results indicated that annotations did not have any effect on students' knowledge, comprehension, or application. However, the authors showed that students' intrinsic motivation was a significant moderator of the effect of annotations on students' learning. The results revealed that students must either be intrinsically motivated or need annotations to be able to learn effectively. These results are in line with previous research suggesting a positive relation between students' motivation (based on the ARCS model) and visual attention in visual search tasks (Baranes et al., 2014; Miranda & Palmer, 2014).

The importance for students to have clear learning goals in order to engage in meaningful learning in VR was also emphasized in a recent study (Chu et al., 2023). The authors proposed a goal-oriented reflection strategy-based VR (GRS-VR) to enhance VR's effectiveness for learning English. Students in the GRS-VR condition (added goal-oriented reflection) significantly outperformed students working with (conventional) VR ; students who received such an intervention had higher learning motivation and reflective thinking and better English oral performance than those who did not (Chu et al., 2023).

1.4.1 Providing motivational support from the perspectives of TAM and EVT

Motivational support in VR seems to be not only beneficial but also necessary. Students who benefit from motivational support may be more likely to take full advantage of the affordances of VR by remaining focused on their learning goals (avoiding potential distractions) and processing the learning content effectively (selection, mental organization, and integration of relevant information into prior knowledge; (Mayer, 2022). Over three decades of research on the role of motivation in learning have shown that students' perception of task values is a solid predictor of students' achievement-related behavior and learning performance (Anderman et al., 2001; Eccles et al., 1983; Liaw & Huang, 2013; Wigfield & Eccles, 2000). In this regard, two distinct theoretical approaches in education sciences and psychology emphasize the central role that perceived usefulness plays in students' effective learning: the Technology Acceptance Model (TAM; Davis, 1989) in learning with technological tools, and the Expectancy-Value Theory (EVT; Eccles et al., 1983; Wigfield & Eccles, 2000), which has mostly been applied to traditional classroom settings. Based on these two theoretical frameworks, the perceived usefulness of VR as a learning tool can be characterized as a learner's subjective belief that VR can significantly enhance their learning outcomes.

With the increased use of digital learning tools, there has been growing interest in using TAM to evaluate students' attitudes toward a given learning tool, specifically their acceptance—

in terms of their intention to use that tool (Granić, 2022a; Granić & Marangunić, 2019). It has been argued that multimedia learning tools such as VR, even with all their affordances, would not contribute significantly to students' learning if they are not initially accepted by students (Davis, 2011; Martins & Kellermanns, 2004). Accordingly, acceptance is a necessary condition for effective learning with multimedia (Davis, 2011; Martins & Kellermanns, 2004). Acceptance can facilitate students' willingness to engage with the learning environment and foster regular usage, thus affecting students' learning performance (Juarez Collazo et al., 2014; Larmuseau et al., 2018; Turner et al., 2010).

As digital natives, contemporary students arguably have a basic understanding of the use of VR, but do they perceive it as useful for learning? This is an important question, since VR is heavily used in entertainment and gaming. Moreover, students are likely to associate VR with gaming rather than learning (Baxter & Hainey, 2019). For instance, students ranked education third behind gaming and entertainment as domains where VR can be applied (Baxter & Hainey, 2019). Furthermore, a recent empirical study suggests that students should be made aware of VR's learning potential and its affordances in order to avoid skepticism (Walter et al., 2021). Such pedagogical preparation can facilitate engagement with the learning content. In this line of thought, Chen and Zhao (2022) showed that acceptance influenced the frequency with which students used a learning app and the amount of time they were willing to invest in the learning content (Chen & Zhao, 2022). In the context of learning with VR, students' attitudes towards VR could be a determining factor affecting which aspect of immersive VR (hedonic or utilitarian) they will prioritize. In other words, students who perceive VR as useful for learning are more likely to accept it and may be more willing to engage with the learning content.

According to the TAM, the acceptance of multimedia learning tools is primarily influenced by technical and psychological factors: technical features lead to students' perceived ease of use, which leads to perceived usefulness and acceptance. The psychology factor is related to students' perceived usefulness of the given tool—the perception that the learning tool can contribute to their learning objectives—which subsequently increases acceptance (Davis, 1989). In addition, empirical studies indicate that hedonic characteristics of multimedia learning tools such as VR may also enhance students' acceptance of those tools (Lee et al., 2019; Sagnier et al., 2020; Yang & Han, 2021). For example, edutainment learning content can increase students' enjoyment, which can influence their intention to use educational tools (Lee et al., 2019; Merhi, 2015). Nevertheless, numerous studies have established that perceived ease of use and perceived usefulness are the most important predictors of acceptance; however, perceived usefulness is the more stable and influential predictor out of those two factors (Ma & Liu, 2004; Yousafzai et al., 2007a, 2007b). Consistent with the TAM, several studies have shown that the perceived usefulness of VR as a learning tool has a positive effect on its adoption as a learning tool (Fagan et al., 2012; van Raaij & Schepers, 2008).

Despite its importance for learning with multimedia and its application in the educational domain over the last three decades (Granić, 2022a, 2022b; Granić & Marangunić, 2019), very few studies have assessed the impact of acceptance on students’ learning performance. The main reason for this lack of attention is that these studies aimed at predicting acceptance; therefore, acceptance is often conceptualized as the main dependent variable in this model. Nevertheless, a few studies have shown how the perceived usefulness of a technology affects its acceptance and how acceptance, in turn, impacts students’ academic performance (Ali et al., 2018). A recent study applying TAM in the context of immersive learning showed a positive relationship between students` acceptance of VR and their presence in the virtual learning environment (Plotzky et al., 2021), suggesting that acceptance might positively affect the learning experience in VR. A second important limitation in the TAM literature is that, so far, no study has tested how experimental variation in students’ perception of VR usefulness may affect their acceptance of VR. Therefore, one of the objectives of this dissertation is to assess whether students’ acceptance can be increased through an experimental intervention involving their perception of VR as a useful tool for learning or daily life. More importantly, this dissertation also investigates whether an increase in acceptance facilitates students’ learning experience in VR and enhances their learning outcomes.

The concept of students’ perceived usefulness of learning activities or a given learning tool is not limited to learning with technology. In fact, perceived usefulness, along with expectancies of success, is a central component of the EVT (Eccles et al., 1983) and has been demonstrated to be a significant factor for enhancing learning effectiveness, mostly in conventional classroom settings. Perceived usefulness is a key predictor of students' learning success and achievement-related behavior, such as engagement and willingness to exert effort (Eccles et al., 1983; Wigfield et al., 2016). For instance, previous research has established a positive relationship between learners' value beliefs in mathematics and reading and their self-concept ability (Anderman et al., 2001). Additionally, it has been found that perceived usefulness predicted students' self-regulation (Liaw & Huang, 2013), which is widely recognized as a critical facilitator of learning with multimedia such as VR (Makransky & Petersen, 2021).

EVT (1983) identifies three sources of values that motivate students: the enjoyment derived from engaging in an activity (intrinsic value), the significance of the activity in relation to one's sense of self and personal goals (attainment value), and the perceived usefulness of the activity either in the present or future (utility value). It is noteworthy that two of the central components of value (intrinsic value and utility value) are very similar to the two perspectives (hedonic and utilitarian) regarding the use of VR in education presented in this dissertation. Whereas the literature suggests that students enjoy learning with VR (hedonic aspect), it is not as evident that students are aware of its usefulness as a learning tool (utilitarian aspect). Therefore, it remains a challenge for educators and researchers to find the best way to help students engage in effective learning in VR.

Usefulness interventions

Contrary to the literature on TAM, empirical evidence based on EVT offers a variety of interventions to enhance students' motivation by increasing their perceived usefulness of a given task (Hulleman & Harackiewicz, 2021). Previous studies have also highlighted the practical importance of perceived usefulness. More especially, it has been argued that amongst the components of value beliefs (e.g., intrinsic value, attainment value, and utility value or perceived usefulness), usefulness is comparatively easier to influence externally and thus represents an important starting point for conducting effective interventions to increase students' motivation and learning achievement (Harackiewicz et al., 2014). Classical usefulness interventions consist of encouraging students to think about the usefulness of a subject or activity by establishing a connection between this activity and their lives or its relevance for everyday life (Hulleman & Harackiewicz, 2021). Educators can implement such interventions through strategies that encourage reflection and increase students' awareness of the significance of the subjects they are about to study or the learning tools they will utilize. In a variety of research studies, participants were directed to engage in activities highlighting the relevance of different academic disciplines, such as biology, physics, statistics, and mathematics, within the context of their personal lives (Brisson et al., 2017; Hulleman & Harackiewicz, 2009, 2021).

Empirical evidence suggests that a usefulness intervention can increase students' motivation and engagement (Hulleman & Harackiewicz, 2021). In this regard, the results of several studies show that increasing perceived usefulness leads to long-term increases in learners' effort, interest, and academic achievement (Hidi & Harackiewicz, 2000; Hidi & Renninger, 2006). Indeed, a usefulness intervention to promote value beliefs in mathematics education also demonstrated that increasing students' perceived usefulness of math promoted achievement-related behaviors (Gaspard et al., 2015). In another intervention study, students in the experimental condition engaged with the relevance of mathematics for their future. The results showed that they reported higher homework self-efficacy compared to a control group up to six weeks and five months after the intervention (Brisson et al., 2017). The intervention also affected students' self-concept, teacher-rated effort, and achievement in mathematics, with some effects extending into the long term (Brisson et al., 2017).

Similar to these interventions, priming students to perceive VR as useful can be accomplished by emphasizing VR's fundamental affordances, such as immersion, interaction, and the ability to transcend time and space, and allowing students to make their own connection between these affordances and their learning goals. More importantly, such an intervention can be integrated into virtual learning simulations as part of the learning instruction. I assume that an intervention involving the usefulness of VR could have major consequences: It could help students stay focused on their learning goals by avoiding distractions. A recent study suggests that simply informing students about the presence of seductive details in multimedia learning can help mitigate their negative effects on learning performance (Bender et al., 2021). This implies when students are aware of possible distractions and have clear learning goals, their learning performance can be enhanced. Moreover, such interventions can increase the acceptance of VR as a learning tool, which, according to the TAM, constitutes a fundamental prerequisite for effective learning with multimedia learning tools. Such acceptance can enhance students' predisposition to learn and engage with the learning materials in VR, thus facilitating students' learning experience in VR and their learning outcomes. Furthermore, such interventions can help students engage in generative processing of the learning content (R. E. Mayer, 2014; Mayer, 2022). Students with higher motivation and clear learning goals would probably have an easier time selecting relevant information in the virtual learning environment (selection), organizing the selected information mentally (organization), and integrating it into prior knowledge (integration).

1.4.2 Research affordance of virtual reality: Assessing the effects of motivational support on students' learning outcomes.

On the basis of CTML and the integrative approach, this dissertation proposes that integrating motivational support into virtual learning simulations can enhance VR's effectiveness in science education. More concretely, this dissertation draws upon insights from more than three decades of research on TAM and EVT and assumes that increasing students' perceived usefulness constitutes a powerful motivational support that can lead to effective processing of the learning content in VR (*selection, organization, and integration*). Although self-reported evaluations and knowledge tests are effective tools to evaluate the effects of such interventions on VR's effectiveness, eye-tracking methods can provide additional information to better evaluate students' attentional behavior and cognitive processing of the learning content. Interestingly, new VR headsets with integrated eye tracking not only allow educators to present the learning content in an immersive and interactive manner but also offer researchers an excellent opportunity to evaluate intervention strategies to increase VR's effectiveness.

Eye tracking as a research method in the education sciences and psychology is based on the assumption that eye movements are related to different cognitive processes, and particularly with mental effort (Chen et al., 2011; König et al., 2016; Nikolaev et al., 2014; Rayner, 2009; Rayner & Kliegl, 2012; Zagermann et al., 2016, 2018). More importantly, the eye-tracking method is a reliable and objective method of tracking students' attentional behavior during learning with multimedia and assessing their cognitive processing of the learning content (Chen et al., 2011; Jacob & Karn, 2003; Mikhailenko et al., 2022; Scheiter & Eitel, 2017). Therefore, eye-tracking methods can effectively support research on the effectiveness of motivational and instructional approaches such as the one proposed in this study (Scheiter & Eitel, 2017; van Gog & Scheiter, 2010). According to Mayer (2010), using eye tracking can help researchers answer three specific questions: Which instructional method works, when does it work, and how does it work?

Numerous studies have already used VR headsets with integrated eye tracking to examine students' attention, cognitive processing, and learning performance in the virtual learning environment (Clay et al., 2019; Mikhailenko et al., 2022; Rappa et al., 2019). The combination of VR and eye tracking is an innovative way to test the assumption that integrating motivational support into the virtual simulation can enhance VR's effectiveness. Assuming that the proposed usefulness intervention can trigger information-seeking behavior (Savolainen, 2012), help students prioritize the processing of task-relevant visual information (Ford et al., 2010; Van der Heijden, 1992), and consequently avoid distractions that can increase their cognitive load, this dissertation aims to unobtrusively capture students' eye movements (e.g., fixations, saccades, blinks) and average pupil diameter. These eye movements and other eye-related features have been linked to various cognitive processes and mental effort during learning activities (Chen et al., 2011; König et al., 2016; Rayner, 2009; Rayner & Kliegl, 2012; Zagermann et al., 2016, 2018).

2

AIMS AND RESEARCH QUESTIONS

2 Aims And Research Questions

Despite its affordances, hedonic and motivational aspects, and high potential for teaching and learning science, immersive virtual reality has not yet been established as an effective learning tool. In this regard, the current literature shows rather mixed results but also provides some support for the added-value approach, consisting of adding educational prompts to VR to increase its effectiveness. In addition, the integrative approach posits that the integration of motivational support into multimedia can facilitate adequate cognitive processing, thus enhancing learning. Therefore, the present dissertation investigates whether VR's effectiveness in science education can be enhanced by integrating classical motivational support (i.e., usefulness interventions) into immersive learning. Based on this theoretical perspective of CTML and the integrative approach, I propose that motivation constitutes a fundamental affective factor that can enhance students' attitudes with regard to learning in VR, focus their attention during learning, and foster generative processing of the learning content. These positive effects of motivation can help students engage in effective cognitive processing and in fewer hedonic activities, which can affect their learning experience in VR (e.g., perceived presence) and enhance their learning performance (see Figure 1). To test these assumptions, I rely on previous research on TAM and EVT that also highlight the role of motivation in learning in multimedia and traditional classrooms, respectively. In particular, empirical EVT-based research provides clear and tested methods to operationalize motivation and conduct motivational interventions. Based on the potential benefits of integrating motivational support into the learning instructions in VR, I formulate three main research objectives:

The first objective is to test whether traditional classroom interventions based on EVT that have been shown to improve students' achievement-related behavior and learning performance in different subjects (e.g., mathematics, physics, and reading) could also enhance VR's effectiveness in science education. Accordingly, this dissertation aims to answer the following questions:

1) How does the integration of a learning-usefulness intervention or a daily-life usefulness intervention into a virtual learning simulation (before presenting the learning content) affect students' presence, interest in the virtual lesson, and learning achievement?

2) How is students' experienced presence in the virtual learning environment related to their interest in the virtual lesson and their learning achievement?

The second objective is to investigate how the usefulness interventions affect students' acceptance of VR as a learning tool and to test whether acceptance subsequently enhances students' learning experience and their learning outcomes in VR. Concretely, this dissertation also addresses the following questions:

3) Do priming interventions involving students' perception of VR increase their acceptance of VR as a learning tool?

4) Does students' acceptance subsequently facilitate students' learning experience in the virtual learning environment and enhance their learning outcomes?

The third objective is to assess how integrating motivational interventions into immersive learning affects students' visual attention and cognitive processing of the lesson content in the virtual learning environment. Accordingly, this dissertation also addresses these questions:

5) How do classical usefulness interventions affect students' visual attention and processing of the lesson content (assessed through eye movements)?

6) How are students' eye movements related to their learning achievement?

To address the main research questions of this dissertation, I applied an experimental approach in the following three studies and used multimodal methods (e.g., self-report paper-pencil tests, integrated questionnaires in VR, knowledge tests, and eye-tracking analysis).

Study 1 (Enhancing the Effectiveness of Virtual Reality in Science Education Through an Experimental Intervention Involving Students' Perceived Usefulness of Virtual Reality) examined whether a classical motivation intervention based on the EVT could also enhance the effectiveness of VR in science education. To do so, we manipulated students' perceived usefulness of VR by using video priming before presenting a virtual biology lesson. The priming interventions were two short videos: in one condition, the specific priming video informs students about the usefulness of VR for learning, and in the other condition, the general priming video informs students about the usefulness of VR in daily life. Both priming videos were integrated into the virtual simulation (The Body VR, 2016) as part of the instructions. We then compared the three conditions (a learning-usefulness condition, a daily-life-usefulness condition, and a control condition—no priming intervention) to assess the effect of the interventions on students' presence, interest in the virtual lesson, and learning achievement. Additionally, we tested the relationships between presence and learning outcomes.

Study 2 (Effective Learning in Immersive Virtual Reality: An Experimental Perspective on the Technology Acceptance Model) is the first to apply an experimental approach to the TAM to enhance immersive VR's effectiveness in science education. Accordingly, we investigated whether students' acceptance of VR as a learning tool could be increased through a priming intervention on students' perceived usefulness of VR before presenting a virtual lesson on biology. Contrary to most previous research on TAM that neglects to assess the effect of acceptance on students' learning outcomes, this study used path analysis to assess how acceptance affects students' learning outcomes (perceived learning and actual learning performance) directly and indirectly. Namely, we tested whether students' acceptance of VR directly affected students' perceived and actual learning; we also tested whether acceptance influenced their learning experience in the virtual learning environment (i.e., presence) and whether presence subsequently affected students' learning outcomes.

Study 3 (The Impact of a Usefulness Intervention on Students' Learning Achievement in a Virtual Biology Lesson: An Eye-Tracking-Based Approach) analyzed how interventions involving students' perceived usefulness of immersive VR led to better cognitive processing of a virtual biology lesson. Based on data from the VR headsets with integrated eye tracking that were used to monitor students' eye movements during a virtual lesson, this study examined how such a motivational intervention affects students' virtual attention and processing of the lesson content. More concretely, we tested how the intervention affected students' eye movements (fixations, saccades, pupil diameter, and blinking behavior) during a virtual biology lesson and their learning achievement. We also assessed the relationship between these eye movements and students' learning achievement.

3

STUDY 1

Ferdinand, J., Soller, S., Hahn, J.-U., Parong, J., & Göllner, R. (2023). Enhancing the Effectiveness of Virtual Reality in Science Education Through an Experimental Intervention Involving Students' Perceived Usefulness of Virtual Reality. *Technology, Mind, and Behavior*. https://doi.org/10.1037/tmb0000084

Abstract

This study examined whether the effectiveness of virtual reality (VR) in science education could be enhanced by providing students with relevant information about VR's usefulness before a virtual lesson. On the basis of expectancy–value theory, we manipulated students' perceived usefulness of VR by using video priming before presenting a virtual biology lesson. We then assessed how the intervention affected students' presence, interest in the virtual lesson, and learning achievement. Additionally, we tested the relationships between presence and learning outcomes. A sample of 196 students in Grade 10 was randomly assigned to a learning-usefulness condition, a daily-life-usefulness condition, or a control condition (no priming intervention) in VR. The results showed that students in both experimental conditions perceived VR as significantly more useful for learning and had greater learning achievement than those in the control condition. In addition, students in the daily-life-usefulness condition experienced less presence than those in the control condition, but there was no difference between the learning-usefulness condition and the control condition in this regard. However, the intervention had no effect on students' interest in the virtual biology lesson. Moreover, students in the two experimental conditions did not differ from each other on any of the outcomes we considered. Furthermore, the results revealed that students' presence was positively associated with their interest in the virtual lesson but was not related to their learning achievement when the intervention's effects were controlled for. These findings suggest that students' awareness of VR's usefulness could be a factor in VR's effectiveness.

Enhancing the Effectiveness of Virtual Reality in Science Education Through an Experimental Intervention Involving Students' Perceived Usefulness of Virtual Reality

In recent years, the use of immersive virtual reality (VR) has become increasingly prevalent in education. Researchers have long predicted that VR technology would revolutionize education in science, technology, engineering, and mathematics domains in particular (Blascovich & Bailenson, 2005; Fernandez, 2017; Honey & Hilton, 2011; Salzman et al., 1997; Salzman et al., 1999). In fact, VR provides a unique way for educators to teach and for students to engage with learning materials (Dede et al., 2017; Georgiou et al., 2007; Karutz & Bailenson, 2015; Won et al., 2019). Moreover, different affordances and characteristics of VR can facilitate learning in a way that is not possible in traditional classrooms (Dede et al., 2017; Karutz & Bailenson, 2015; Winn, 1993; Won et al., 2019). For example, VR can mirror natural environments very precisely at both a microlevel and a macrolevel. Furthermore, VR can create unusual or unnatural learning environments that motivate students and enhance their learning experience (Lau & Lee, 2015; Allcoat & von Mühlenen, 2018).

However, empirical research on VR's effectiveness in learning and teaching has shown rather mixed results (Makransky et al., 2019; Parong & Mayer, 2018). Two recent meta-analyses (Wu et al., 2020; Luo et al., 2021) showed that VR is slightly more effective than other non immersive learning methods, but they also reported that a considerable number of the considered studies found no effect or a negative effect of VR on students' learning achievement. Different factors are assumed to negatively affect VR's effectiveness: potential distractions due to the seductive aspects of VR and its highly interactive nature (Makransky et al., 2020), increased cognitive load while learning with VR (Moreno & Mayer, 2000; Parong & Mayer, 2018; Makransky et al., 2019; Meyer et al., 2019), and a lack of pedagogical support in the currently available virtual learning simulations (Fowler, 2015). Moreover, learners might also associate VR much more with entertainment and gaming than with learning (Baxter & Hainey, 2019), which can be seen as another reason why the effectiveness of VR for learning is lower than one might expect. In this study, we investigated whether VR's effectiveness in science education could be enhanced by integrating priming information into a virtual simulation to highlight VR's usefulness for learning or daily life before presenting a virtual lesson.

VR's Effectiveness in Science Education

Different pedagogical strategies have been developed to increase VR's effectiveness in science education. Accordingly, a few studies have recently shown that VR's effectiveness can be increased when used in conjunction with various scaffolding strategies (e.g., pretraining, summary prompts, and enactment). For instance, Meyer et al. (2019) showed that students who received pretraining before a biology lesson with a virtual simulation (The Body VR, 2016) performed significantly better on subsequent knowledge and transfer tests than those who learned with VR without pretraining or those who learned from watching videos with or without pretraining.

Similarly, Parong and Mayer (2018) also showed that adding summary prompts can enhance VR's effectiveness. In this study, students had to pause the virtual biology lesson after each section to write a summary of the previous section. The results showed that students who implemented such a strategy performed as well as those who learned with PowerPoint. Another recent study showed that using enactment after a virtual lesson led to better procedural knowledge and transfer (Makransky et al., 2020). Procedural knowledge refers to knowledge about how to do something (Anderson et al. 2001), and transfer of learning occurs when knowledge that is gained in one context is applied in another (Makranksy & Petersen, 2021). Enactment is an activity-based instructional method. Students are physically engaged with concrete objects related to the lesson as a follow-up activity to better understand the learning procedures presented previously in virtual learning environments (Fiorella & Mayer, 2016; Makransky et al., 2020).

These research findings indicate that VR's effectiveness can be increased by using additional instructional support that can be implemented during different phases of the learning process: either before, during, or after the lesson. However, the following specificities should be considered. First, these instructional supports are very useful for effective learning with VR, but each one has their own mechanism. For example, pretraining helps students familiarize themselves with similar content before the actual learning takes place. Summary prompts foster active cognitive processing during the lesson, and enactment enables students to better integrate the lesson they learned. Second, some of the scaffolding strategies are specifically shaped to apply to the content of the virtual lesson (pretraining and enactment). On the other hand, educators might be interested in practical strategies that are more independent from specific lessons but can simultaneously be integrated into the virtual learning simulation as a whole. Third, if the virtual simulation has to be stopped (summary prompts), students' experiences and interactions in the virtual learning environment end up being repeatedly disrupted. Such repeated disruptions could probably affect students' perceived presence (Cummings & Bailenson, 2016; Mestre & Fuchs, 2006). This is an issue because disrupting students' immersion in the virtual learning environment may lessen one of VR's primary advantages over other multimedia learning tools.

In contrast to these scaffolding strategies, we investigated whether VR's effectiveness in science education increased when we added a brief instructional element that was not directly related to the lesson and did not stop the flow of the virtual simulation. In concrete terms, we aimed to increase students' perceived usefulness of VR as a learning tool by using a brief video- priming procedure and assessing how it impacted VR's effectiveness during a science lesson.

Perceived Usefulness and Students' Learning Outcomes

In the present study, we argue that increasing students' perceived usefulness of VR might be a very parsimonious pedagogical approach yet an effective way to increase VR's effectiveness. The crucial role that students' perceived usefulness of a school subject plays in, for example, the learning of that subject has been stressed in motivation psychology. According to expectancy-value theory (EVT; Eccles et al., 1983; Eccles & Wigfield, 2002; Wigfield & Eccles, 2001), perceived usefulness is the subjective value attributed to a task or a topic. A large body of research on EVT has shown that the perceived usefulness of a subject leads to more effective learning in traditional school settings and provides essential insights into how to increase students' perceived usefulness of particular school subjects (Durik et al., 2015; Harackiewicz et al., 2014). Furthermore, empirical evidence has suggested that usefulness interventions lead to long-term positive effects on students' persistence, effort, interest, and academic achievement in various school subjects (Anderman et al. 2001; Brisson et al., 2017; Gaspard et al., 2015; Hidi & Harackiewicz, 2000; Hidi & Renninger, 2006).

Interestingly, the pivotal role that students' perceived usefulness of a multimedia learning tool plays in its effectiveness has also been stressed in the Technology Acceptance Model (TAM; Davis, 1989). Students' perceived usefulness is the most consistent predictor of students' acceptance of an educational technology (Ma & Liu, 2004; Yousafzai et al., 2007a, 2007b), and acceptance is a fundamental prerequisite for the effective use of educational technology (Martins & Kellermanns, 2004; Davis, 2011). Given the fundamental role of students' perceived usefulness in traditional classrooms and in learning with educational technology, we tested whether students' perceived usefulness of VR as a learning tool could be increased through video priming. Subsequently, we tested whether the priming intervention would help enhance VR's effectiveness in science education.

The Role of Presence in Learning With VR

In addition to students' perceived usefulness of VR, students' presence in the virtual learning environment may also influence their learning outcomes. Presence can be described as the illusion of being physically present in the virtual environment (Ijsselsteijn & Riva, 2003; Slater, 2018) and seems to play an essential role in VR's effectiveness for educational purposes (Kontogeorgiou et al., 2008; Mikropoulos, 2006; Winn et al., 1999). In learning with VR, presence can be seen as a central source for driving students' motivation and may increase students' willingness to engage with the learning materials (Lok et al., 2006). In this regard, several studies have found positive correlations between presence and different expressions of achievement-related behavior. For instance, recent empirical studies have shown that presence positively affected students' intrinsic motivation and enjoyment of learning (Makransky & Lilleholt, 2018), influenced learners' satisfaction (Bulu, 2012; Vrellis et al., 2016), and was associated with higher perceived learning (Makransky & Lilleholt, 2018).

Apart from students' motivation, however, it is still unclear how presence affects students' learning achievement. On the one hand, the feeling of being in a realistic environment might be a highly engaging experience that fosters students' processing of the subject matter. On the other hand, experiencing a high level of presence in a virtual learning environment may constitute such a novel experience that it distracts learners from focusing on the learning material. Correspondingly, some studies have shown a positive effect of presence on students' learning achievement (Kontogeorgiou et al., 2008; Mikropoulos, 2006; Winn et al., 1999), whereas other studies have shown the opposite effect (Makransky et al., 2020; Schrader & Bastiaens, 2012; Whitelock et al., 2000). Different explanations have been offered for why presence may negatively affect students' learning achievement. First, it has been argued that students' presence in VR could distract them from their learning goals (Makranksy & Lilleholt, 2018), especially because advancements in VR technology facilitate the creation of high-quality immersive simulations (Bailenson et al., 2008). This could particularly be the case for students who are using VR for the first time or who have less experience with VR (Goncalves, 2005). Second, it has been shown that presence can consume too much of a learner's attention, thereby resulting in cognitive overload, which can negatively affect conceptual understanding (Makranskey & Petersen, 2021; Whitelock et al., 2000) and even decrease learning (Schrader

& Bastiaens, 2012).

The Cognitive Affective Model of Immersive Learning (CAMIL; Makransky & Petersen, 2021) considers factual knowledge (i.e., knowledge about discrete, isolated content elements; Anderson et al. 2001), conceptual knowledge, procedural knowledge, and transfer of knowledge. Students' presence may indirectly affect these different types of knowledge in different ways (Makransky & Petersen, 2021). For example, presence can create conditions that foster situational interest (Makransky & Petersen, 2021), which in turn can support behavior that facilitates knowledge acquisition (Hidi & Renninger, 2006; Knogler et al., 2015). Therefore, presence may have an indirect positive effect on all of these different types of knowledge (Makransky & Petersen, 2021). On the other hand, presence can lead to higher cognitive load, which may hinder effective learning (Parong & Mayer, 2018; Makransky et al., 2019; Meyer et al., 2019). This is particularly the case for the acquisition of factual and conceptual knowledge (Makransky et al., 2019a; Makransky & Petersen, 2021). Moreover, Makransky and Petersen (2021) argued that VR's effectiveness for learning factual or procedural knowledge depends on how the virtual lesson is designed. For instance, virtual simulations that include seductive elements that distract students from learning (Moreno & Mayer, 2002; Makransky et al., 2020), may increase cognitive load.

Considering the role of presence in learning with VR, we assumed that providing students with relevant information about VR's usefulness might also affect how students perceive their presence in the virtual learning environment. For instance, a VR usefulness intervention could help students focus more on the relevant aspects of the virtual lesson and increase their willingness to engage with the learning materials (Lok et al., 2006). This could also help reduce the influence of the seductive aspects of VR that are linked to higher presence. Therefore, a usefulness intervention through video priming could lead to less presence in a VR environment.

The Present Study

Inspired by EVT research, in this study, we examined the extent to which a usefulness intervention involving students' perceived usefulness of VR would enhance VR's effectiveness for learning in a virtual biology lesson. To do so, we used the virtual application *The Body VR* (2016), which is about the anatomical and physiological functions of cells in the human body. Then we assessed whether this intervention led to higher perceived usefulness of VR for learning and explored how it affected students' presence. Subsequently, we also tested the relationship between presence and students' interest in the virtual biology lesson and learning achievement.

The present study used an experimental design to address the following questions:

1. To what extent does a brief intervention that uses a video to prime the usefulness of VR for learning or for daily-life before a virtual biology lesson increase the perceived usefulness of VR for learning?

2. To what extent does a brief intervention on the usefulness of VR for learning or for daily- life positively impact students' learning outcomes (interest in the virtual biology lesson and learning achievement)?

3. How does a brief intervention on the usefulness of VR for learning or for daily-life affect students' presence in the virtual learning environment?

4. To what extent is students' experience of presence in VR related to their interest in the virtual biology lesson and their learning achievement?

Method

Participants

One hundred ninety-six 10th-grade students (97 female adolescents; mean age *M* = 15.56, *SD* = 0.68) from 10 different high schools (academic track) in Germany participated in this study voluntarily. Both the participants and their parents or legal guardians were informed about the procedure, benefits, and risks of participating in the study and signed informed consent forms. Moreover, the Ethics Committee of the University of University of Tübingen reviewed and approved this study (Reference Number: 2019_1003_169).

Materials

Description of the Usefulness Intervention Using Video Priming

We used two versions of the priming video intervention to manipulate students' perceived usefulness of VR for learning purposes. Each video was about 3.5 min long and was narrated by a professional speaker. In the first video, we presented several characteristics of VR as a useful tool for learning. We pointed out to participants that a unique feature of VR is that it enables students to immerse themselves in the virtual learning environment on a microlevel (e.g., studying the chemical composition of objects) or a macrolevel (e.g., studying the planets in the galaxy). We also told them they could observe and interact with the lesson materials as if they were actually in the virtual world themselves. In addition, participants were informed that in VR, students can conduct classroom experiments in different science subjects independently without the risk of accidents happening, and they can travel back in time to observe and analyze our ancestors' ways of life. In the second video, however, we presented VR as an instrument that is useful in daily life. We also presented them with the same VR characteristics (e.g., immersion) that enabled the users to immerse themselves in a virtual world to observe and interact with its elements as if they were actually in the virtual world themselves (e.g., observing planets in the galaxy or traveling back in time). However, we focused more on concrete and useful applications in daily life without presenting any examples of explicit learning situations or mentioning learning. For instance, participants were informed about the increasing use of VR in different everyday life domains (e.g., physical therapy, observation of historical events, visiting museums). A translated version of the two scripts used to create the video is provided in Appendix D.

To ensure that the priming materials were well-conceived, we first conducted a pilot study. Accordingly, we tested whether students' perceived usefulness as a learning tool could be increased through the viewing of the priming videos. We also compared the two videos to assess to what extent the priming video on VR's usefulness for learning lead to greater students' perceived usefulness of VR as a learning tool. A convenience sample of 71 first-year university students (15 female students; mean age, $M = 22.10$, $SD = 5.17$) participated voluntarily in the pilot study and watched one of the priming videos (i.e., usefulness of VR for learning purposes or for daily life) or did not watch a video (control group). A one-way between-subjects ANOVA was computed to compare the effect of the priming intervention on the perceived usefulness of VR. The results showed that the intervention had a significant effect on students' perceived usefulness of VR for learning, $F(2, 68) = 9.23$, $p < .001$, $\eta^2 = .21$. Post hoc comparisons using the Tukey honestly significant difference test indicated that students who watched the priming video on the usefulness of VR for learning purposes perceived VR as significantly more useful for learning ($M = 3.21$, $SD = 0.30$) than those in the control group ($M = 2.80$, $SD = 0.38$), $p < .001$. Similar results emerged when students who watched a video on the usefulness of VR for daily life ($M = 3.13$, $SD = 0.36$) were compared with those in the control group ($M = 2.80$, $SD = 0.38$), $p < .01$. There was no difference between the two experimental conditions ($p > .05$). These results showed that the priming materials were well-conceived for the purposes of the study.

The Virtual Biology Lesson

The biology lesson is an interactive VR simulation about the cells in the human bloodstream called *The Body VR: Journey Inside a Cell* (The Body VR, 2016). This lesson presents factual knowledge about how the circulatory system functions. The virtual lesson is around 13 min long and contains narration and immersive animations of the circulatory system and different parts of human cells. The simulation utilizes a specific characteristic of VR to enable learners to *travel* on a microlevel through an artery and into a cell while different parts of the cell and their functions are explained. Learners can also interact with the elements of the cell. For instance, they can move, rotate, or closely examine a blood cell. This simulation is available free of charge for noncommercial use and was previously used by Parong and Mayer (2018) and Meyer et al. (2019). Screenshots of the virtual lesson are provided in Appendix E.

Pretest Questionnaire

The paper-pencil pretest consisted of questions about participants' demographic characteristics (e.g., gender, age, and mother tongue), prior experience with VR, general interest, self-concept, and biology grades from the previous semester. For the prior experience scale, participants rated five statements (e.g., "I use a VR headset regularly") on a 4-point Likert scale ranging from 1 (*strongly disagree*) to 4 (*strongly agree*). Cronbach's alpha as a measure of the internal consistency reliability of the scale for participants' prior experience with VR was .74. The general interest in biology scale (Gaspard et. al., 2015) consisted of five statements that students rated accordingly (e.g., "Biology is one of my favorite subjects"; α = .92). With regard to self-concept in biology (Arens et al., 2011; Arens et al., 2013), participants rated four statements (e.g., "It is easy for me to learn biology"; α = .84).

Postpriming Questionnaire in VR

Directly after the manipulation (video priming) in VR, participants were presented with a scale about their perceptions of the usefulness of VR for learning. After finishing the biology lesson, participants were presented with a scale regarding their perceived presence. They used the VR controller to fill out the survey in the virtual learning environment. The perceived usefulness of VR scale (Davis, 1989) consisted of seven statements that students rated accordingly (e.g., "Using VR can help me better understand various topics in school"; α = .78). In terms of presence (Schubert et al., 2001; Lombard et al., 2009), participants rated five statements about their experience and perception of themselves in the virtual learning environment (e.g., "In the virtual environment, I had the impression that I was actually there"; α = .73). All the scales are provided in Appendix B.

Posttest Questionnaire

The paper-pencil posttest consisted of a scale concerning participants' interest in the virtual biology lesson and a knowledge test (learning achievement). Using a 4-point scale, participants rated four statements about their interest (Bürgermeister et al., 2011) in the virtual biology lesson (e.g., "I would like to learn more about human cells in this way [with VR]"; α = .76). In this study, we used the same 16 multiple-choice questions from the knowledge test (see Appendix C) administered by Parong and Mayer (2018) to assess students' learning achievement (factual knowledge about cells and the functions of the circulatory system). Participants received 1 point for each correct answer, for example, "Which molecule(s) cannot pass through a cell's membrane without the help of a receptor protein?" The choices were: A) Water, B) Oxygen, C) Glucose, D) All of the above.

Apparatus

To present the virtual biology lesson to the students, we used a computer (Omen Laptop: Omen 15-dh0004ng i7/16GB/1TB HDD + 512GB SSD /GeForce® RTX 2060 (Shadow Black)) in conjunction with the Virtual reality set HTC VIVE Pro. This virtual set includes two sensors, a head-mounted display, and two controllers. The sensors were placed in diagonally opposite corners of the classroom to create a virtual space where the students could access and interact with the virtual learning environment. The head-mounted display enabled students to access the lesson using Steam Software installed on the computer. The head-mounted displays had integrated headphones that facilitated each individual' experience and blocked outside noise to improve immersion. Students used one of the controllers to start the simulation, answer questions (i.e., integrated scales in the virtual simulation), and interact with the lesson material.

Procedure

Data were collected in different schools in groups consisting of five to 10 individual students who were supervised by at least two test assistants. Participants were randomly assigned to the learning-usefulness condition (VR as an instrument that is useful for learning), the daily- life-usefulness condition (VR as an instrument that is useful in daily life), or the control group (no intervention). Before the lesson, participants first filled out a questionnaire (pretest). They then used head-mounted displays to watch one of the priming videos on VR's usefulness, or they did not watch either video (control group). Directly after watching the video, while they were still in the virtual learning environment, they used a VR controller to answer questions about their perceptions of the usefulness of VR as an educational tool. We decided to measure students' perceived usefulness of VR right after the manipulation to ensure that the lesson's difficulty or their experience in the virtual learning environment did not affect their judgment in this regard. Next, they participated in a virtual lesson on cells in the human body. After the virtual lesson, participants used the VR controller to report their perceived presence in the virtual learning environment. We assumed that it would be much better to assess students' presence while they were still in VR instead of using a pencil-and-paper test to assess it at the end of the session.

Finally, participants took off the head-mounted displays, filled out a second questionnaire (posttest), and took the final knowledge test. All participants were seated for the entire session. Each session lasted approximatively 50 min, which included: the general instructions and the pretest (10 min); the priming, the virtual lesson, and the assessments in VR (18 to 21.5 min); the posttest and the knowledge test (20 min).

Data Analysis

We first tested students' backgrounds—in terms of prior experience with VR and their biology backgrounds (interest, self-concept, and prior grades)—to make sure that the randomization of the participants into the three conditions was well balanced. The results of this analysis are presented in Table 1. To evaluate the effects of the intervention on the learning outcomes, we conducted a regression analysis with dummy variables using the control group as the baseline. As the data were collected in different schools, we took special care to account for the resulting nested structure of the data (number of clusters $N = 10$) by correcting the standard errors using the TYPE=COMPLEX specification, which was implemented in Mplus. For all direct effects, we report the standardized coefficients, and in Table 3, we report both the unstandardized and the standardized coefficients. All data and the code for the experiment are openly available via the Open Science Framework (Ferdinand et al., 2021).

Results

First, we tested for whether the students in the three conditions differed in terms of their prior experience with VR and their biology backgrounds (general interest, self-concept, and self- reported grades in biology from the previous semester) by comparing the two experimental groups and the control group. The results of the regression analyses revealed no differences between the three conditions in this regard (all ps > .05). Table 1 presents descriptive statistics for all the background and outcomes variables separately for each condition, and Table 3 presents a summary of the regression analyses, the standardized coefficients, and the *p*-values.

Students' Perceived Usefulness of VR as a Learning Tool

We tested for whether the intervention had a significant effect on students' perceived usefulness of VR as a learning tool across the three conditions. The results showed that students in the learning-usefulness condition (M = 3.58, SD = 0.32) perceived VR as significantly more useful for learning than those in the control group (M = 3.35, SD = 0.41); B = 0.35, t = 3.76, p < .001. Similarly, students in the daily-life-usefulness condition (M = 3.56, SD = 0.35) perceived VR as significantly more useful for learning than those in the control group; B = 0.29, t = 3.31, p < .01. There was no difference between students in the learning-usefulness condition and those in the daily-life-usefulness condition (p > .05). The results demonstrated that the two interventions were both capable of increasing students' perceived usefulness of VR.

Effects of Each intervention on Students' Presence, Interest in the Virtual Biology Lesson, and Learning Achievement

Regarding students' experience of presence in the virtual learning environment, the results showed a descriptive difference between the control group (M = 3.56, SD = 0.40) and the learning-usefulness condition (M = 3.39, SD = 0.48), but this difference was not statistically significant (B = -0.21, t = -1.74, p = .082). However, the results showed that students in the control group (M = 3.56, SD = 0.40) reported a significantly higher presence than those in the daily-life-usefulness condition (M = 3.39, SD = 0.51), B = -0.23, t = -2.20, p = .028. There was no difference between students in the two experimental groups (p > .05) in this regard. The statistical analysis also revealed no significant differences between any of the groups with regard to students' interest in the virtual biology lesson: learning-usefulness condition (M = 3.53, SD = 0.47), daily-life-usefulness condition (M = 3.50, SD = 0.53), control group (M = 3.56, SD = 0.50); all *p*s > .05.

When comparing students' learning achievement, however, the results showed a positive effect of the intervention. Students in the learning-usefulness condition performed better on the biology test after the virtual lesson (M = 7.38, SD = 2.70) than those in the control group (M = 6.66, SD = 2.74), B = 0.18, t = 2.83, p < .01. Similarly, there was a significant difference between the students in the daily-life-usefulness condition (M = 7.21, SD = 2.74) and those in the control group (*M* = 6.66 *SD* = 2.74), *B* = 0.12, *t* = 1.98, $p = .048$. There was no difference in learning achievement between the students in the two experimental groups ($p > .05$).

Relationships Between Students' Presence, Interest in the Biology Lesson, and Learning Achievement

We also examined the relationships across the different learning outcomes. The results indicated that students who experienced higher presence in the learning environment also reported greater interest in the virtual biology lesson ($r = .51$, $p < .001$) when the impact of the usefulness intervention was controlled for. Further analysis revealed that students' experience of presence in VR was not related to their learning achievement ($r = -.07$, $p > .05$) when we controlled for the effect of the intervention. Finally, there was no relationship between students' interest in the virtual biology lesson and their learning achievement ($r = .10$, $p > .05$). In sum, we found that level of presence was strongly associated with students' interest in the virtual biology lesson, but presence was not associated with their learning achievement. Table 2 presents the bivariate correlations between all the predictor variables, background variables, and learning outcomes. Additionally, we presented in Appendix A detailed results of correlation analyses between students' background variables and their learning outcomes.

Discussion

In this study, we aimed to determine whether VR's effectiveness could be increased through an intervention on students' perceived usefulness of VR for learning and for daily life. To do so, we conducted a usefulness intervention involving video priming and assessed the intervention's effects on different learning outcomes in a student sample.

The empirical contributions of this study are threefold: First, informing students about the usefulness of VR for learning or for daily life increased students' perceived usefulness of VR as a learning tool and reduced students' presence in the virtual environment when students in the daily-life usefulness group were compared with those in the control group. Second, the brief intervention on VR's usefulness also positively impacted students' learning achievement but did not affect students' interest in the virtual biology lesson. Compared with those who did not receive either kind of priming information, students in both VR usefulness conditions performed significantly better on the biology test. Finally, our results showed that students' presence in the virtual environment was positively associated with their interest in the virtual biology lesson but was not related to their learning achievement.

Usefulness Intervention in VR and Students' Learning Outcomes

Contrary to previous scaffolding strategies (Parong & Mayer, 2018; Meyer et al., 2019; Makransky et al., 2020) used to enhance VR's effectiveness, our approach was more general, parsimonious, and practical; thus, it can be integrated into any virtual learning simulation as a whole. More importantly, the empirical evidence from this study shows that this parsimonious approach can be effective for improving VR's effectiveness in science education. In fact, the intervention increased students' perceived usefulness of VR as a learning tool, lowered students' presence in the virtual environment and more importantly, led to better learning achievement.

In line with previous EVT research in traditional school settings (Anderman et al. 2001; Gaspard et al., 2015, Brisson et al., 2017), we showed that students' perceived usefulness of VR for learning is a contributing factor for students' effective learning in VR. Providing students with very brief information about the usefulness of VR for learning or daily-life resulted in greater learning achievement. As such, our findings also help extend common concepts from EVT regarding students' learning motivation (Brisson et al. 2017; Eccles et al., 1983; Gaspard et al., 2015; Wigfield et al., 2016) to science education in VR.

Relationships Between Students' Experience of Presence in VR and Their Learning Outcomes

Some studies have shown that presence is an important contributing factor to students' motivation and learning in VR (Kontogeorgiou et al., 2008; Mikropoulos, 2006; Mikropoulos & Natsis, 2011; Winn & Windschitl, 2000), whereas other empirical studies have not confirmed the effect of presence on students' learning achievement (Makranksy et al., 2019; Parong & Mayer, 2018; Vrellis et al., 2016). We showed that the relevance of presence for learning in VR may depend on the outcome measure that is being considered. Whereas presence showed a positive association with students' interest in the virtual biology lesson, there was no association between presence and students' learning achievement. A virtual simulation, such as the one we used here, can provide a learning environment that learners find fascinating as it includes realistic graphics and a perception of space that can induce a feeling of immersion. Thereby, experiencing this immersive and exciting environment might increase students' interest in learning with VR (Makransky & Petersen, 2021), even though students' interest was not found to be related to their actual learning.

Makransky and Petersen (2021) proposed that high presence could facilitate interest, intrinsic motivation, self-efficacy, and embodiment, which in turn could enhance VR's effectiveness. However, the authors also stressed the possible negative effect of high presence on cognitive load and self-regulation in VR. In this vein, the current findings provide a potential way to control for students' presence in a virtual learning environment to some extent. Specifically, our results showed that stressing the usefulness of VR can suppress students' presence in the virtual environment, which might have helped them to be more engaged with the contents of the lesson and less involved in the experience of being in the virtual environment.

Furthermore, our findings suggest that higher presence does not depend exclusively on students' immersion in VR due to the technical features, but it can also result from students' individual perceptions (Slater, 2004) or a lack of focus during the virtual learning session. In this study, students with similar backgrounds (e.g., similar levels of experience with VR) experienced the same simulation in this study, yet they reported different levels of presence after they had been primed to perceive VR as useful for learning or for daily life. It seems that students in the different conditions experienced the virtual learning environment differently (Slater, 2004) due to the priming information. In sum, controlling students' level of presence in VR by implementing a usefulness intervention did not undermine students' interest in learning with VR or their learning achievement. On the contrary, the intervention had no impact on students' interest. Moreover, students who received such an intervention experienced less presence but performed significantly better on the knowledge test than those who did not.

The empirical evidence from this study suggests that students' presence in the virtual learning environment was not associated with their learning achievement when the effect of the intervention was controlled for. However, in this study, we considered only factual knowledge. Therefore, this study's findings do not necessarily demonstrate that students' experience of presence in VR is not related to students' learning. The type of knowledge (e.g., factual, conceptual, and procedural knowledge) presented in VR may moderate the relationship between presence and learning outcomes (Makransky & Petersen, 2021). For instance, if the virtual simulation presents conceptual or procedural material rather than factual knowledge, presence may have a stronger relationship with conceptual or procedural learning outcomes. Some initial evidence points to differences in the associations between presence and learning depending on the type of knowledge that is presented as well as the specific content of the lesson. For example, increased presence during a factual VR lesson was associated with lower learning outcomes for factual knowledge (Makransky et al., 2019), but there were no differences in learning for conceptual knowledge (Parong & Mayer, 2018). On the other hand, increased presence in procedural lessons in VR is often associated with increased learning of procedural material (Radianti et al., 2020). Future research may want to focus on the exact mechanisms and interactions of knowledge learned and tested in VR that facilitates learning.

Future Directions and Limitations

Although this study contributes to the current literature on how to enhance VR's effectiveness for learning and teaching science, it has three major limitations that should be addressed in future research.

First, the interactivity of the actual virtual simulation used in this study (The Body VR, 2016) is limited to a few functions (e.g., rotation of various cell elements, production of proteins…). Whereas interactive multimedia learning tools, such as VR, can facilitate deep learning by engaging learners in the lesson and activating their interest (Evans & Gibbons, 2007), interactivity in multimedia tools is also a very complex process, and its effects on learning are not straightforward. Interactivity in multimedia involves the learning tool's affordances, the learners' characteristics (e.g., prior knowledge, self-regulation), and behavioral, cognitive, and affective activities (Domagk et al., 2010). Moreover, interactivity can also impose a higher cognitive load (Paas et al., 2003) and can have a negative effect on learning achievement (Moreno & Valdez, 2005; Song et al., 2014). Therefore, VR simulations that allow learners to be more interactively engaged might result in different findings. Given these issues, we would be very interested in doing a similar study with other virtual applications that offer students more opportunities to interact with the lesson materials.

Second, our usefulness intervention reduced students' level of presence in the virtual learning environment. Considering that higher presence was related to greater interest in the virtual biology lesson but had no association with students' learning achievement, it seems that a higher level of presence fosters motivational and affective aspects of learning (e.g. situational interest). However, higher level of presence is not necessarily beneficial for effective learning, especially when factual learning is considered. Future research could try to answer the questions raised in this paper about the relationship between an increased level of presence and learning achievement. In this study, presence is also defined as the illusion of *being there*. However, different conceptualizations of presence (Schubert et al., 2001; Witmer & Singer, 1994) in which presence is defined from a more autonomous and agentic perspective could have different results. For this reason, future research is needed to test whether the effects of presence presented in this study can also be found with other presence measures that operationalize presence in different ways.

Third, students in the two experimental conditions spent about 3.5 min longer in the virtual learning environment than those in the control condition. In evaluating this limitation, it is important to ask whether the extra time spent could have served as a buffer that helped reduce a potential novelty effect and might subsequently have affected students' learning achievement. It should also be considered possible that this period might have negatively affected students' experience of presence in VR. However, despite the plausibility of these alternative explanations, they were not supported by the data in this study.

A novelty effect can result from information or experience (e.g., innovative content or a new multimedia learning tool; Huang, 2003; Huang, 2020). It has been argued that the novelty effect may lead to an increase in effort, which in turn may lead to learning gains (Clark 1983; Clark & Craig, 1992). However, such novelty effects tend to disappear over time as students get used to the medium (Clark 1983; Clark & Craig, 1992), and as a result, learning achievement would be reduced. Nevertheless, a recent longitudinal study concluded that the novelty effect might not steeply decrease when individuals become familiar with the use of VR and that it does not necessarily increase learning (Huang, 2020). Accordingly, the time students spent in the VR environment due to a possible reduced novelty effect cannot explain the current findings.

With regard to presence, the results of this study show that there was no difference between the learning-usefulness condition and the control condition, suggesting that students' experience of presence is not due to the extra 3 min they spent in VR. Until now, there has not been enough empirical evidence to definitively determine whether or not students' presence would diminish with the time spent in the virtual learning environment. In this regard, Stanney et al. (1998) argued that time spent in VR will lead to a higher level of presence due to increased familiarity and sensory adaptation to the virtual environment, but it can also lead to lower presence if adverse effects (e.g., motion sickness) intensify over time. However, a previous study on presence in video games showed that short-term time differences had no effect on presence (Lachlan & Krcmar, 2011). Accordingly, it would be interesting to replicate this study by ensuring that students in all three conditions spend the exact same amount of time in VR.

Conclusion

The current findings reveal that students' awareness of the usefulness of VR for learning purposes can be successfully increased by presenting a brief video that informs students of the usefulness of VR before a virtual lesson. Most importantly, the results suggest that such priming intervention also impacts students' presence in the virtual environment and learning achievement. Students' lack of awareness about the usefulness of VR seems detrimental for VR’s effectiveness as it had a negative effect on students’ learning achievement. These results suggest that a usefulness intervention could help control presence without reducing interest in learning with VR and at the same time foster learning. Considering the positive effect of this parsimonious approach to students' learning achievement, it is recommended that students be pedagogically prepared and fully aware of VR's usefulness before using VR for learning and teaching.

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Table 1

Descriptive Statistics [M ±SD or n (%)] for Demographic Variables, Background Variables, and Learning Outcomes in the Three Groups, Randomized to the Learning-Usefulness, Daily- Life-Usefulness, and Control Conditions

Variables	**Learning usefulness**	**Daily-life usefulness**	**Control**
Sample size	*n* = 81	*n* = 57	*n* = 58
Demographics			
Age	15.5 (0.63)	15.5 (0.68)	15.7 (0.73
Gender			
Female	38 (46.9%)	34 (59.6%)	25 (43.1%)
Male	43 (53.1%)	23 (40.4%)	33 (56.9%)
Mother tongue			
German	76 (93.8%)	50 (87.7%)	53 (91.4%)
Other	5 (6.2%)	7 (12.3%)	5 (8.6%)
Biology-related variables			
Grades	2.22 (0.74)	2.33 (0.86)	2.35 (0.95)
Interest	2.80 (0.74)	3.07 (0.61)	2.89(0.71)
Self-concept	3.02 (0.55)	3.05 (0.53)	3.00 (0.63)
VR-related variable			
Prior experience	2.10 (0.54)	2.20 (0.49)	2.13(0.52)
Students learning outcomes			
Perceived usefulness of VR	3.58(0.32)	3.56 (0.35)	3.35 (0.41)
Presence	3.39 (0.48)	3.39 (0.51)	3.56 (0.40)
Interest in the virtual lesson	3.53 (0.47)	3.50 (0.53)	3.56 (0.50)
Learning achievement	7.38 (2.70)	7.21 (2.74)	6.66 (2.74)

Note. Grades refer to self-reported biology grades from the semester prior to this study.

Table 2

Correlation Matrix for All Background Variables and Outcome Variables (N = 196)

Variables	1	2	3	4	5	6	7	8	9	10
1. Perceived usefulness										
2. Presence	.16									
3. Learning achievement	.03	-.09*								
4. Interest in the virtual biology lesson	.27***	.46***	.06							
5. Grade in biology[a]	-.09	-.13**	.38***	-.00						
6. Prior experience with VR	.21*	-.07**	-.09	.08	-.10					
7. General interest in biology	.15	.15***	.11	.38***	.31***	.11				
8. Self-concept in biology	.08	-.00	.23***	.21*	.57***	.15*	.68***			
9. Age	-.04	.01	-.19	.00	-.18***	.20	-.04	-.02		
10. Gender	.06	-.08	.04	-.12	-.12	.31***	-21*	-.03	.13***	
11. Mother tongue	-.02	.01	-.13	.04	-.01	-.01	-.03	-.05	.07	n.s.[b]

Note. Pearson correlations were computed for all correlations between continuous variables, and point-biserial correlations were computed for the correlations between continuous and categorical variables.

[a]Grades refer to students’ self-reported biology grades from the first half of the school year (2019 - 2020). Moreover, in German schools, grades range from 1 (*excellent*) to 6 (*unsatisfactory*); therefore we reverse-coded the grades so that a positive correlation means that a variable was positively associated with students' biology grade. [b] *n.s. = nonsignificant. To assess the relationship between gender and mother tongue (two categorical variables), a* Chi-Square analysis was computed. There was no significant relationship between the two variables, $X^2(1, N = 196) = .65, p = .421$.

* $p < .05$. ** $p < .01$. *** $p < .001$.

Table 3

Summary of Regression Analyses for All the Predictors, Background Variables Related to Biology, and Prior Experience With VR and Outcome Variables (N = 196)

	Learning-usefulness vs. control				Daily-life-usefulness vs. control			
	Direct effects							
Variables	**B**	***SE***	**β**	***p***	**B**	***SE***	**β**	***p***
Prior experience with VR	-0.02	0.07	-0.02	.807	0.05	0.08	0.06	.544
Grades	0.13	0.18	0.08	.461	0.01	0.18	0.01	.892
Interest	-0.10	0.11	-0.06	.367	0.21	0.13	0.13	.063
Self-concept	-0.02	0.06	-0.02	.773	0.02	0.08	0.02	.767
Perceived usefulness of VR	0.31	0.06	0.35	**<.001**	0.28	0.09	0.29	**.001**
Presence	-0.19	0.11	-0.21	.078	-0.23	0.11	-0.23	**.038**
Interest in the VR lesson	-0.01	0.05	-0.02	.804	-0.05	0.06	-0.06	.447
Learning achievement	0.24	0.10	0.18	**.014**	0.18	0.10	0.12	.053

Note. Values in bold indicate statistically significant results

Appendix A

Relationships Between Students' Background Variables and Their Presence in VR, Interest in the Biology Lesson, and Learning Achievement

We also tested the relationship between the background variables related to prior experience with VR and biology and students' presence, interest in the virtual lesson, and learning achievement. The results revealed that students' prior experience with VR was positively related to their perceived usefulness of VR ($r = .21$, $p = .047$). Students who had more experience with VR also perceived VR as more useful for learning than those who had less experience with VR. By contrast, greater experience with VR was associated with less presence in the VR environment ($r = -.07$, $p = .010$). In other words, students with greater experience with VR reported less presence in the learning environment. However, students' prior VR experience was not related to their interest in the virtual biology lesson or their learning achievement (all *p*s > .05).

Students' general interest in biology was positively associated with students' presence in the virtual learning environment ($r = .15$, $p < .001$) and their interest in the virtual lesson ($r = .38$, $p < .001$), but students' general interest was not related to their learning achievement ($p > .05$). With regard to students' self-concept in biology, the analysis showed that students' self-concept in biology was not associated with their presence in the VR environment ($p > .05$). However, students' self-concept was positively associated with both their interest in the virtual lesson ($r = .21$, $p = .019$) and their learning achievement ($r = .23$, $p < .001$).

The results also showed that students' self-reported grades in biology from the previous semester had a strong positive association with their learning achievement after the virtual lesson ($r = .38$, $p < .001$). Students who had better grades also performed significantly better than those with poorer grades in biology. Furthermore, students who reported better prior grades in biology also experienced less presence in VR ($r = - .13$, $p < .01$). Table 2 presents the bivariate correlations between all the predictor variables, background variables, and learning outcomes.

Appendix B

A Translated Version of the Relevant Scales From German Into English

A- Prior Experience with VR

1. I know exactly what is meant by “virtual reality.”
2. I have already explored the topic of "virtual reality" more deeply.
3. I have often come into contact with the topic of "virtual reality" (e.g., on the internet or on television).
4. I regularly use "virtual reality" myself.
5. I am already very familiar with VR technology.

B- General interest in Biology (adapted from Gaspard et. al., 2015)

1. Biology is one of my favorite subjects.
2. I find it easy to pay attention in biology class because I find the topics exciting.
3. I enjoy learning about topics in biology class.
4. I simply like biology class.
5. I work hard in biology because I enjoy the topics in biology.

C- Self-concept in Biology (adapted from Arens et al., 2011; Arens et al., 2013)

1. I simply have no talent for biology.
2. I do not feel especially strong in biology.
3. I am good in biology.
4. I find it easy to learn biology.

D- Perceived usefulness of VR for learning (adapted from Davis, 1989)

1. VR technology is useful for learning.
2. Using VR can help me better understand various topics in school.
3. Even difficult subjects can be learned well with VR technology.
4. VR technology helps me imagine complex things more easily.
5. VR technology can make learning much more exciting.
6. Students can learn significantly better with VR technology.
7. The use of VR technology would also certainly enrich learning in schools.

E- Presence (Adapted from Schubert et al., 2001 and Lombard et al., 2009)

1. In the virtual environment, I had the impression that I was actually there.
2. When I was in the virtual learning environment, I almost forgot about the environment outside of VR.
3. I felt like I was directly in the bloodstream.
4. I could observe the different elements of the somatic cells really well.
5. The somatic cells in the virtual learning environment really looked real.

F- Interest in the virtual biology lesson (adapted from Bürgermeister et. al., 2011)

1. I found the virtual lesson exciting.
2. I liked the topic of the virtual lesson.
3. I enjoyed this virtual lesson on the topic of somatic cells.
4. I would like to learn more about human cells in this way [with VR].

Appendix C: Knowledge Test on the Virtual Biology Lesson

1. Which molecule(s) cannot pass through a cell's membrane without the help of a receptor protein?
    a. Water
    b. Oxygen
    c. Glucose
    d. All of the above

2. List the order of filaments in the cytoskeleton from narrowest to widest.
    a. Microfilament, intermediate filament, microtubule
    b. Intermediate filament, microtubule, microfilament
    c. Microtubule, intermediate filament, microfilament
    d. Microfilament, microtubule, intermediate filament

3. Which type of cells in the bloodstream are more commonly known as platelets?
    a. Leukocytes
    b. Monocytes
    c. Erythrocytes
    d. Thrombocytes

4. In what process are ribosomes involved?
    a. Adenosine triphosphate (ATP) production
    b. Protein synthesis
    c. Protein transportation
    d. Both B and C

5. Up to how many steps can kinesin motor protein take in a second?
    a. 50
    b. 100
    c. 150
    d. 200

6. Along which filament of the cytoskeleton does the kinesin motor protein move?
    a. Microfilament
    b. Intermediate filament
    c. Microtubule
    d. All of the above

7. What is the function of red blood cells?
    a. Defending against pathogens
    b. Oxygen transport
    c. Protein synthesis
    d. b and c

8. In what structure do proteins get transported?
    a. Vesicle
    b. Rough endoplasmic reticulum
    c. Kinesin motor protein
    d. Ribosome

9. Which type of blood cell can turn into a macrophage?
    a. Erythrocyte
    b. Monocyte
    c. Thrombocyte
    d. None of the above

10. What is produced as a by-product during ATP production in the mitochondria?
    a. Actin and kinesin
    b. Formic acid and water
    c. Adenosine diphosphate (ADP) and carbon dioxide
    d. Water and carbon dioxide

11. Where are mitochondria located?
    a. Free floating in the cytoplasm
    b. On the rough endoplasmic reticulum
    c. In the nucleus
    d. Attached to vesicles

12. Which type of blood cell takes up almost of half of the blood's volume?
    a. Leukocytes
    b. Monocytes
    c. Erythrocytes
    d. Thrombocytes

13. What is the main source of energy in the cell?
    a. DNA
    b. ADP
    c. ATP
    d. Both B and C

14. What transports larger structures within the cell?
    a. Ribosomes
    b. Vesicles
    c. Kinesin motor protein
    d. Cytoplasm

15. Which of the following elements determines the structure of proteins?
    a. Ribosomes
    b. The endoplasmic reticulum
    c. DNA
    d. The cytoskeleton

16. Which structure allows entry and exit of larger molecules into the nucleus?
    a. Cytoskeleton
    b. Protein filaments
    c. Sodium potassium pump
    d. Ribosomes

Appendix D: Scripts of the Videos

Version 1: VR as an Effective Tool for Learning

Thank you very much for your participation in this short teaching unit. Before we start with the content, we would like to first show you, in this short video, some features of virtual reality (VR) and its great potential for learning.

VR is increasingly being used to teach educational material and lessons in an interesting and exciting way. In VR, students in chemistry or physics can see things that you would not be able to see in your typical classroom. For example, students can visit a damaged nuclear reactor such as in Fukushima or Chernobyl as part of a lesson on radioactivity and analyse chemical residues and measure radioactivity there.

Furthermore, in VR, students can experience things for themselves that are completely beyond our ability to physically observe. For example, they can enter distant planets and explore their composition in space directly, as if the students were right in the middle of the action. In history lessons, students can take trips back in time to explore and learn how extinct animals, such as dinosaurs or certain underwater animals, lived. Or they can visit a market in the 13th century to learn how our ancestors organised their lives at that time.

In particular, VR is increasingly used to learn new and complex topics. Here again, there are three reasons why learning with virtual reality can bring many benefits:

1. VR can present difficult and complex concepts in a simple and playful way.
A virtual simulation allows students to better understand how complex things work. For example, virtual realities can also be used to better understand the topic of "linear functions" in mathematics by allowing students to sketch graphs and view them in a three-dimensional environment.

2. **Learning with VR is much more motivating and interesting.**

Learning with VR contributes to making students more motivated and more interested in learning. The student is in the middle of the action and experiences the learning material much more vividly. In the virtual classroom, for example, the student will not only consult books on global warming, but will be able to observe the consequences for animals or Antarctic glaciers first hand.

3. **Students play a more active role.**

Instead of just sitting in class and listening, students can look at things closely in VR and compare and combine them with one another. It is even possible that they may even try things out for themselves that would be impossible or difficult to carry out in reality. For example, during chemistry class, students with VR can look at the composition of different chemical elements in detail, or can try to execute chemical reactions explained in the schoolbook themselves.
VR offers the opportunity to learn many new concepts and lessons in an exciting way. Students can try out and discover a wide range of things in virtual lessons or even carry out experiments themselves.

Version 2: General Information on VR and a few of its Uses in Daily-life

Thank you very much for your participation in this short teaching unit. Before we start with the content, we would like to first show you, in this short video, some characteristics and the great potential of virtual reality (VR) and its various applications in many areas.

With the help of these VR headsets, you can immerse yourself in an artificial world that can be very similar to our real world. Maybe you have already had some experience with this technology yourself. VR is now widely used to experience different things in a realistic way or even to help people. For example, VR was already used in 2005 to help people relearn body movements and to prevent possible physical impairments.

In addition, VR technology allows visitors to experience the past first-hand. For example, you can visit a market in the 13rth century to see how our ancestors organised their lives or watch different animals that have already gone extinct. It is also possible to experience things that are completely beyond our ability to physically observe. VR users can experience space up close or enter different planets of the solar system. You can also observe the underwater world and the animals that live there as if you were right in the middle of the action.

VR is used in everyday life and in different areas. Here are three characteristics of VR that show how diverse this technology is:

1 VR is used as an aid in everyday life.

VR users can participate in various events remotely, as if they were at the event in person, with the help of a virtual simulation. For example, when children are in hospital, there are already programmes that allow patients to share beautiful moments with their families during their stay in hospital. Some news agencies are now reporting with the help of VR as if they were right there at the actual event.

2. The VR experience looks real.

VR users typically perceive a VR simulation as real. For example, people suffering from acrophobia can be trained in VR to repeatedly enter and jump up and down on a balcony of a skyscraper in a virtual simulation, which allows them to gradually reduce their phobia. One of the largest real estate *internet portals for flat or rental searches also makes use of the feature of VR by allowing VR users to view the various rooms of a flat from home as if they were in that flat themselves.*

3. Users play a more active role.

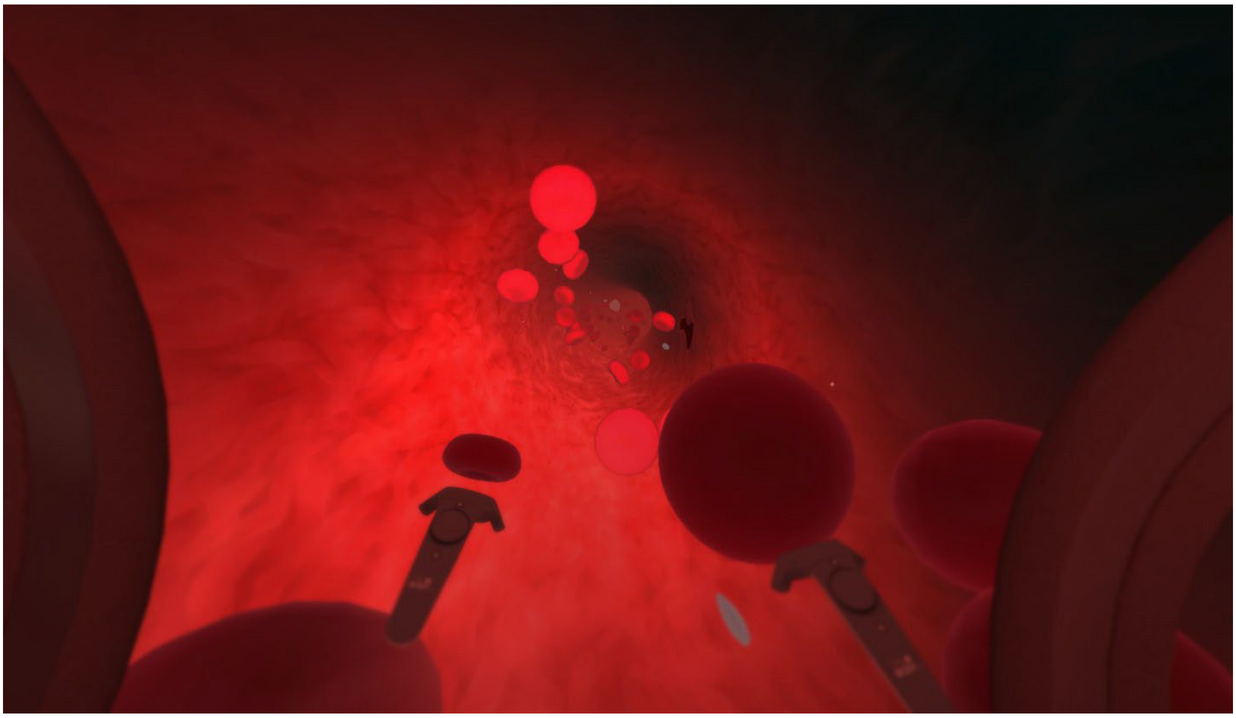
With the increasing use of VR in various areas, users have the opportunity to take a hands-on look at many things. In a virtual museum, users can touch exhibits without damaging them. Or users can "dive" into a painting to get a closer look at the setting in all its details.

VR offers a very wide range of opportunities to try out new things and experiences. VR opens the door to a world that is not always accessible in real life. That is why many users are very convinced and enthusiastic about VR technology.

Appendix E: Screenshots of the Virtual learning Simulations

Figure E1

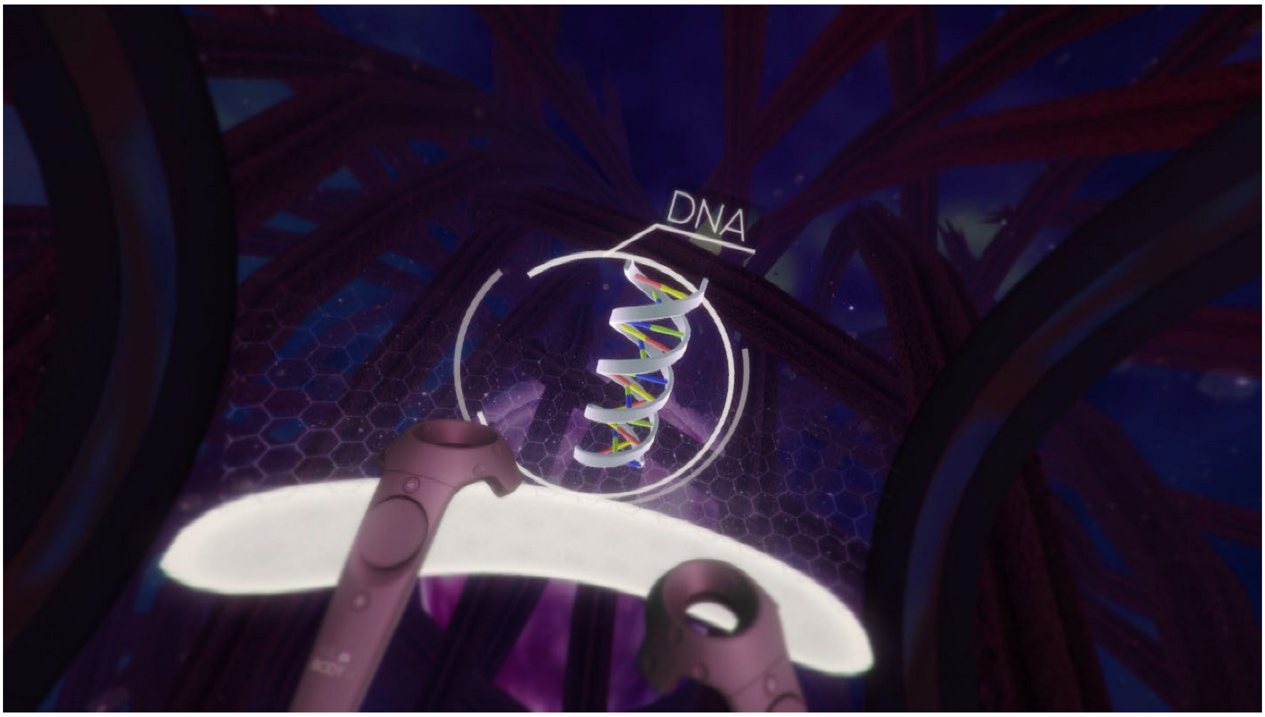
Screenshot of the Virtual Learning Simulation (The Body VR, 2016)



Note. This screenshot shows the students' journey inside an artery, while the function of the red blood cells (represented here by the red spheres) are explained. The image of the two VR controllers represent the real controllers students used to interact with the virtual learning environment. The Steam platform also provides a short video (Steam, 2016a) of this learning sequence on their website. VR = virtual reality

Figure E2

Graphic Representation of the Structure of DNA (The Body VR, 2016)



Note. This screenshot shows that the students are inside of the nucleus, the control center of the cell containing the majority of the cell's deoxyribonucleic acid (DNA) and presents a graphic representation of the structure of DNA (Steam, 2016b; The Body VR; 2016).

4

STUDY 2

Ferdinand, J., Hahn, J.-U & Göllner, R. (2023). *Effective Learning in Immersive Virtual Reality: An Experimental Perspective on the Technology Acceptance Model* [Manuscript submitted for publication]. University of Tübingen.

Abstract

This study is the first to apply an experimental approach to the Technology Acceptance Model (TAM) to enhance immersive virtual reality's (VR) effectiveness in science education. Accordingly, we predicted that students' acceptance of VR as a learning tool could be increased through a priming intervention on students' perceived usefulness of VR before presenting a virtual lesson on biology. Additionally, we hypothesized that acceptance would enhance students' presence, which would affect their learning outcomes. 196 students in the 10th grade were randomly assigned to a learning-usefulness condition, a daily-life-usefulness condition, or a control condition (no intervention). The results showed that, compared with the control condition, the learning-usefulness intervention led to greater acceptance of VR, whereas the daily-life-usefulness did not. Moreover, the results revealed two paths by which students' acceptance affected their learning outcomes: First, students' acceptance of VR enhanced presence, which was positively related to their perceived learning but negatively related to their learning achievement. Second, students' acceptance had a positive effect on their perceived learning but had no effect on their learning achievement. After controlling for the effects of acceptance and presence, the results also showed that students in the control condition believed they had learned more than those in the experimental conditions; but in fact, students in the learning-usefulness condition had better learning performance than those in the control condition. The findings suggest that providing students with relevant information about VR's usefulness before a science lesson can increase their acceptance of VR, which can positively affect their learning experience.

Effective Learning in Immersive Virtual Reality: An Experimental Perspective on the Technology Acceptance Model

1. Introduction

The extent to which a multimedia learning tool, such as immersive virtual reality (VR), contributes to effective learning depends on many different factors. These factors range from the instructional design and technical implementation of a tool, to teachers' instructional approaches, to learners' individual characteristics such as interest, ability self-concept, and motivation (Abdulrahaman et al., 2020; Li et al., 2019; Noetel et al., 2022; Samaras et al., 2004). Besides these factors, students' general attitudes—in terms of acceptance—toward the educational learning tool constitute a fundamental prerequisite for its effectiveness (Davis, 2011; Martins & Kellermanns, 2004). However, there are few studies on how and whether students' acceptance can be increased. Moreover, students' acceptance of an educational learning tool and its subsequent effects on their learning outcomes have been overlooked (Giannakos, 2013; Larmuseau et al., 2018).

We apply the Technology Acceptance Model (TAM; Davis, 1989) in the context of learning VR, which has become more affordable and is being used more and more in science education (Di Natale et al., 2020; Karutz & Bailenson, 2015; Radianti et al., 2020). Accordingly, we assume that learners' acceptance of virtual reality as a learning tool (as opposed to just a gaming gadget) is inherent to its effectiveness. Therefore, this study aims to test whether students' acceptance of VR as an educational tool can be experimentally increased and whether acceptance as a result of such an intervention can enhance their learning outcomes in a virtual learning environment.

1.1. The Technology Acceptance Model (TAM)

With the increased use of multimedia tools in all spheres of life, researchers have developed different models to study and predict users' acceptance in terms of their intention to use such tools and the subsequent effects on performance (Granić, 2022a; Granić & Marangunić, 2019). As the most predominant of all these models, the TAM (Davis, 1989) originated from established psychological theories that aim to predict human behavior and explain relationships between people's attitudes and actions (Ajzen, 1991; Fishbein & Ajzen, 1975). In the last three decades, the TAM has also established itself as the most robust and parsimonious model for predicting users' attitudes toward a given technology (Davis, 1989; Yousafzai et al., 2007a, 2007b). As multimedia tools have become more prevalent in education, there has been an increase in interest in applying the TAM in educational contexts to predict students' acceptance of such tools (Al-Emran et al., 2018; Granić, 2022a, 2022b; Granić & Marangunić, 2019).

The TAM emphasizes that in order for a multimedia learning tool to be effective, learners must first accept it (Davis, 2011; Martins & Kellermanns, 2004). According to the TAM, learners' acceptance of multimedia learning tools is determined by two fundamental psychological factors: (a) learners' perceptions of how easy it is to use the educational tool (perceived ease of use) and (b) their perceptions of how useful it is for their learning goals (perceived usefulness). Perceived ease of use is the subjective belief that one can successfully utilize the multimedia learning tool, and perceived usefulness is the belief that the learning tool can improve one's performance (Davis, 1989). However, numerous studies have demonstrated that, between these two factors, learners' perceived usefulness of a given technology is the most reliable predictor of learners' acceptance, with the greatest impact on their propensity to use or adopt a learning tool (Ma & Liu, 2004; Yousafzai et al., 2007a, 2007b).

Because most of the multimedia tools in education are also used in several other domains in everyday life (including gaming and entertainment), it seems fundamental to distinguish between the inherent value of these tools and their specific value as learning tools. Yet no research has established how the relationship between perceived usefulness and acceptance can vary on the basis of whether students perceive a given technology to be useful in general or specifically for learning. In accordance with the TAM, we assume that students' perceived usefulness of an educational tool specifically for learning will have a greater impact on their acceptance of such a tool because, on a psychological level, their perception of the tool will be more aligned with their learning goals. On this basis, we propose that it is not necessarily the intrinsic value of the tool that drives the effect of perceived usefulness on acceptance but rather the belief that the tool can help students study more effectively.

The TAM has been used to predict learners' attitudes toward diverse educational technologies (Granić, 2022b; Granić & Marangunić, 2019; Venkatesh et al., 2003), including the acceptance of e-learning (Abdullah & Ward, 2016; Cheung & Vogel, 2013; Salloum et al., 2019), web-based virtual learning environments (van Raaij & Schepers, 2008), and most recently, immersive virtual reality (Lee et al., 2019; Manis & Choi, 2019; Plotzky et al., 2021).

However, studies on the TAM have generally used correlational analyses to examine the relationships between the variables in this model (Granić, 2022a; Granić & Marangunić, 2019). Consequently, these studies might have tested only students' a priori perceived usefulness and acceptance or examined these variables only after students had experienced the multimedia learning tools. In any case, we assume that the lack of experimental empirical studies diminishes the predictive power of the model. For instance, most studies on the TAM assessed students' acceptance only after the students had experienced the multimedia learning tool, namely, after the learning session. By contrast, in the current study, we tested whether students' perceptions of VR—prior to their experience in the virtual learning environment—would lead to greater acceptance of VR as a learning tool. Furthermore, educators might also be interested in finding ways to increase students' acceptance of VR as a learning tool in order to enhance its effectiveness. Taking this idea into account, we applied an experimental approach to the TAM and tested whether students' acceptance of VR as a learning tool could be increased when providing students with relevant information about VR's usefulness for learning or daily life before they took part in a virtual biology lesson (The Body VR, 2016).

1.2. The Technology Acceptance Model (TAM) and Academic Performance

In applying the TAM in educational contexts, recent empirical findings have provided valuable insights regarding the key factors that determine students' acceptance of VR and other multimedia learning tools (Granić, 2022a; Granić & Marangunić, 2019; Huang & Liaw, 2018). However, it remains unclear how students' acceptance of VR—in terms of their willingness to use it—affects their learning outcomes. This lack of clarity exists because most of the studies on the TAM so far have neglected to include students' learning outcomes (e.g., learning performance) in this model (Giannakos, 2013; Larmuseau et al., 2018). Although students' acceptance as a fundamental prerequisite deserves to be studied and understood thoroughly, students' learning outcomes (e.g., academic performance) in learning with multimedia learning tools should remain a priority simply because testing for achievement effects is the most critical stage before modern technologies are used in an educational context. Simply put, besides students' acceptance of a multimedia learning tool, the educational tool's capacity to facilitate information acquisition and knowledge construction (Mayer & Fiorella, 2021) should also be assessed.

Nevertheless, a few studies have examined the relationship between students' acceptance of educational technology and their actual use of it as well as the relationship between students' acceptance and their academic performance (Ali et al., 2018; Giannakos, 2013; Larmuseau et al., 2018). These studies have established a positive link between acceptance (intention to use a given educational technology) and actual use (Juarez Collazo et al., 2014; Larmuseau et al., 2018; Turner et al., 2010). Other studies have gone a step further and tested how students' acceptance affects their performance in learning with multimedia. For instance, it has been shown that students' perceived usefulness of diverse educational tools, including a Moodle-based virtual learning environment, had a positive effect on their adoption or actual use, which in turn, positively affected their academic performance (Ali et al., 2018; Juarez Collazo et al., 2014; Larmuseau et al., 2018; Zogheib & Daniela, 2021). Conversely, Giannakos (2013) revealed that students' acceptance of a math game was strongly correlated with students' enjoyment of the math game (r = .59), which had a positive effect on their performance. However, acceptance itself did not have any effect on their learning performance, even though the game was more effective than traditional instruction. These findings raise questions about the nature of acceptance, its relationship with other motivational factors, and its effects on students' learning outcomes.

In learning with multimedia tools, it has been proposed that acceptance constitutes a fundamental prerequisite that increases students' readiness to engage with the learning environment, thus enhancing their learning experience (Chen Hsieh et al., 2017; Huang & Liaw, 2005, 2018). As a result, acceptance can positively affect students' learning outcomes. On the basis of these assumptions, we examined whether students' acceptance of VR could be increased through an intervention on students' perceived usefulness of VR for learning or daily life. Additionally, we investigated whether an increase in students' acceptance of VR as a result of this intervention would also positively affect students' presence in VR, which in turn would influence their learning outcomes. Similar to Lee et al. (2010), we considered two types of learning outcomes: perceived learning (affective domain) and learning achievement (cognitive domain). Perceived learning refers to students' judgments of their level of understanding of and the knowledge gained from the lesson (Rovai, 2002), whereas learning achievement represents students' learning performance on the knowledge test after the virtual lesson.

1.3. The Importance of Presence in Learning With VR and its Relationship With Students' Acceptance of VR as a Learning Tool

In the case of VR, besides students'acceptance of VR as a learning tool, an additional construct comes into play, namely, students' presence in the virtual learning environment, which may also impact their learning outcomes. Presence is defined as the illusion of being there (Held & Durlach, 1992; Minsky, 1980; Sheridan, 1992), that is, the subjective and illusory perception of being physically present in the virtual environment (IJsselsteijn & Riva, 2003; Slater, 2009, 2018; Slater & Sanchez-Vives, 2016), even though one is aware that it is a simulated environment. Because most virtual learning applications aim to produce a simulated reality in which perceptions of visual and auditory stimuli from the real world are minimized, presence seems to play an important role in VR's effectiveness for educational purposes. Accordingly, it has been shown that presence has a fundamental effect on students' motivation, engagement in and enjoyment of the learning environment (Makransky & Lilleholt, 2018; Mikropoulos & Natsis, 2011), and satisfaction (Bulu, 2012; Vrellis et al., 2016). However, the current literature has shown rather contradictory results regarding the effect of presence on students' learning achievement. For example, it has been shown that presence enhances students' learning achievement (Kontogeorgiou et al., 2008; Mikropoulos, 2006; Selzer et al., 2019). Other empirical studies have shown that presence instead hinders learning achievement (Ahn et al., 2022; Bailey et al., 2012; Ferdinand et al., 2023; Makransky et al., 2017). Nevertheless, presence is fundamental for students to be able to engage with the learning materials (Dengel & Mägdefrau, 2019; Mikropoulos, 2006; Mikropoulos & Natsis, 2011).

Although presence plays an essential role in learning with VR, very few empirical research studies that have applied the TAM in the context of learning with VR have examined the relationships between acceptance, presence, and learning outcomes (e.g., Plotzky et al., 2021). Considering that VR is a unique educational tool with specific characteristics (e.g., students' presence and interaction in VR), it seems necessary to understand how different variables in the TAM (e.g., students' perceived usefulness and acceptance) are related to their experience of presence in VR (Mütterlein & Hess, 2017). Acceptance as a psychological construct that is defined as students' intention to use an educational technology could increase students' willingness to engage with the learning materials. Therefore, students' acceptance of VR as a learning tool could create the appropriate attitude toward the virtual learning environment, thus enhancing students' presence in VR.

A limited number of studies have offered initial evidence of a positive relationship between presence and acceptance or between presence and perceived usefulness (Plotzky et al., 2021; Sagnier et al., 2020; Shin et al., 2013). However, these studies have aimed to predict learners' acceptance. Consequently, in these studies, learners' experience with the learning tool was considered as the antecedent of acceptance. For example, in one model, Shin et al. (2013) proposed that presence affects students' perceived usefulness, which in turn should affect students' acceptance. Similarly, in their pilot study, Plotzky et al. (2021) showed a strong positive correlation between students' presence and their acceptance of VR (i.e., their intention to use a virtual learning simulation). The authors interpreted this result as an indication that when students experience a higher presence in VR, they are more likely to accept the virtual simulation.

By contrast, we argue that the direction of the relationship between students' acceptance of VR as a learning tool and their presence in VR depends on how acceptance is conceived. If acceptance is understood as the most important factor to be predicted (i.e., as a dependent variable) and measured only after students have taken part in the virtual lesson, then students' experience in the virtual learning environment (including the perceived difficulty of the lesson, interactivity, and presence) is likely to influence their acceptance of this learning tool. However, if acceptance is conceived of as a prerequisite for effective learning in VR (Davis, 2011; Martins & Kellermanns, 2004), then acceptance should facilitate students' interaction with the learning material, thus affecting their presence in the virtual learning environment. In line with this assumption, we investigated how students' acceptance of VR, as an important factor for effective learning with VR, can be increased and to what extent acceptance can in turn enhance students' experience of presence in VR. Additionally, we assessed how students' presence can subsequently affect their perceived learning (affective domain) and learning achievement (cognitive domain).

1.4. The Present Study

Despite its relevance in predicting students' attitudes toward digital educational learning tools (e.g., immersive virtual reality), the TAM has been studied nearly exclusively through correlational analyses. Moreover, most of the studies in this field of research have focused only on predicting students' acceptance of VR in terms of their intentions to use it. This approach has two major consequences: (a) These studies have examined students' experience in the virtual learning environment (notably presence) as an antecedent of acceptance, and (b) these studies have neglected to examine how students' acceptance impacts their learning outcomes (notably, their learning performance). By contrast, in the present study, we chose an experimental approach to increase students' acceptance of VR as a learning tool, examine the effects of increased acceptance of VR on students' presence in VR, and test whether presence subsequently affects students' perceived learning (affective domain) and learning achievement (cognitive domain). Figure 1 presents the conceptual model for this study.

1.4.1 Predictions

The main research questions were based on the TAM, namely, whether students' acceptance could be increased by providing students with information about VR's usefulness for learning or daily life. This distinction helped us test whether students' perception of VR's usefulness specifically for learning would lead to greater acceptance of VR as a learning tool or whether their general perception of VR as a useful instrument (in daily life) could also enhance their acceptance of VR as a learning tool. Accordingly, we formulated the following hypotheses:

(1) The usefulness interventions will lead to greater acceptance of VR as a learning tool than the control condition. However, the learning-usefulness intervention will have a greater effect on students' acceptance of VR as a learning tool than the daily-life-usefulness condition.

(2) Students' acceptance of VR as a learning tool will enhance students' presence in the virtual learning environment.

(3) Students' presence will subsequently have different effects on the two types of learning outcomes: Presence will have a positive effect on students' perceived learning (affective domain) but a negative effect on their learning achievement (cognitive domain).

(4) Students' acceptance will also have a positive effect on students' learning outcomes.

2. Method

2.1. Participants and Design

On the theoretical basis of the TAM, we used a between-subjects design to test our hypotheses. A sample of 196 students (97 female adolescents; mean age M = 15.56, SD = 0.68) in Grade 10 from 10 academic-track high schools in Germany participated voluntarily in this study. Before participating in this study, the students and their parents signed a consent form that explained the study's objectives, methodology, advantages, and potential risks. Moreover, before data collection began, participants were reminded that their participation was voluntary and that they were free to decide to discontinue or revoke their consent at any time. Furthermore, this study was reviewed and approved by the Ethics Committee of the University of XXX [the name was removed] (Reference Number: 2019_1003_169).

2.2. Materials

2.2.1. Priming Interventions to Increase Students' Acceptance of VR as a Learning Tool

To increase students' acceptance of VR as a learning tool, we created two distinct brief priming videos. In each experimental condition (VR as useful for learning and VR as useful in daily life), we integrated the corresponding priming video into the virtual simulation as a whole. Each priming video provided students with pertinent information about why VR is useful for learning or in daily life (two experimental conditions) before they took part in the virtual biology lesson about the cells in the human body.

Each video was around 3.5 min long, narrated by a professional speaker and integrated into the virtual biology lesson as a whole. Students in each of the experimental conditions watched the corresponding priming video. One of the priming videos presented specific information on the benefits of VR for education purposes. It also emphasized that VR offers special advantages and unique characteristics that enable students to immerse themselves in the virtual learning environment to study microscopic or macroscopic elements. The video also explained how VR enables students to interact with lesson materials and carry out their own experiments as though they were truly there. The other video focused on the usefulness of VR for daily life and highlighted relevant and practical aspects of VR. To do so, the priming video also gave the learners different examples of how VR was being used more frequently on a daily basis, including the use of VR in physical therapy and for touring a rental apartment or a museum. Even though the second video did not explicitly promote or portray VR as a tool for education, it also emphasized the immersive aspects of VR in a manner that was similar to the priming video on the usefulness of VR for learning.

2.2.2. The Body VR: Journey Inside a Cell

The Body VR (2016) is a 13 min interactive virtual biology lesson that presents animations of the circulatory system and different parts of human cells to enhance learners' immersion with the goal of explaining the functions of the cells in the human bloodstream. This VR simulation uses the full potential of VR and makes the impossible possible: It is designed so that, during the learning session, the learner can travel through an artery and into a cell. During this excursion inside the human body, a narrator guides learners while presenting and explaining the different parts of the cell and their functions. Learners also have the opportunity to interact with the elements in the virtual learning environment. For instance, they can use the

VR controller (as in video games) to move, rotate, and examine a blood cell. They can even produce cell elements, such as proteins and red blood cells. The Body VR is a well-known virtual application that has already been tested by different researchers (Ferdinand et al., 2023; Meyer et al., 2019; Parong & Mayer, 2018).

2.2.3. Measures

The test instruments consisted of three parts: a paper-and-pencil pretest, a survey in VR, and a paper-and-pencil posttest. For each scale, participants rated different statements on a 4-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree). The internal consistency reliability of the scales used in this study was acceptable, with Cronbach's alpha values ranging from .73 to .92. Appendix A presents all the scales used in this study, including the references and Cronbach's alpha as a measure of the internal consistency reliability for each scale.

The pretest included questions about the participants' demographic characteristics (e.g., gender, age, class), prior experience with VR (e.g., "I am already very familiar with VR technology"), and interest in biology (e.g., "Biology is one of my favorite subjects"). The second part was a survey that was implemented into the virtual learning environment to assess students' acceptance of VR as a learning tool directly after the manipulation (e.g., "VR should be used in school regularly") and students' experience of presence right after the biology lesson (e.g., "In the virtual environment, I had the impression that I was actually there"). Lastly, the posttest contained a scale concerning participants' perceived learning (e.g., "After participating in this virtual lesson, I can now better explain the different functions of the cell") and a knowledge test. The knowledge test, which was previously developed by Parong and Mayer (2018), consisted of 16 multiple-choice questions. For each correct answer, participants received 1 point. For example, one question was: "Which type of blood cell takes up almost half of the blood's volume?" The possible answers were: (a) Leukocytes, (b) Monocytes, (c) Erythrocytes, or (d) Thrombocytes.

2.3. Apparatus

In this study, we used the virtual reality headset HTC VIVE Pro and the accompanying sensors, Omen Laptops (Omen 15-dh0004ng i7/16GB/1TB HDD + 512GB SSD /GeForce® RTX 2060, Shadow Black), and the Steam Software. Two VR sensors were placed in diagonally opposite corners of the classroom to create a virtual space in which the students could access the virtual learning environment. To access the lesson, students wore the head-mounted displays that were linked to the Steam Software installed on the laptops in front of them. Finally, the VR controllers facilitated students' interactions within the virtual learning environment (e.g., to start the virtual biology lesson, to answer questions [i.e., integrate scales in the virtual simulation], and to interact with the lesson materials).

2.4. Procedure

Two or more trained test assistants supervised the data collection, which was conducted in 10 different schools. The participants were randomly assigned to the learning-usefulness condition (VR as a useful instrument for learning), the daily-life-usefulness condition (VR as a useful instrument in daily life), or the control group (no intervention). They took part in this study in small groups of between five to 10 students. First, they filled out the paper-and-pencil pretest, and then they used head-mounted displays to access the virtual learning environment. Prior to starting the biology lesson, students in the experimental conditions watched the corresponding priming video, which was implemented in the VR simulation as an introduction to the virtual lesson; students in the control condition did not watch either video. Directly after the priming intervention, the participants used the controller to fill out the questionnaire about their acceptance of VR as a learning tool. We believe this approach offered the best way to ensure that the lesson's difficulty or students' experience in the virtual learning environment would not affect their judgments in this regard and thereby did not interfere with the priming intervention. Once they had finished filling out the questionnaire, they used the controller to start the virtual biology lesson. Following the virtual lesson, the participants also used the VR controller to answer the final questionnaire in VR about their experience of presence. Finally, they removed their head-mounted displays and completed the paper-and-pencil posttest and the knowledge test.

2.5. Data Analysis

To test the research hypotheses, we used a path analysis (Figure 1 depicts the conceptual model). For the path analysis, we created two dummy variables that referred to the three conditions with the control group as the baseline, which enabled the comparison of the mean values of each experimental condition with the control group. For the main analyses, we tested the effects of the usefulness interventions on students' acceptance of VR as a learning tool, presence, and learning outcomes (perceived learning and actual learning achievement). Additionally, we also assessed whether students' acceptance of VR as a learning tool enhanced their experience of presence and whether presence subsequently affected students' perceived learning and learning achievement. We also accounted for the nested structure of the data resulting from the data collection in different schools by correcting the standard errors by applying the TYPE=COMPLEX specification before computing the regression analyses, which were conducted in Mplus.

3. Results

First, we conducted a series of analyses to ensure that the randomization in the three groups was successful. The results of these analyses indicated that students in the two experimental conditions and the control condition were similar with regard to their demographic characteristics (gender, $X^2(2, N = 196) = 3.52$, $p = .172$; age, $F(2, 193) = 1.11$, $p = .333$), their interest in biology, $F(2, 193) = 2.32$, $p = .101$, and their prior experience with VR, $F(2,191) = 0.66$, $p = .520$. Table 1 presents descriptive statistics for the sample separately for the three conditions, and Table 2 presents the bivariate correlations between the variables considered in the path analysis.

3.1. Interventions' Effects on Students' Acceptance

In the second set of analyses, we examined the impact of the interventions on students' acceptance of VR as a learning tool. When we compared the learning-usefulness condition (M =3.60, SD = 0.37) with the control condition (M = 3.42, SD = 0.45), the results showed that the learning-usefulness intervention had a positive effect on students' acceptance of VR, $\beta = .19$, $t = 2.36$, $p = .018$. However, there was no difference between the daily-life-usefulness condition (M = 3.52, SD = 0.51) and the control condition (M = 3.42, SD = 0.45) in this regard ($\beta = .10$, $t = 1.56$, $p = .118$). There was no difference between the two experimental conditions with regard to students' acceptance of VR as a learning tool ($p > .05$).

3.2. Effects of Acceptance on Students' Perceived Learning and Learning Achievement

In this section, we report a series of analyses that were conducted to determine whether an increase in students' acceptance of VR as a learning tool enhanced students' presence in VR and whether presence subsequently affected their learning outcomes. In addition, we tested whether acceptance also directly affected students' perceived learning (affective domain) and learning achievement (cognitive domain). The results showed that students' acceptance of VR led to higher presence in VR ($\beta = .36$, $t = 386$, $p < .001$). Presence, in turn, was positively related to students' perceived learning (β = .25, 7.34, $p < .001$) but negatively related to their learning achievement (β = -.10, $t = -2.94$, $p = .003$).

After controlling for the effects of acceptance, the path analyses also revealed that the learning-usefulness (β = -.24, $t = -2.97$, $p = .003$) and daily-life-usefulness interventions had negative effects on students' presence in VR (β = -.20, $t = -2.50$, $p = .013$). Similarly, the learning-usefulness (β = -.20, $t = -3.82$, $p < .001$) and daily-life-usefulness interventions lowered students' perceived learning (β = -.16, $t = -2.03$, $p = .042$). However, the learning-usefulness intervention led to higher learning achievement (β = .10, $t = 2.01$, $p = .044$). Figure 2 shows *the path analysis* models that specify how the interventions affected students' acceptance and how acceptance in turn influenced their learning experience in VR.

4. Discussion

4.1. Empirical Contributions

We applied an experimental approach to the TAM to examine whether VR's effectiveness in science education could be enhanced by increasing students' acceptance of VR as a learning tool. In accordance with this theoretical framework, the findings showed that students' acceptance of VR for learning could be experimentally increased when informing students specifically about the usefulness of VR for learning before a science lesson. That is, only the specific intervention on VR's usefulness for learning led to greater acceptance of VR for learning when compared with the control condition. Moreover, increasing students' acceptance led to higher presence, which in turn was positively related to students' perceived learning (affective domain) but negatively related to their learning achievement (cognitive domain). Furthermore, students' acceptance also directly enhanced students' perceived learning but had no effect on students' learning achievement.

After controlling for the effects of acceptance and presence, the results also revealed that students in the control condition reported higher perceived learning than those in the experimental condition. However, in reality, students in the learning-usefulness condition had greater learning performance than those in the control condition.

4.2. Theoretical Implications and Methodological Contributions

Taking into account multiple issues in research on the TAM, we aimed primarily to test the predictive value of this model in the context of learning with immersive virtual reality. Therefore, we examined whether students' acceptance could be enhanced when students were primed to perceive VR as useful for learning or for daily life. Although many studies have previously confirmed the link between the perceived usefulness of VR and students' acceptance of VR (King & He, 2006; Ma & Liu, 2004; Yousafzai et al., 2007a, 2007b), this study is the first to use an experimental approach to test this relationship in the context of learning with VR. Accordingly, we manipulated students' perceived usefulness using video priming and assessed students' acceptance immediately after the intervention (i.e., before students participated in the virtual lesson). Consistent with the theoretical foundation of the TAM (Davis, 1989), we found that providing students with relevant information about VR's usefulness for learning led to greater acceptance of VR as a learning tool.

Considering that almost all previous research on the TAM has relied on correlational analyses, choosing an experimental method to investigate the model is an important change. By applying an experimental approach, this study showed that students' acceptance can be increased through a careful and parsimonious intervention. In particular, it showed that such a usefulness intervention must be aligned with students' learning goals, as the findings showed that students' perceptions of the usefulness of VR for learning (i.e., they were shown that VR is a multimedia learning tool that can improve their learning performance as opposed to being simply a useful gadget in everyday life) led to greater acceptance of VR as a learning tool. Moreover, this approach provides some understanding of the questions of whether students' perceptions of VR as a learning tool or their experience in the learning environment lead to greater acceptance. In this sense, the findings from this study support the inherent value of perceived usefulness as a psychological construct and a solid antecedent of acceptance. At the same time, these new findings show that is not necessarily students' positive experiences during the learning session in VR that primarily determine their acceptance of VR as a learning tool.

Students' acceptance was also examined in relation to presence, which constitutes one of the fundamental factors in learning with VR. Specifically, we tested how students' acceptance of a multimedia learning tool (i.e., VR) affected their experience in the learning environment, notably, their presence in VR. In contrast to the rare studies that have considered the relationships between perceived usefulness, acceptance, and presence (Plotzky et al., 2021; Sagnier et al., 2020; Shin et al., 2013), we proposed that acceptance constitutes a prerequisite for learning in VR and not a finality in itself that almost all the past studies on the TAM have aimed to predict. On the basis of this assumption, the study was carefully designed so that variations in students' acceptance could be attributed solely to the usefulness intervention and not to students' experiences in VR. Contrary to Sagnier et al. (2020) who found no correlation between presence and acceptance, the empirical results of this study show that acceptance had a positive effect on students' presence. Specifically, students' acceptance of VR as a learning tool led to higher presence in the virtual learning environment, which subsequently was positively related to students' perceived learning but negatively related to their learning performance. Consequently, this study contributes to our understanding of how students' acceptance as a prerequisite influences their learning experience in a virtual learning environment.

These findings also raise intriguing questions about the role of acceptance on students' experience of presence in VR and the extent to which acceptance indirectly affects students' learning achievement. Students' acceptance enhanced presence, which is considered a fundamental factor that affects students' motivation and learning in VR (Makransky & Lilleholt, 2018) but that can also have a negative effect on their learning achievement (Ferdinand et al., 2023; Makransky et al., 2017). In this sense, acceptance of VR as a learning tool seems to play an important role in learning in VR. That is, acceptance indirectly helped students experience the fascinating virtual simulation in which they were guided throughout this journey inside the cell. Therefore, they might have felt that they had learned a great deal in the VR environment. This reasoning is in line with the idea that students reported higher perceived learning in passive learning situations (Deslauriers et al., 2019; Van Sickle, 2016). In fact, however, overstimulation from the virtual learning environment can make actual learning less likely to occur (Makransky et al., 2017; Meyer et al., 2019). Accordingly, the negative effect of acceptance on learning achievement via presence suggests that students' acceptance can enhance their learning experience in VR but not necessarily their learning performance. On the contrary, acceptance can increase presence, which can also cause distractions that are linked to poor learning performance (Makransky et al., 2017; Parong & Mayer, 2018).

In this study, we also tackled an important aspect in applying the TAM in an educational context that has also been mostly neglected so far. Namely, we addressed whether students' acceptance of multimedia learning tools has a positive effect on their learning outcomes—students' perceived learning (affective domain) and students' learning achievement (cognitive domain). The results indicated that students' acceptance of VR had a positive effect on students' perceived learning but had no effect on students' learning achievement. Perceived learning is viewed as an indicator of learning (Herron & Wright, 2006) and is determined by different motivational factors, including interactions with the learning content, self-efficacy, motivation, and enjoyment (Alavi, 1994; Alqurashi, 2019; Kim, 2005). In light of the present results, it seems that acceptance as a prerequisite positively influenced students' learning experience from motivational and affective standpoints (by increasing their presence in VR and their perceived learning). However, it did not improve their learning performance (cognitive domain).

The empirical evidence of an effect of students' acceptance on their learning outcomes remains limited and inconclusive. On the one hand, a few studies have shown that students' acceptance is likely to enhance students' learning achievement (Ali et al., 2018; Larmuseau et al., 2018). On the other hand, Giannakos (2013) has found that acceptance did not affect students' learning achievement. Considering these inconsistencies, we suppose that increasing students' acceptance before a learning session in VR fosters their readiness to engage with learning materials and enhances their learning experience, thus demonstrating a direct positive effect of acceptance on students' perceived learning. However, this effect does not automatically translate into an actual gain in knowledge. Furthermore, it is possible that the effect of acceptance on students' learning achievement would instead consolidate over time, as previous studies have found a positive relationship between acceptance and actual use (Larmuseau et al., 2018; Turner et al., 2010; Venkatesh & Bala, 2008). In such circumstances, it is likely that acceptance affects actual use, which subsequently may have a positive effect on students' learning achievement (Juarez Collazo et al., 2014; Larmuseau et al., 2018).

4.3. Limitations and Future Directions

Despite its contributions and theoretical implications, this study also has a few limitations that should be addressed in future research. First, the results indicate that acceptance positively affects motivation-related outcomes (i.e., presence in VR and perceived learning) but has no effect on students' actual learning achievement. The limited and inconsistent empirical literature with regard to the relationship between acceptance and learning achievement and the lack of experimental studies on the TAM make it challenging to interpret these results and to determine the extent to which acceptance affects students' learning outcomes on subjective and objective levels. Furthermore, in contrast to all previous research on the TAM, students' acceptance of VR as a learning tool in this study resulted from the learning-usefulness intervention and not from students' previous experience with VR. Increasing students' acceptance created the a priori condition for students to learn with VR and not reject it (Davis, 2011; Martins & Kellermanns, 2004). Expressed differently, the acceptance of VR as an educational tool established the necessary condition for its utilization. The question that arises is whether students' actual utilization or repeated utilizations of VR affect the relationship between acceptance and learning achievement. Further experimental studies are needed to determine whether students' acceptance of VR affects students' learning performance by increasing their VR utilization. During such a period, future studies could also assess whether acceptance affects motivation-related factors, such as persistence and effort in learning with VR.

Second, this study is amongst the rare studies that have considered presence in applying the TAM in the context of learning with VR. The empirical evidence supports the assumption that students' acceptance constitutes a fundamental prerequisite that facilitates their experience in VR (by increasing students' presence). However, we propose that a reciprocal effect between acceptance and presence is likely: First, students' acceptance of VR can lead to high presence (as shown in this study), and then students' experience of presence can subsequently also have a positive effect on students' acceptance of VR. Not only might students who experience the virtual learning environment and notice how realistic their interactions within VR can be experience higher presence, but they may also gain a better understanding of VR's affordances for learning. Such an understanding could also reinforce their acceptance of VR as a learning tool. In this context, we argue that more empirical studies are required to further investigate the causal and eventual reciprocal relationship between students' acceptance of VR as a learning tool and their presence in VR. A cross-lagged panel study design in which acceptance and presence are assessed at two different time points could help address this question.

The findings suggest that the interventions also created a learning framework that helped students be more engaged with the learning materials, which reduced their perceived learning but enhanced their actual learning. These counterintuitive results are in line with previous research that showed that when students are actively engaged with the learning materials, they report lower perceived learning, but they actually learn more than those who passively follow the lesson (Deslauriers et al., 2019; Van Sickle, 2016). We wonder whether students' self-regulation could also explain these results, especially when considering that self-regulation is believed to be a fundamental factor in VR's effectives in science education (Makransky & Petersen, 2021; Sakdavong et al., 2019). It appears that the interventions helped put the students in the appropriate mindset for learning; thus, the seductive elements in the learning environment did not distract them from their learning goals (Makransky et al., 2017; Meyer et al., 2019). In future research, we want to assess whether similar interventions can strengthen students' self-regulation, which in turn may reduce their presence and their perceived learning but may in fact enhance their actual learning in VR.

4.4. Conclusion

The present study was designed primarily to determine whether students' acceptance of VR as a learning tool could be increased when students are primed to perceive VR as useful for learning or for daily life. The second aim of this study was to investigate whether acceptance in turn would lead to higher presence in VR, which would subsequently have a significant effect on students' learning outcomes. The results showed that the learning-usefulness intervention was effective: It increased students' acceptance, which affected students' learning outcomes directly and indirectly. First, students' acceptance enhanced their presence in VR, which, in turn, was positively related to their perceived learning but negatively related to their actual learning achievement. Second, acceptance also directly increased students' perceived learning but did not affect their learning achievement.

The findings from this study make several contributions to the current literature: First, they provide significant insight into how students' acceptance of VR can be increased before a science lesson. Specifically, the evidence highlights the necessity for interventions aimed at increasing students' acceptance of multimedia learning tools to demonstrate how a specific multimedia learning tool, such as VR, can enhance students' learning performance. Second, they show how students' acceptance as a fundamental prerequisite subsequently affects their learning experience in VR both directly (presence and perceived learning) and indirectly (via presence). However, acceptance did not directly affect students' learning performance. The findings suggest that students' acceptance may create the necessary but insufficient condition for learning effectively with VR. Other factors that are relative to effective learning with VR (presence, knowledge types, and instruction quality) and those related to the TAM (perceived usefulness and repeated utilizations) could still play important roles.

5. Tables and figures

Table 1

Descriptive Statistics for Students' Interest in Biology, Prior Experience With VR, Acceptance, Presence, and Learning Outcomes in the Three Conditions

Variables	**Learning usefulness**	**Daily-life usefulness**	**Control**
Sample size	*n* = 81	*n* = 57	*n* = 58
Interest in biology	2.80 (0.74)	3.07 (0.62)	2.89 (0.71)
Prior experience	2.10 (0.54)	2.20 (0.49)	2.14 (0.52)
Acceptance of VR	3.60 (0.37)	3.52 (0.51)	3.42 (0.45)
Presence	3.39 (0.48)	3.39 (0.51)	3.56 (0.40)
Perceived learning	2.97 (0.48)	2.95 (0.48)	3.13 (0.50)
Learning achievement	7.38 (2.70)	7.21 (2.74)	6.66 (2.74)

Note. Descriptive statistics are presented as *M* (*SD*).

Table 2

Correlations Between the Variables Used in the Path Analysis

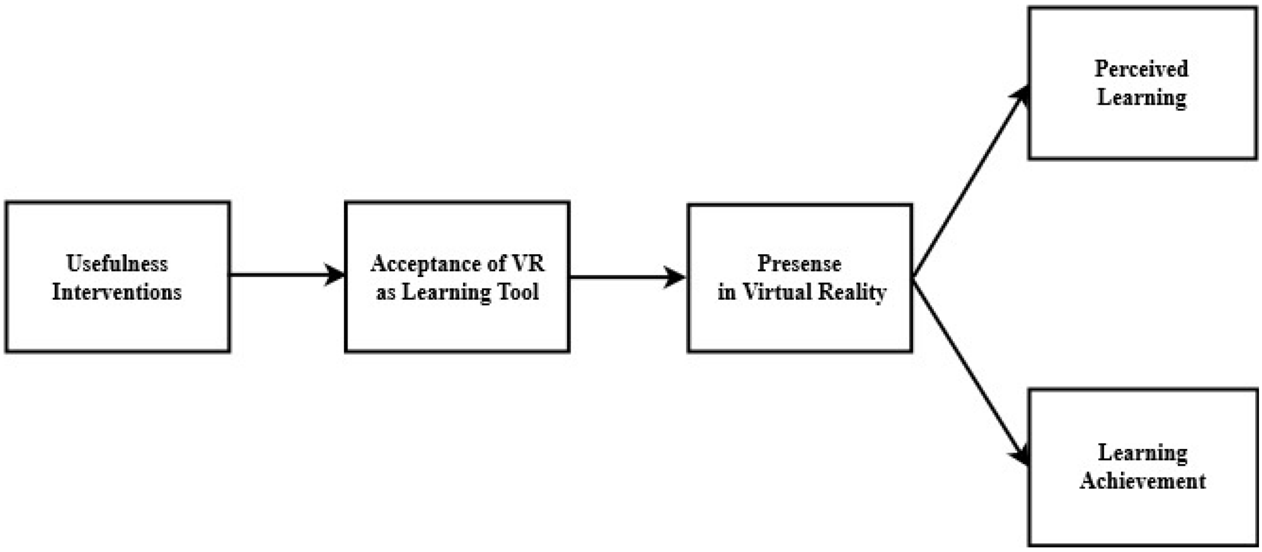
Variables	1	2	3
1. Acceptance of VR			
2. Presence	.33**		
3. Perceived learning	.45***	.41***	
4. Learning achievement	.06	-09	.04

Note. *N = 196.*

* *p* < .05. ** *p* < .01. *** *p* < .001.

Figure 1

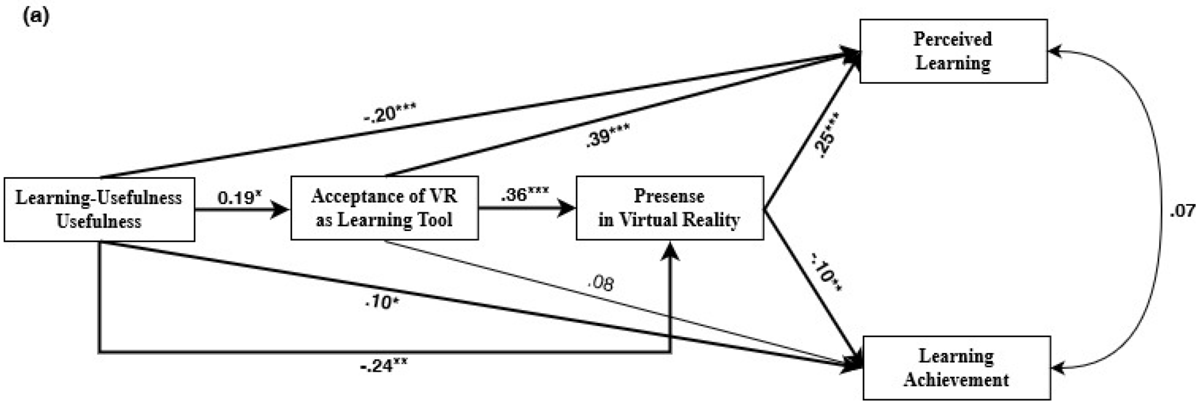
The Conceptual Model of the Role of Acceptance of Virtual Reality as a Prerequisite for Effective Learning

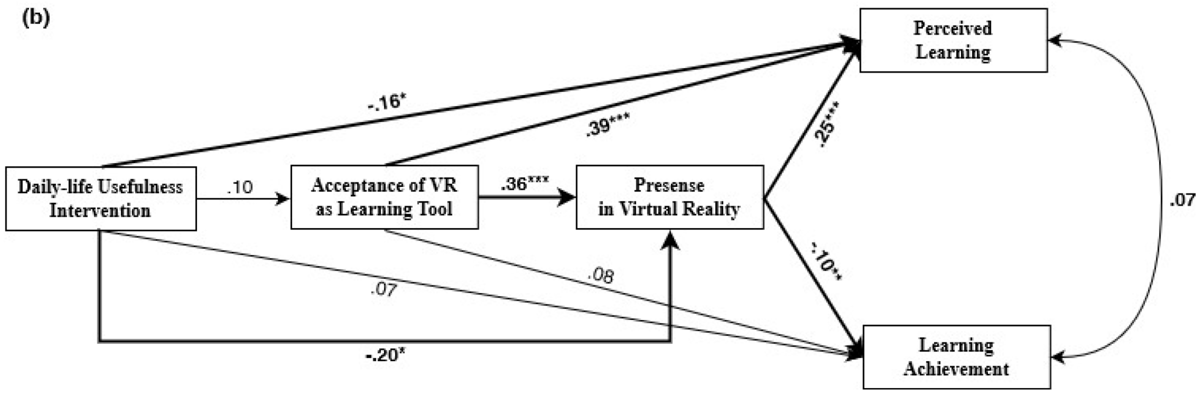


Note. The conceptual model based on the TAM.

Figure 2

Path Analysis Models Testing the TAM in the Context of Learning With Immersive Virtual Reality





Note. These two models show how the usefulness interventions affect students' acceptance of VR as a learning tool, which in turn affect students' learning outcomes directly or indirectly via presence. The usefulness interventions were dummy coded with the control condition as the reference variable. The results are presented here in two separate models to better highlight the effect of each intervention: Model a shows the effects of the learning-usefulness intervention, and Model b shows the effect of the daily-life-usefulness intervention. Values close to the arrows are standardized path coefficients. Bold lines and values represent significant effects.

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$

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STUDY 3

Ferdinand, J., Gao, H., Stark, P., Bozkir, E., Hahn, J.-U., Kasneci, E., & Göllner, R. (2022). *The Impact of a Usefulness Intervention on Students' Learning Achievement in a Virtual Biology Lesson: An Eye-Tracking-Based Approach* [Manuscript submitted for publication]. University of Tübingen.

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Abstract*

Background: Studies have shown that the effectiveness of virtual reality (VR) can be improved by using learning prompts (e.g., summary prompts, pretraining, and priming). However, less is known about how such learning prompts affect students' processing of the learning content within the virtual learning environment.

Aims: This study aimed to shed light on students' processing of learning content in VR by analyzing their eye-movements during a virtual biology lesson after they had been primed to perceive VR as useful for learning or for daily life.

Sample: Participants were 171 German students in the 10th grade from ten high schools.

Methods: Participants were randomly assigned to a learning-usefulness condition (i.e., priming video highlighting VR's usefulness for learning), a daily-life-usefulness condition (i.e., priming video highlighting VR's usefulness in daily life), or a control condition (i.e., no priming video). We integrated the priming interventions at the beginning of the virtual lesson and used VR headsets with integrated eye tracking to monitor students' eye movements during the lesson.

Results: When compared with the control condition, the learning-usefulness intervention positively affected students' fixation duration and saccade amplitude, which in turn were positively related to students' learning achievement. Regarding students' learning achievement, the daily-life-usefulness condition did not differ from the other two conditions. There was no difference between the three conditions in terms of interest in the virtual lesson.

Conclusions: These results indicate that a brief priming intervention about VR's usefulness for learning can induce appropriate cognitive processing, which can positively affect students' learning achievement.

*The format used for this abstract was required by the journal.

The Impact of a Usefulness Intervention on Students' Learning Achievement in a Virtual Biology Lesson: An Eye-Tracking-Based Approach

1. Introduction

With the increased use of immersive virtual reality (VR) in science education, there has been a renewed focus on VR's effectiveness as a promising educational tool. However, recent empirical results have been rather mixed (Makransky et al., 2019; Parong & Mayer, 2018) or have revealed a slight advantage of VR over other learning methods in some cases (Luo et al., 2021; Wu et al., 2020). One factor that might impair VR's effectiveness is the extent to which seductive details are present in VR simulations, as these have the potential to distract students from learning and increase students' cognitive load (Makransky et al., 2021; Makransky & Petersen, 2021; Moreno & Mayer, 2002). However, a growing number of empirical studies have shown that VR's effectiveness can be increased by using different learning prompts, characterized by Mayer et al. (2022) as the *value-added approach*. This approach includes: (a) instructional design principles, such as pretraining (Meyer et al., 2019) and the modality principle (O'Neal et al. 2000); (b) generative learning strategies, such as summary prompts (Parong & Mayer, 2018) and enactment (Makransky et al., 2021); and (c) the integration of motivational clues (Huang et al., 2022; Mayer, 2014), which are most important for the present study.

As an example of such motivational clues, studies have provided a usefulness intervention in which learners were informed about the usefulness of a subject (e.g., mathematics), which in turn was shown to be associated with learners' higher motivation and learning achievement (Brisson et al., 2017; Gaspard et al., 2015). Several studies have also highlighted the role of students' perceived usefulness of multimedia tools in effective learning (Liaw & Huang, 2013; Song et al., 2021; Zhai & Shi, 2020). However, no study has used an experimental approach to test for whether students' perceived usefulness of such multimedia tools could be increased or how such interventions affect students' learning outcomes. By contrast, for the current study, we chose an experimental design and tested how a specific and a general priming intervention involving the usefulness of VR affected VR' effectiveness in science education.

Although the value-added approach seems to facilitate learning in VR (Makransky et al., 2021; Meyer et al., 2019; Parong & Mayer, 2018), how students process the learning content in the virtual learning environment has yet to be fully understood. So far, our understanding that such scaffolding strategies enhance VR's effectiveness has been based almost exclusively on postprocessing measurements (e.g., students' self-reports and achievement test scores). Therefore, this study aimed to use eye-tracking methods to analyze students' cognitive processing of a biology lesson in VR after they had been primed to perceive VR as useful for learning or daily life. Unlike self-reported pre- or posttests, which suffer from a considerable number of limitations (e.g., subjectivity and various kinds of biases; Gonyea, 2005), features derived from students' eye-tracking data—collected while the students interact with the learning materials—can provide objective indicators of students' cognitive processing (König et al., 2016; Nikolaev et al., 2014; Rayner, 2009; Rayner & Kliegl, 2012; Rudmann et al. 2003) of the learning content in VR.

In comparison with other scaffolding strategies within the framework of the value-added approach, usefulness interventions have been shown to be parsimonious, easy to implement, and highly efficient (Brisson et al., 2017; Gaspard et al., 2015). Additionally, they fit well with the motivational aspect of the cognitive theory of multimedia learning (CTML; Mayer, 2022) and the cognitive-affective theory of learning with media (CATLM; Moreno, 2005; 2009; Moreno & Mayer, 2007). The two theories are similar and posit that students' cognitive capacity is limited. Consequently, learning in a virtual learning environment can be very demanding for learners, as it places three types of demands on students' cognitive capacity: *extraneous processing*, which is caused by overstimulation and distractions within the virtual simulations;

essential processing, which is caused by the inherent complexity of the lesson content; and *generative processing*, which greatly depends on students' motivation and is the processing capacity that students need to make sense of the lesson content (Mayer, 2022).

Effective learning with VR requires a reduction in extraneous processing, the management of essential processing, and the fostering of generative processing (Mayer, 2022). According to CTML, “motivation to learn is reflected in the learner’s willingness to exert effort to engage in appropriate cognitive processing during learning (such as the processes of selecting, organizing, and integrating that are needed for meaningful learning). The learner’s motivation to exert effort on a multimedia lesson can be shaped by the learner’s affect, beliefs, interest, and feelings of social connection” (Mayer, 2022, p. 70). In this regard, priming students to perceive VR as useful can help increase their focus on and willingness and persistence to engage with the learning content (Fong et al., 2021; Hood et al., 2012). This motivational aspect is crucial for students to actively and effectively process the lesson content (Mayer, 2022). Therefore, increasing students’ perceived usefulness of VR for learning or daily life can lead to appropriate processing in VR (i.e., selecting, organizing, and integrating relevant elements of the virtual lesson), which in turn can increase VR's effectiveness for learning and teaching.

1.1 The role of perceived usefulness in learning and virtual attention

The pivotal role that perceived usefulness plays in students’ effective learning has been stressed in two distinct theoretical approaches in education sciences and psychology: the Technology Acceptance Model (TAM; Davis, 1989) and Expectancy-Value Theory (EVT; Eccles et al., 1983; Eccles & Wigfield, 2002; Wigfield & Eccles, 2001). In line with the TAM and EVT, the perceived usefulness of VR as a learning tool can be described as the subjective perception that VR can substantially contribute to one’s learning goals. Perceived usefulness has been demonstrated to be one of the most important determinants of learning motivation and academic success (Eccles et al., 1983; Wigfield et al., 2016) and has predicted students' self-regulation (Liaw & Huang, 2013), which is considered a major factor for facilitating learning in VR (Makransky & Petersen, 2021).

In recent years, there has been increasing interest in the TAM in the educational context (Granić & Marangunić, 2019). The TAM highlights the role of perceived usefulness in technology acceptance, performance, and achievement. In the TAM, students' perceived usefulness of multimedia learning tools constitutes the most important predictor of acceptance of these learning tools (Ma & Liu, 2004; Yousafzai et al., 2007a, 2007b). Acceptance is a major prerequisite for effective learning with multimedia learning tools because, no matter how well-designed, dynamic, or motivating multimedia learning tools may be, they will not contribute much to students' learning without students' prior acceptance of such educational technologies (Davis, 2011; Martins & Kellermanns, 2004). Consistent with this model, a recent study examined the relationship between the perceived usefulness and adoption of cloud computer technology in predicting students' academic performance (Ali et al., 2018).

In EVT, it has been shown that usefulness interventions have long-term positive effects on students' persistence, effort, interest, and academic achievement (Hidi & Harackiewicz, 2000; Hidi & Renninger, 2006).-More notably, the long research tradition in EVT has tested and provided different methods to manipulate and increase students' perceived usefulness (Durik et al., 2015; Harackiewicz et al., 2014). Generally, priming interventions are designed to make students aware of the relevance of a certain subject that is being taught or the tools that are being used. For instance, students have been instructed to reflect on statements about the usefulness of science (e.g., biology, physics, or mathematics) in their own lives (Brisson et al., 2017; Hulleman & Harackiewicz 2009). Therefore, we propose that students can be primed to perceive VR as useful in a similar fashion, namely, by highlighting fundamental affordances of VR, such as immersion, interaction, and the possibility of transcending time and space, all of which are relevant for effective learning (Makransky & Petersen, 2021; . Shin, 2017).

So far, almost all of the studies related to EVT have focused on the macrolevel of students' learning outcomes (behavioral aspects), such as persistence, effort, and academic choices and decision-making (Eccles & Wigfield, 2020). However, in the most recent review of this theory, which has been renamed Situated Expectancy-Value Theory (SEVT; Eccles & Wigfield, 2020), the authors have also highlighted the microlevels (Eccles & Wigfield, 2020), that is, the cognitive process beneath the behavioral aspects (e.g., effort, focus, and persistence), as it is this cognitive process that leads to the positive effects of usefulness interventions on students' learning outcomes. Thus, we also aim to assess the impact of usefulness interventions on students' learning in VR and further investigate how a specific priming (i.e., learning usefulness of VR) and a general priming (daily-life usefulness of VR) affect students' processing of the lesson content. In this regard, a recent meta-analysis showed that both general and specific priming had positive effects on achievement-related behavior and performance; however, the specific priming yielded a greater effect (Chen et al., 2021).

It has also been proposed that perceived usefulness can trigger information-seeking behavior that is relevant to the task at hand (Savolainen, 2012). This assumption has garnered empirical support from studies that have shown that priming is linked to goal-oriented behavior (Chen et al., 2021; Latham & Seijts, 2016; Latham & Locke, 2018). Therefore, a priming intervention involving VR usefulness should help students prioritize the processing of task-relevant visual information (Ford et al., 2010; Van der Heijden,1992). In such cases, eye movements result from cognitive processes that are related to internal goals rather than external circumstances (König et al., 2016). Accordingly, priming students to perceive VR as useful for learning or for daily life by giving them essential information about VR's usefulness by highlighting the affordances of VR before a science lesson could enable students to look for relevant elements of the virtual simulation and therefore pay less attention to seductive and irrelevant details. Consequently, such interventions could help students engage in effective processing of the learning content (Mayer, 2022). However, we expected that the specific priming of the usefulness of VR for learning would have a much greater effect on students' learning performance.

Eye-tracking methods can effectively help assess visual behavior that is linked to information seeking and other cognitive processes during learning (Józsa & Hámornik, 2011; König et al., 2016; Nikolaev et al., 2014; Rayner & Kliegl, 2012; Zagermann et al., 2016). Interestingly, a recent study used eye tracking to assess how goal-oriented priming affected behavior through changes in visual attention (Van der Laan et al., 2017). Thus, a priming intervention may help increase attention to task-relevant elements (Jurkat et al., 2021; Theeuwes & Van der Burg, 2013; Van der Laan et al., 2017). These results further support the assumption that a priming intervention on students' perceived usefulness of VR could focus their attention, prompt them to seek relevant aspects of the virtual lesson, and, more importantly, trigger changes in their visual attention in the virtual environment. Accordingly, in this study, we used an eye-tracking-based method to assess how students process the learning content in VR after a priming intervention on VR's usefulness for learning or for daily life. Correspondingly, this approach can help us better understand how specific and general priming interventions affect students' learning outcomes and provide much needed evidence for the microlevel assumptions in SEVT.

1.2 The dual function of virtual reality: VR as an educational tool and VR as a research instrument

VR offers students the opportunity—from a first-person perspective—to observe, interact with, and manipulate different lesson materials in a virtual laboratory in chemistry or physics without fear or risk of accidents (Georgiou et al., 2007; Won et al., 2019). Moreover, VR can help educators engage students when remote learning is necessary, such as during a pandemic (Nesenbergs et al., 2021; Qin et al., 2020; Yoshimura & Borst, 2020). These unique characteristics make the use of VR in education very promising (Bailenson et al., 2008; Fagan et al., 2012; Karutz & Bailenson, 2015), especially because students can play more active roles in the learning process (Allcoat & von Mühlenen, 2018; Roussou, 2004).

Not only does the recent acceleration of advancements in VR technology allow educators to present the learning content in a more engaging way (Lau & Lee, 2015), but it also helps researchers study and evaluate specific learning processes in highly realistic and ecologically valid environments. For example, researchers can isolate and manipulate specific aspects of instruction and classroom interactions. Particularly, some of the modern head-mounted displays that are commercially available have been created with built-in eye-trackers that can help assess students' attentional behavior and cognitive processing during the virtual lesson. Measuring eye-tracking features in VR confers two main advantages. First, students can experience the virtual lesson without interruptions, external distractions, or interactions with external measurement instruments. Second, researchers can unobtrusively analyze students' attentional behavior and their cognitive processing of the lesson under highly ecologically valid conditions.

Recent studies have used eye-tracking-based methods to capture students' eye movements in order to study students' attentional behavior, learning experiences, and cognitive processing of learning content in immersive VR (Clay et al., 2019; Mikhailenko et al., 2022; Soler et al., 2017). These studies have been able to establish that VR as a research instrument can effectively capture students' eye movements (e.g., fixations, saccades) and other eye-related features that have been linked to various cognitive processes and mental effort during learning activities (Chen et al., 2011; König et al., 2016; Nikolaev et al., 2014; Rayner, 2009; Rayner & Kliegl, 2012; Zagermann et al., 2016; Zagermann et al., 2018). Moreover, head-mounted displays with integrated eye-trackers allow researchers to unobtrusively assess students' fixations, saccades, pupil diameter, and blinking behavior. These four variables belong to the main eye-tracking variables have been used for many decades to assess the cognitive processing of visual information (Chen et al., 2011; Mahanama et al., 2022; Rayner & Kliegl, 2012;

Rudmann et al. 2003; Zagermann et al., 2016; Zagermann et al., 2018; Yarbus, 1967). Clay et al. (2019) argued that the combination of eye-tracking method and VR enables researchers to tackle research questions about instruction and cognitive processing in a radically innovative way.

1.3 Fixations, saccades, pupil diameter, and blinking behavior and their meaning for learning

Eye tracking can be considered a reliable and objective method for capturing students' eye movements during learning (Chen et al., 2011; Jacob & Karn, 2003; Mikhailenko et al., 2022; Scheiter & Eitel, 2017); thus, eye-tracking approaches enable researchers to assess the effectiveness of different instructional approaches in multimedia learning (Scheiter & Eitel, 2017; Van Gog & Scheiter, 2010). More specifically, Mayer (2010) proposed that eye-tracking approaches can be used to address three kinds of questions about instructional methods: Which instructional method works, when does it work, and how does it work? For instance, fixations, saccades, pupil diameter, and blinking behavior can provide richer information about students' attentional behaviors and cognitive processing during the learning activity than self-reported measurements can (Lai et al., 2013; Nikolaev et al., 2014; Rayner & Kliegl, 2012). Thus, eye-tracking methods can provide important insights into why, for example, interventions using the value-added approach lead to better learning outcomes in VR for students.

Considering the potential of students' perceived usefulness of VR for effective learning in VR, we analyzed students' eye-tracking features to assess how an intervention on students' perceptions of VR's usefulness for learning or daily life affected their learning in a virtual biology lesson. For this purpose, we considered fixations, saccades, average pupil diameter, and blinking behavior; each of which reveals a different aspect of the underlying cognitive processes during the execution of a task (Chen et al., 2011; Keskin et al., 2020; Van Gog & Scheiter, 2010; Zagermann et al., 2016). In the following section, we present an overview of fixations, saccades, pupil diameter, and blinking behavior and establish their relationships with students’ cognitive processes. Moreover, Table 1 also summarizes the section on eye-tracking variables by including brief definitions of these variables and their relationships with specific cognitive processes.

1.3.1 Fixations

Fixations refer to the maintenance of the eye gaze on a specific location of interest for a certain time span (Behroozi, et al., 2018; Keskin et al., 2020) and can be viewed as the learners' interpretation of the presented visual information (Ooms, 2012; Privitera & Stark, 2000). According to Privitera and Stark (2000), most cognitive processing occurs during fixations; students acquire most of the lesson content during the time they spend fixating (Hoffman, 1999). In the literature, two characteristics of fixations have often been examined in relation to students' learning processes: average fixation duration and the number of fixations. Fixation duration indicates students' attention to specific information, and the number of fixations indicates how much students change their attentional focus during the timespan of the stimulus presentation. A longer average fixation duration indicates higher cognitive processing (Keskin et al., 2018; Keskin et al., 2019). That is, in order to effectively process the content of the lesson, students maintain a longer eye gaze on specific locations of interest (longer fixation duration) and consequently pay less attention (shorter fixation number) to irrelevant elements of the learning content (Walter & Bex, 2021; Zagermann et al., 2016).

1.3.2 Saccades.

Saccades are fast eye movements that occur between two fixations. Saccades are characterized by their amplitude, duration, velocity, and number, thus providing great insight into students' exploration of the learning content (Keskin et al., 2020; Rayner & Kliegl, 2012). For example, saccade amplitude is strongly associated with mental effort and cognitive load (Appel et al., 2021; Behroozi et al., 2018; Keskin et al., 2020). Saccade amplitude tends to decrease with higher task difficulty or higher extraneous processing (Rayner & Kliegl, 2012; Zagermann et al., 2016). Saccade number indicates the frequency of saccadic eye movements for a time span (Mahanama et al., 2022). With increasing task difficulty or higher cognitive load, saccade number also decreases (Nakayama et al., 2002).

Saccade velocity refers to the speed of the saccade, whereas saccade duration corresponds to the amount of time it takes to complete a saccade (Rayner, 2009). Saccade duration and velocity indicate how quickly learners are able to scan the learning materials. Higher saccade velocity can indicate stress, task complexity, or a lack of concentration while the task is being carried out (Keskin et al., 2020). Therefore, a higher saccade velocity is associated with a higher cognitive load (Behroozi et al., 2018). Taken together, saccadic eye movements are influenced by cognitive processes; thus, they can provide valuable information about how students scan the virtual learning environment. For instance, when students experience higher cognitive load, their saccade velocity is also higher, but the frequency of their saccadic eye movements decreases (Nakayama et al., 2002), and their saccade amplitude is shorter (Behroozi et al., 2018; Keskin et al., 2020; Rayner & Kliegl, 2012; Zagermann et al., 2016).

1.3.3 Pupil Diameter

Average pupil diameter refers to the average change in the pupil's size during a specific period. Pupil diameter is generally considered to be a reliable indicator of cognitive and affective information processing when variation in illumination can be held constant or accounted for (Hyönä et al., 1995; Partala & Surakka, 2003; Tummeltshammer et al., 2019). For instance, both positive and negative emotions have been found to lead to a considerable expansion in pupil size (Partala & Surakka, 2003). Similarly, task difficulty has also been shown to lead to greater pupil diameter (Kahneman & Beatty, 1966; Van Orden et al., 2001).

1.3.4 Blinking Behavior

Blinks can be reflexive, voluntary, or spontaneous. Spontaneous blinks are also called endogenous blinks (Irwin & Thomas, 2010) and constitute most human blink reactions (Stern et al., 1984). Endogenous eye blinks are associated with attentional processing and mental effort

(Chen et al., 2011; Irwin & Thomas, 2010; Kramer, 1991). Therefore, in this article, blinks refer to the endogenous type of blinks. With more visually demanding tasks, learners tend to blink less, which can facilitate a better perception of the visual information (Irwin & Thomas, 2010; Kramer, 1991). However, it is not just the blink rate that is affected by cognitively demanding tasks but also the duration of the blinks, whereby shorter blinks are associated with higher cognitive load (Appel et al., 2021; Irwin & Thomas, 2010; Kramer, 1991). In other words, while students work on cognitively demanding tasks, their blinks occur with a lower frequency so that they can better process the visual information presented in the lesson.

Although we have presented overviews of fixations, saccades, pupil diameter, and blinking behavior separately, their relationships with each other are fundamental for understanding how students' attention is distributed and how they process information during a virtual lesson. For instance, saccades and fixations are closely related: Fixations indicate how students pay attention to specific visual information and acquire the relevant information during this time, whereas saccades indicate how students explore and scan the virtual learning environment. Therefore, instructional approaches that increase students’ visual attention could be very beneficial for learning in multimedia, as visual attention is linked with greater average fixation duration (Hoffman, 1999) and precedes saccadic eye movement (Hoffman & Subramaniam, 1995; Posner, 1980; Rayner & Kliegl, 2012).

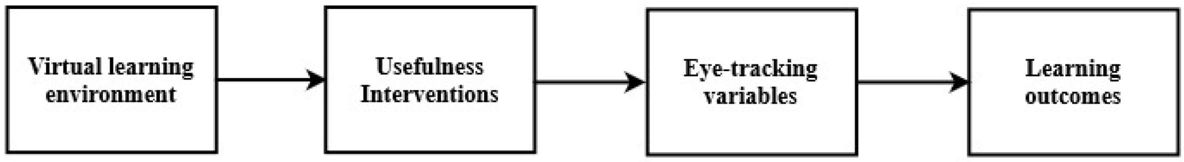
Based on the affordances of VR with integrated eye-tracking technology, this study investigated fixations, saccades, pupil diameter, and blinking behavior in order to better understand how students process the learning content in immersive VR after they have been primed to perceive VR as useful for learning or for daily life. Moreover, we also considered the relationships between fixations, saccades, pupil diameter, and blinking behavior to better assess how students process the learning content while in the virtual learning environment.

1.4 The present study

On the basis of the CTML, we expected that students' perceived usefulness of VR would prove to be an important motivational factor that would help students engage in effective cognitive processing (selecting relevant information, organizing it, and integrating it into prior knowledge), which would enhance their learning outcomes. Figure 1 illustrates the mechanism behind this expectation. Furthermore, empirical studies on EVT have shown how to effectively increase students' perceived usefulness (Durik et al., 2015; Harackiewicz et al., 2014) and that students' perceived usefulness of VR helps enhance students' learning outcomes in VR (Liaw & Huang, 2013; Makransky & Lilleholt, 2018; Song et al., 2021). Considering the theoretical assumptions of the CTML and empirical evidence from EVT, we aimed to assess how brief interventions on students' perceived usefulness of VR for learning or daily life affected students' fixations, saccades, pupil diameter, and blinking behavior during a biology lesson. We assumed that this eye-tracking-based approach would be helpful for assessing how such interventions might affect how students process the virtual lesson, as similar approaches have also been used to determine how different learning goals affect students' visual attention and learning (Brunyé & Taylor, 2009). In addition, we analyzed how students' eye movements affected their learning process in the virtual learning environment. These eye-tracking variables (fixations, saccades, pupil diameter, and blinking behavior) are sensitive to task complexity and cognitive processing (Chen et al., 2011; Keskin et al., 2020) and have been used since the 1970s as objective variables to assess cognitive processing (Mahanama et al., 2022; Rayner & Kliegl, 2012; Rudmann et al. 2003; Zagermann et al., 2016; Zagermann et al., 2018; Yarbus, 1967).

Figure 1

Theoretical Framework Based on the Cognitive Theory of Multimedia Learning



Note. This figure was adapted from CTML (Mayer, 2022). It has been modified to include the learning environment (instructional approach), the usefulness interventions (motivational processes), the eye-tracking variables (as indicators of cognitive processes), and the learning outcomes.

Research questions and predictions

In this study, we investigated three main research questions: The first assessed whether interventions on students' perceived usefulness of VR for learning or for daily life would in fact affect students' perceptions of VR as a learning tool and their learning outcomes. Considering empirical evidence from EVT and research on priming interventions, we predicted:

H1a: The learning-usefulness intervention (specific priming) and the daily-life-usefulness intervention (general priming) will have positive effects on students' learning outcomes.

H1b: The learning-usefulness intervention will have a greater effect on students' learning outcomes than the daily-life-usefulness intervention.

The second research question assessed how interventions on students' perceived usefulness of VR for learning or for daily life would affect students' fixations, saccades, pupil diameter, and blinking behavior during a virtual biology lesson. On the basis of the CTML, we assumed that increasing students' perceived usefulness of VR for learning or for daily life would constitute an important motivational factor that would help them engage in appropriate cognitive processing of the lesson content. We expected this outcome especially because virtual simulations can also contain seductive details that can distract students from learning and result in extraneous processing. Therefore, we predicted:

H2a: Both interventions will lead to higher average fixation duration (time invested in understanding the virtual information) and saccade amplitude (deliberate selections of locations of interest).

Assuming less extraneous processing, we predicted:

H2b: The interventions will lead to a lower fixation number (task-relevant locations of interest), saccade number (selective visual attentional deployment), saccade velocity, and saccade duration (higher concentration).

As empirical studies have shown that extraneous processing leads to greater changes in pupil size than generative processing does (Zu et al., 2020), and blink behavior is sensitive to active cognitive processing (Appel et al., 2021; Irwin & Thomas, 2010; Kramer, 1991), we proposed:

H2c: The interventions will lead to a smaller average pupil diameter, a slower blink rate, and a shorter blink duration (perception of virtual information).

The third research question referred to how students' fixations, saccades, pupil diameter, and blinking behavior are related to their learning outcomes. Following the theoretical rationale of this study, we predicted:

H3a: All eye-tracking variables that are linked to better processing of the lesson content (higher fixation duration and saccade amplitude, lower blink rate and blink duration) will be associated with better learning outcomes; by contrast, those that are more sensitive to extraneous processing (higher fixation number, higher saccade duration, higher saccade velocity, higher saccade number, and larger pupil diameter) will be negatively related to students' learning outcomes.

2. Method

2.1 Participants and design

A total of 196 students in the 10th grade from 10 different high schools (academic track) in Germany volunteered to participate in this study (see also Ferdinand et al., 2023). Participants for whom less than 80% of their eye-tracking signals were recorded were not included in the final analysis. After the data cleaning process, a final sample size of 171 participants could be considered for further analysis (87 female adolescents; mean age, $M = 15.54$, $SD = 0.70$). Both the students and their parents were fully informed about the study's goals and the conditions of their participation and signed consent forms to certify their voluntary participation. Furthermore, this study was reviewed and approved by the Ethics Committee of the University of XXX [the name was removed] (Reference Number: 2019_1003_169).

This study used a between-subjects design, in which student participants were randomly assigned to one of three conditions: a learning-usefulness condition (n = 69; informative video about VR's usefulness for learning), a daily-life-usefulness condition (n = 52) informative video about VR's usefulness in daily life), or a control condition (n = 50; no information).

2.2 Materials

2.2.1 The experimental interventions.

Before starting the virtual biology lesson, students from the experimental conditions watched either a 3 min 30 s video about the usefulness of VR for learning or a similar video about the usefulness of VR in daily life. Both priming videos were carefully designed and had the same structure. They were narrated by the same professional speaker and integrated into the virtual simulation as a whole. Furthermore, the two videos highlighted fundamental affordances of VR (immersion, interaction, and the possibility of transcending space and time): The specific priming video presented VR as useful for learning. This video highlighted the key VR characteristics that enable participants to immerse themselves in the virtual learning environment on a microlevel (e.g., observing chemical reactions) or a macrolevel (e.g., space exploration). The video also explained that they could observe and interact with the lesson materials as if they were actually in the virtual world themselves. By contrast, the general priming video also highlighted the same characteristics of VR but presented examples of daily applications. The general priming video also presented events with the VR characteristics that enable the learners to immerse themselves in a virtual world and observe and interact with its elements as if they were actually in the virtual world themselves. For example, the general video explained that VR is used to treat patients, observe recent or long past historical events, and visit museums or art galleries. The most important difference was that, in the general priming video, we did not mention learning explicitly, even though observing past historical events or visiting museums can constitute a form of learning. Both priming videos are available at this link [Priming videos].

2.3.2 The virtual biology lesson

The virtual biology lesson is an interactive virtual simulation called *The Body VR: Journey Inside a Cell* (The Body VR, 2016), which teaches learners about the cells in the human body. This virtual biology lesson was previously used in two experimental studies (Meyer et al., 2019; Parong & Mayer, 2018). The simulation uses a unique feature of VR that enables learners to travel on a microengine through an artery and into a cell. At different stations of this microlevel virtual trip, different parts of the cell and their functions are presented visually and are explained verbally. Learners can go inside the cells and learn about their anatomy and physiology. They can learn and observe the mechanisms viruses use to penetrate into cells and how the cells react to defend the organism. Moreover, students can interact with the cells, rotate different elements of the cells to better observe them, and even produce proteins in the cells. The following link leads to a teaser about the virtual learning simulation [The Body VR, 2016].

2.3.3 Questionnaires

Students filled out three different questionnaires: a paper-pencil pretest, a questionnaire while they were in the VR environment, and a paper-pencil posttest. The pretest included participants' demographic characteristics (e.g., gender, age, class), prior experience with VR, and students' background in biology (general interest in biology, self-concept in biology, and grades in biology for the semester prior to the study). All the variables on the pretest were used as control variables to ensure that students' individual characteristics or prior experience with VR did not affect the results without being detected. Similar to Parong and Mayer (2018), we did not include a prior knowledge test in biology before the intervention because such a procedure could lead to a testing effect. That is, the pretest could have primed participants to construct answers before the virtual biology lesson and could be considered a form of instruction in itself (Fiorella & Mayer, 2015; Parong & Mayer, 2118). Furthermore, we believed that the assessment of students' general interest in biology, self-concept in biology, and grades would provide valuable information about students' knowledge about and affinity for biology.

In order to avoid interrupting students while they were in the VR environment, a questionnaire about students' perceived usefulness of VR (administered right after the priming intervention) was incorporated into the virtual environment. This was also done to ensure that students' perceived usefulness of VR would result from the usefulness interventions and not from their experience or the perceived difficulty of the virtual lesson. Finally, the posttest was administered as a paper-pencil test, which included a measure of participants' interest in the virtual biology lesson and a knowledge test. All the scales had acceptable internal consistency reliabilities ranging from .72 to .92. The knowledge test consisted of 16 multiple-choice questions that were similar to those previously used in two research projects that also used the same virtual biology lesson (Meyer et al., 2019; Parong & Mayer, 2018). Participants received 1 point for each correct answer. An example question is, “Which of the following elements determines the structure of proteins?” The choices were: (a) Ribosomes, (b) The endoplasmic reticulum, (c) DNA, (d) The cytoskeleton.

2.4 Apparatus

Students used the Virtual Reality set HTC VIVE Pro Eye, which was connected to Steam software installed on a computer (Omen Laptop: Omen 15-dh0004ng i7/16GB/1TB HDD + 512GB SSD /GeForce® RTX 2060; Shadow Black), to take part in the virtual biology lesson. This VR headset has an integrated Tobii eye tracker with a 120 Hz sampling rate and a default calibration with 0.5° to 1.1° accuracy that enables the capture of students' eye movements during the learning session in VR. Students also used a hand-held VR controller to start the lesson, answer questions in the virtual learning environment, or interact with the lesson materials.

2.5 Procedure

Participants were randomly assigned to either the learning-usefulness condition, the daily-life-usefulness condition, or the control condition. Before taking part in the virtual biology lesson, they filled out the pretest questionnaire; then, they used head-mounted displays to access the virtual learning environment. In VR, the participants in each experimental condition watched the corresponding priming video; for example, students in the learning-usefulness condition watched the specific priming video about VR's usefulness for learning. Students in the control condition did not watch either video. All participants used the controller to answer the questions from the scale about their perception of VR as an educational tool. After this section, students started the virtual biology lesson. Finally, they took off their head-mounted displays, filled out the posttest, and took the knowledge test. The whole experiment lasted about 50 min, which included the pretest (10 min); the manipulation, the virtual lesson, and the questionnaire in VR (18 to 21.5 min); and the posttest (20 min).

2.6 Data analysis of students' fixations, saccades, pupil diameter, and blinking behavior

2.6.1 Data preprocessing

To implement a high-quality visual behavior analysis, we followed multiple steps to preprocess the raw data. Then, we applied linear interpolation on gaze vectors. In addition, we applied the Savitzky-Golay filter (Savitzky & Golay, 1964) to smooth the pupil diameter values to account for noisy eye-tracking data. Table 2 presents the thresholds and parameters used to determine the fixations and saccades. Additionally, Appendix A provides a detailed description of the methods used to aggregate the fixations, saccades, pupil diameter, and blinking behavior.

2.7 Analysis of students' learning outcomes

As the participating students were clustered within schools, the standard errors of all the statistical tests needed to be adjusted. Therefore, we also accounted for the nested structure of the data (number of clusters N = 10) by correcting the standard errors using the TYPE=COMPLEX specification before we conducted structural equation modeling in Mplus. In addition, we log-transformed all the eye-tracking features due to positive skewness in some of the variables. In the following analysis, we first tested whether there was a difference between the three groups in terms of basic characteristics (e.g., age, sex, prior experience with VR, interest in biology). The results of these univariate analyses, which are reported in Table

3, showed that the three groups did not differ in background characteristics: age, $F(2, 168) = 0.98$, $p = .376$; gender, $X^2(2, N = 171) = 4.80$, $p = .091$. The groups also did not differ in prior experience with VR, $F(2, 167) = 0.50$, $p = .606$; biology grades, $F(2, 168) = 0.59$, $p = .569$; general interest in biology, $F(2, 168) = 2.49$, $p = .086$; or self-concept in biology, $F(2, 168) = 0.37$, $p = .695$). As such, these results showed that the participants' characteristics were well-balanced across the three groups.

Second, we conducted a manipulation check, which revealed that the two experimental interventions were in fact very similar. Students who received the specific and general priming interventions perceived VR as significantly more useful for learning than those who did not receive either priming intervention, $F(2, 168) = 3{,}530$ $p < .032$. An LSD post hoc analysis showed that the learning-usefulness intervention ($M = 3.54$, $SD = 0.33$) led to higher perceived usefulness of VR for learning than the control condition ($M = 3.39$, $SD = 0.36$), $p = .022$. The daily-life-usefulness intervention also led to higher perceived usefulness of VR as a learning tool ($M = 3.55$, $SD = 0.58$), when compared with the control condition ($M = 3.55$, $SD = 0.58$), $p = .020$. However, there was no difference between the two priming interventions in this regard, $p = .845$. The results of these univariate analyses are presented in Table 3.

Then we assessed the effects of the interventions on students' learning outcomes (interest in the virtual lesson and learning achievement) in the three groups. To compare the two experimental groups with the control group, we created two dummy variables, with the control condition as the baseline. In addition, for the comparison between the two experimental conditions, we created a second set of dummy variables with the learning-usefulness condition as the baseline. Finally, we tested how the VR usefulness interventions affected students' fixations, saccades, pupil diameter, and blinking behavior and whether these eye-tracking variables, in turn, were related to the learning outcomes. For all direct effects, we report the standardized coefficients.

3. Results

3.1 How did the leaning-usefulness and daily-life-usefulness interventions affect students' learning outcomes?

On the basis of EVT and studies on priming interventions, we predicted that both the specific priming (learning-usefulness intervention) and the general priming (daily-life-usefulness intervention) would have positive effects on students' learning achievement. However, we expected the learning-usefulness intervention to have a much greater effect. The results are presented in the first line of the learning outcomes section of Table 5. These results revealed that students who were primed to perceive VR as useful for learning (M = 7.72, SD = 2.66) performed significantly better on the knowledge test after the biology lesson (β = .18, t = 3.09, p = .002) than their counterparts in the control condition (M = 6.71, SD = 2.80). However, students who were primed to perceive VR as useful for daily life (M = 7.20, SD = 2.74) did not differ significantly from the control condition in their learning test performance (β = .09, t = 1.80, p = .071). There was also no difference between the two experimental conditions on the learning test (β = -.08, t = -1.29; p = .196).

Similarly, we predicted that the two interventions would have positive effects on students' interest in the virtual biology lesson. The second line in the learning outcomes of Table 5 provided the summary statistics. The results showed there were no differences between the learning-usefulness condition (M = 3.53, SD = 0.48), the daily-life-usefulness condition (M = 3.51, SD = 0.54), and the control condition (M = 3.53, SD = 0.50), all ps >.05. Table 4 presents descriptive statistics for all outcomes variables (learning outcomes and eye-tracking variables) separately for each condition.

3.2 How did the leaning-usefulness and daily-life-usefulness interventions affect students' fixations, saccades, pupil diameter, and blinking behavior during the virtual biology lesson?

We hypothesized that the two interventions would lead to a greater average fixation duration and a higher average saccade amplitude. The analysis of students' fixations and saccades showed that the interventions significantly affected how students processed the learning content in the virtual learning environment. Students in the VR learning-usefulness condition had a greater average fixation duration ($\beta = .31$, $t = 4.73$, $p < .001$) and a greater average saccade amplitude ($\beta = .22$, $t = 3.56$, $p < .001$) than those in the control condition. These results indicate that students in the learning-usefulness condition spent more time on average on relevant visual information and more deliberately selected the visual information to focus on than those who did not receive any priming intervention.

Students in the daily-life-usefulness condition did not differ from those in the control condition in average fixation duration ($\beta = .07$, $t = 0.60$, $p = .550$). However, the daily-life group had a greater average saccade amplitude than the control group ($\beta = .18$, $t = 2.65$, $p = .008$), indicating that they were more deliberate in selecting areas of interest. When the two experimental groups were compared, the results revealed that students in the learning-usefulness condition also had a greater fixation duration than those in the daily-life-usefulness condition ($\beta = -.22$, $t = -2.25$, $p = .024$). However, the groups did not differ in terms of average saccade amplitude ($\beta = -.03$, $t = -0.77$, $p = .443$). A summary of these results is presented in the eye-tracking features of Table 5.

We also predicted that the interventions would lead to a lower fixation number, saccade duration, saccade number, and saccade velocity. The results showed that there were no statistically significant differences between the three conditions in average fixation number, saccade duration, saccade number, or saccade velocity (all *p*s > .05). Table 5 provides a summary of the regression analyses for students' eye-tracking features, pupil diameter, blinking behavior, and learning outcomes.

We hypothesized that the interventions would have negative effects on students' mean pupil diameter, blink duration, and blink rate. With regard to mean pupil diameter ($\beta = .08$, $t =$

1.75, $p = .080$) and average blink duration ($\beta = .01$, $t = 0.14$, $p = .891$), students in the learning-usefulness condition did not differ from those in the control condition. Similarly, there were also no differences in mean pupil diameter ($\beta = -.11$, $t = -1.25$, $p = .212$) or average blink duration ($\beta = .13$, $t = 1.75$, $p = .079$) between the daily-life-usefulness and control conditions. When the two experimental conditions were compared, students in the learning-usefulness condition had a lower blink duration ($\beta = .12$, $t = 2.09$, $p = .037$) but a higher average pupil diameter ($\beta = -.18$, $t = -2.22$, $p = .027$) than those in the daily-life-usefulness condition. Finally, there were no statistically significant differences between the three conditions in blink rate (all ps > .05).

3.3 How are students' fixations, saccades, pupil diameter, and blinking behavior related to students' learning outcomes?

We predicted that higher fixation duration and saccade amplitude and lower blink rate and blink duration would be associated with better learning outcomes for students; however, we expected higher fixation number, higher saccade duration, higher saccade velocity, higher saccade number, and larger pupil diameter to be negatively related to students' learning outcomes. When the intervention effects were controlled for, the findings indicated that students' average saccade amplitude ($\beta = .14$, $t = 2.39$, $p = .017$), fixation duration ($\beta = .13$, $t = 2.27$, $p = .023$), and number of fixations ($\beta = .10$, $t = 1.98$, $p = .048$) were positively related to their learning achievement, whereas students' blink duration ($\beta = -.20$, $t = -5.98$, $p < .001$) was negatively related to their learning achievement. None of the other eye-tracking features were related to students' learning achievement (all ps > .05). Table 6 presents a complete correlation matrix between students' fixations, saccades, pupil diameter, blinking behavior, and learning outcomes.

Furthermore, the results revealed that average fixation duration was positively associated with students' interest in the virtual biology lesson ($\beta = .12$, $t = 3.20$, $p = .001$). This suggests that students who, on average, spent more time considering relevant visual information in the end expressed greater interest in the virtual lesson. However, students' average blink duration was negatively related to their interest in the virtual lesson (β = -.15, t = -2.27, p = .023). The other eye-tracking features were not related to students' interest in the virtual lesson (all ps > .05).

3.4 Did students' average fixation duration and saccade amplitude each mediate the effect of the learning-usefulness intervention on students' learning achievement?

Two separate series of regression analyses were also conducted to test for whether students' average fixation duration and saccade amplitude each mediated the effect of the learning-usefulness intervention on students' learning achievement. The results showed that the learning-usefulness intervention positively affected students' learning achievement (β = .18, t = 3.09, p = .002). Analyzing the indirect effects, the results revealed that the learning-usefulness intervention positively affected fixation duration (β = .31, t = 4.73, p < .001), which in turn positively affected students' learning achievement (β = .13, t = 2.27, p = .023). However, students' fixation duration did not mediate the relationship between the learning-usefulness intervention and fixation duration (ab = .22, SE = .12, p = .059), 95% CI [.03, .42]. Nevertheless, the results also suggested that even after accounting for the effect of fixation duration, the effect of the intervention on students' learning achievement remained (β = .14, t = 3.20, p = .001). These results suggest that the learning-usefulness intervention helped students spend more time on average on visually relevant information, which in turn was positively related to their learning achievement.

Similarly, the results showed that the learning-usefulness intervention positively affected students' average saccade amplitude (β = .22, t = 3.56, p < .001), which in turn had a positive effect on students' learning achievement (β = .20, t = 2.81, p = .005). However, it did not mediate the relationship between the learning-usefulness intervention and fixation duration (ab = .24, SE = .13, p = .057), 95% CI [.03, .45]. Even after controlling for the effect of saccade amplitude, the effect of the intervention on students' learning achievement remained significant (β = .14, t = 2.57, p = .010).

These findings provide some evidence that priming students to perceive VR as a useful instrument for learning leads to a higher average fixation duration and saccade amplitude than the control condition. In turn, these higher values were positively related to students' learning achievement. In fact, these two important eye-tracking variables are essential for adequate cognitive processing, as they are involved in selecting, organizing, and integrating visual learning content.

4. Discussion

4.1 Empirical contributions

This study used an eye-tracking-based approach to investigate how students process biology lesson content in VR after they have been primed to perceive VR as a useful tool for learning or daily life. The study provides three main insights into students' cognitive processing of lesson content in VR and how such an intervention can enhance VR's effectiveness: First, the results extend previous evidence that acknowledging the perceived usefulness of VR as a learning tool is a fundamental factor in learning with VR (Liaw & Huang, 2013; Makransky & Lilleholt, 2018; Song et al., 2021) by showing that a specific priming intervention involving VR's usefulness for learning could help increase VR's effectiveness in science education. Second, to go one step further, this eye-tracking-based approach shows how an intervention based on the value-added approach works; that is, how a learning-usefulness intervention positively affected students' processing of the lesson content in VR. In particular, students who received the priming intervention on VR's usefulness for learning had a higher average saccade amplitude and fixation duration than those in the control condition. They also had a greater fixation duration, pupil diameter, but a lower blink duration than those in the daily-life-usefulness condition. Third, the results revealed that saccade amplitude, fixation duration, and fixation number were positively related to students' learning achievement, whereas blink duration was negatively correlated with learning achievement and interest in the virtual biology lesson.

4.2 Theoretical contributions

The results of this study support the CTML's motivational assumption that motivational aspects in learning with VR can help students engage in adequate cognitive processing of the lesson content and thereby help them mitigate the potential distracting effects of seductive details in VR. Moreover, this study expands the EVT (Eccles et al., 1983; Eccles & Wigfield, 2002; Wigfield & Eccles, 2001) to include VR by showing that a brief intervention on students' perceived usefulness of VR for learning can produce positive effects on students' learning outcomes. These results are in line with other typical usefulness interventions (Brisson et al., 2017; Gaspard et al., 2015). Additionally, this study also provides some evidence for the microlevel aspects of the SEVT (i.e., the cognitive process beneath the effects of usefulness interventions on students' learning outcomes).

When compared with the control condition, the results showed that the learning-usefulness intervention had a positive effect on students' learning achievement but had no effect on their interest in learning biology with VR. These results are consistent with our assumption based on the CTML (Mayer 2022), according to which, motivational aspects (e.g., students' perceived usefulness of VR for learning) can help students engage in effective processing of the learning content. In CTML, effective cognitive processing can be understood as a cognitive activity that reduces extraneous processing (less focus on the seductive aspects of VR) and induces more engagement in essential and generative processing (selecting task-relevant visual information, organizing and integrating such information into prior knowledge). Such effective processing is expected to enhance students' learning achievement, as the empirical results of this study have also shown. With regard to students' interest in learning biology with VR, we assume that learning with VR is quite a novel and interesting experience that generally positively affects students' interest (Makransky et al., 2020; Parong & Mayer, 2018). Therefore, neither the specific nor the general priming intervention offered an advantage for either group in this regard.

4.2.1 Positive effect of the learning intervention on students' visual attention

Informing students about the usefulness of VR for learning had a positive effect on how students scan and process the learning content. These findings are in line with previous eye-tracking studies that have suggested that students need instructional support to effectively process learning content in multimedia learning tools (Hannus & Hyönä, 1999; Scheiter & Eitel, 2015). For instance, Scheiter and Eitel (2015) used signaling to draw students' attention toward relevant visual learning content by making relevant learning elements more salient (Lemarié et al., 2008; Mautone & Mayer, 2001; Scheiter & Eitel, 2015), thus enhancing students' learning outcomes. By contrast, the current study uses a more psychological motivational approach by increasing students' perceived usefulness of VR for learning. The empirical findings indicate that this motivational approach foster attentional behavior and cognitive processing, which are beneficial for learning.

Students who were primed to perceive VR as useful for learning had a higher average saccade amplitude than those in the control condition, which is much more relevant for identifying visual elements that have low frequencies. By contrast, a shorter saccade amplitude is much more involved in identifying visual elements that have higher frequencies (Tatler et al., 2006). Learning with highly dynamic learning environments, such as "the Body VR" (2016), can make it challenging for students to distinguish between relevant and irrelevant visual elements because flashy and animated visual elements can capture students' attention (Kiili et al., 2014), thereby distracting them from learning (Makransky et al., 2021; Makransky & Petersen, 2021). Taking into consideration that most of the virtual simulations include many seductive elements, the learning-usefulness intervention appeared to help students to be task-oriented in selecting visual information and more selective in how they scanned and explored the lesson content in the virtual learning environment.

Although the learning-usefulness intervention seemed to enhance students' cognitive processing of the learning content, it did not affect all the eye-tracking features, especially those that are more sensitive to extraneous processing (average fixation number, saccade duration, saccade number, saccade velocity, or blink rate). Moreover, students in the learning-usefulness condition had a lower blink duration and a higher average pupil diameter than those in the daily-life-usefulness condition. This suggests that the learning-usefulness students were able to mitigate the extraneous processing and were better engaged in more active processing than their counterparts were, as students' blink duration decreases when they must intensely process virtual information (Irwin & Thomas, 2010; Kramer, 1991). However, students in the learning-usefulness and control conditions did not differ in average blink duration or pupil diameter. The results on average pupil diameter are in line with a recent study that showed that both extraneous processing (caused by seductive aspects of VR) and generative processing (fostered by the intervention) can lead to increases in pupil diameter (Zu et al., 2020).

4.2.2 The role of eye tracking in processing the lesson content in VR

The present study provides valuable insights into how students process the learning content in VR and supports the notion that eye-tracking features can predict learning in immersive virtual reality (Rappa et al., 2019). In fact, three of the most important eye-tracking features (average fixation duration, fixation number, and saccade amplitude) that are involved in the active processing of visual information positively affected students' learning achievement. In addition, fixation duration also positively affected students' interest in the virtual lesson. By contrast, blink duration was negatively related to students' learning achievement.

In general, a higher fixation duration corresponds to greater attention and learning (Khedher & Frasson, 2016; Mason et al., 2013; Scheiter & Eitel, 2015), mainly because most of the processing of the learning content happens during fixation (Hoffman, 1999; Privitera & Stark, 2000). The only exception is experts, who, because of their expertise in recognizing and processing information faster than novices (Ooms et al., 2012a; Ooms et al., 2014), generally have a lower fixation duration. However, in the current study, students from the experimental conditions and the control condition were very similar in terms of their prior knowledge in biology. Considering that students' average fixation duration positively affected students' learning achievement and interest in the learning lesson, the students who were primed with learning usefulness had a substantial advantage; they were more focused and engaged with the learning content.

Saccade amplitude is greatly involved in the identification and selection of relevant visual information (Tatler et al., 2006). The relationships between saccade amplitude and students' learning outcomes suggest that students who were primed to perceive VR as a useful tool for learning were very selective in choosing which visual elements of this dynamic virtual learning environment to target. Therefore, they performed significantly better on the knowledge test than those who did not receive the priming. Similarly, Kickmeier-Rust et al. (2011) also found a positive relationship between higher average saccade amplitude and learning performance. These findings suggest that students who learned more effectively were very selective, as indicated by how they transitioned between fixations (Kickmeier-Rust et al., 2011).

As an indicator of cognitive load, students' average blink duration (Appel et al., 2021) was negatively associated with students' learning outcomes. Previous studies have established the link between task difficulty and blink duration (Cho, 2021; Irwin & Thomas, 2010; Kramer, 1991) and have indicated that task difficulty also impairs students' learning outcomes (Capa et al., 2008; Nuutila et al., 2021). To adequately respond to cognitively demanding tasks, students' blinks are shorter and occur less frequently so that they can process the visual information that is presented (Irwin & Thomas, 2010; Kramer, 1991). Consequently, a higher blink duration is associated with less effective processing of learning content. That is, the more student participants focused on particular pieces of visual information, the less they blinked, and the shorter their blinks were. By contrast, when students' blink duration was longer, the students were having trouble effectively processing the information.

4.3 Educational implications

Our results showed that a brief presentation about the usefulness of VR can affect how learners scan the virtual environment and select relevant visual information. Thereby, how specifically the priming referred to learning also seemed to be important. Priming VR to be specifically useful for learning also affected the intensity with which students obtained visual input (fixation duration), whereas students in the daily-life-usefulness condition did not differ from their counterparts in the control condition. Not only do these findings suggest that a short priming intervention at the beginning of the lesson in VR makes a difference in how learners process learning information in a VR environment, but they also indicate that specifically referring to learning is one crucial determinant of effective learning in VR. In line with other motivational conceptions, such as the goal theory or goal-orientation theory (Chen et al., 2021; Latham & Seijts, 2016; Latham & Locke, 2018), specifically priming the usefulness of VR for learning seems to provide guidance for students and help induce a more focused processing of the learning information presented in the VR environment (Hoffman, 1999; Privitera & Stark, 2000). This finding is also in line with the CTML, which proposes that students' motivation is one crucial building block for understanding students' learning with multimedia by affecting students' generative processing to make sense of the lesson content (Mayer, 2022). Inasmuch, the specificity of priming appears to tap into learners' motivation while they learn in VR.

From an educational perspective, the empirical evidence suggests that priming students to perceive VR as useful for learning before a science lesson in VR is very beneficial, as it helps increase VR's effectiveness because students are then better able to cognitively process what they are learning than those who did not receive the priming intervention. Such preparation can be achieved by a brief intervention that provides students with relevant information about VR's usefulness for learning, which can help students remain more engaged in and focused on the lesson content and less sidetracked by the seductive aspects of VR. Educators who currently use VR to teach science or those who plan to do so could try to apply such interventions as they embed VR into their regular lessons. In learning with multimedia (e.g., VR), it seems fundamental that students are psychologically prepared and aware of the added value of a such tool, as this awareness implicitly motivates them to engage in adequate cognitive processing of the learning content.

4.4 Limitations and future directions

The simulation used in this study (The Body VR, 2016) has been used in two separate empirical studies (Meyer et al., 2019; Parong & Mayer, 2018). Contrary to other approaches that have been used to enhance VR's effectiveness by explicitly encouraging students to either learn similar materials (pretraining) or to summarize the material (summary prompts), we chose a more implicit approach for the current study. Because we provided relevant information regarding the usefulness of VR for learning, students were motivated to be more active and were able to focus better while learning with VR. Even though such an intervention positively affected how students processed the lesson and confirmed the relevance of eye-tracking features for understanding students' learning in VR, we used only one interventional setup. Future research can also use eye-tracking methods to evaluate whether other kinds of effective instructional supports within the value-added approach (e.g., summary prompts or pretraining) might lead to similar effects concerning students' eye-tracking features.

The virtual biology lesson used in this study presented factual knowledge (i.e., discrete, isolated elements of information; Anderson et al. 2001) about how the circulatory system functions. To evaluate the effects of the interventions on students' learning achievement, the study assessed only factual knowledge. In future research, we could test whether such interventions improve students' learning achievement when different types of knowledge (procedural knowledge and transfer) are considered. Furthermore, a recent study using an eye-tracking-based method showed that instructional support had different effects on students with different knowledge levels (Scheiter et al., 2018). In future research with a much more heterogeneous sample, it would be interesting to test how students' prior knowledge affects how they process the learning content and whether distinctive strategies emerge between students with higher prior knowledge and those with lower prior knowledge.

In this virtual simulation, students followed a preprogrammed trajectory that takes them inside the human body (traveling through the bloodstream) while learning about how cells function. Consequently, fixation- and saccade-related features were calculated using only the gaze vectors reported by an integrated eye-tracker in the head-mounted displays. To do so, we used conventional thresholding algorithms with an assumption of nonparallelism. Future research may focus on other virtual simulations that present information in such a way that students need to shift their visual attention so significantly that head movements are required to see the relevant learning content in their view. In such a situation, the head movements would be accounted for when calculating the eye-tracking features. Comparing the results of such virtual simulations with the current results may provide additional insights into the learning process in VR and the different methodological approaches that are used to assess eye-tracking features.

Finally, in the present study, we used two different usefulness priming conditions with one condition that specifically referred to the usefulness of VR for learning and the other to daily-life usefulness. Our results showed that the learning-usefulness condition resulted in a more focused processing of information as well as higher achievement than the daily-life-usefulness condition. Although the investigation of these differences was not the study’s main focus, we think that these findings tap directly into a very current issue on why usefulness interventions work. Our findings indicate that the specificity of a priming intervention might be directly relevant for guiding students’ learning. For this reason, future studies should examine the extent to which the specificity of a priming intervention is related to students' goal-directed behavior and processing of learning content in multimedia.

4.5 Conclusion

We found that informing students about the usefulness of VR for learning before a science lesson had a significant impact on their learning achievement. Moreover, the results of this study provide some evidence for motivational aspects of the CTML, according to which students' motivation can enhance students' cognitive processing of the lesson content in the virtual learning environment. In addition, our findings indicate that the specificity of a priming intervention is one crucial determinant for explaining the mechanism through which a usefulness intervention becomes effective for students' learning.

In sum, the learning-usefulness intervention helped students better engage with the learning content and be less distracted by the seductive aspects of VR that could hinder learning. Indeed, students who received such an intervention selected the virtual information more deliberately and spent more time focusing on the relevant visual information. This strategy was revealed to be beneficial, as their performance on the knowledge test after the virtual lesson was also better than that of their counterparts who did not receive the priming intervention. Finally, using the VR headsets with integrated eye-trackers helped to provide much needed evidence for the cognitive processes beneath the effects of typical usefulness interventions and showed the extent to which a parsimonious intervention can enhance VR's effectiveness for teaching and learning.

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Table 1

Summary of All Included Eye-Tracking Variables (Including the Type, the Definition, and the Associated Cognitive Processes)

Eye tracking variables	**Definition**	**Associated cognitive processes**	**References**
Fixations	Maintenance of the eye gaze on specific locations of interest for a certain time span	Information processing; acquisition and interpretation of the presented visual information	Behroozi, et al., 2018; Hoffman, 1999; Keskin et al., 2020
Fixation duration	Time spent maintaining the eye gaze on a specific location of interest (during a fixation)	Indication of students' attention to specific information; time invested in processing the virtual information	Keskin et al., 2018; Keskin et al., 2019;Walter & Bex, 2021;
Fixation number	Number of times the eye gaze was maintained on specific locations of interest	Indication of how much students change their visual attentional focus (input processing from certain locations of interest to others)	Walter & Bex, 2021; Zagermann et al., 2016
Saccades	Fast eye movements that occur between two fixations	Indicators of how students explore the learning materials; association with mental effort and cognitive load	Keskin et al., 2020; Rayner & Kliegl, 2012;
Saccade amplitude	Distance traveled by the eye between two fixation points	Involvement in students' selection of visual information; association with mental effort and cognitive load	Rayner & Kliegl, 2012; Walter & Bex, 2021; Zagermann et al., 2016

Saccade number	Number of saccadic eye movements in a certain time span	Association with visual attention deployment; negative relationship between increasing task difficulty and saccade number	Nakayama et al., 2002; Mahanama et al., 2022
Saccade velocity	Speed of the saccadic eye movement	Indication of how quickly students explore the learning materials; association with concentration and cognitive load	Behroozi et al., 2018; Keskin et al., 2020
Saccade duration	Amount of time taken to complete a saccade	Indication of how quickly students change their attention from a location of interest to another; strong association with saccade velocity	Rayner, 2009; Walter & Bex, 2021;
Blinking behavior	Reflexive, voluntary, or spontaneous movements to close and open the eyes rapidly	Association between endogenous eye blinks and attentional processing and mental effort	Irwin & Thomas, 2010; Stern et al., 1984
Blink rate	Frequency of (endogenous) blinks per unit of time	Perception of the visual information; Negative association with task difficulty or cognitive load	Irwin & Thomas, 2010; Kramer, 1991
Blink duration	Duration of a blink (time during which the eye is closed before the next opening)	Perception of the visual information; Negative association with cognitive load	Appel et al., 2021; Irwin & Thomas, 2010; Kramer, 1991
Pupil diameter	Average change in the pupil's size during a specific period	Reliable indicator of cognitive and affective information processing when variation in illumination can be held constant	Hyönä et al., 1995; Partala & Surakka, 2003

Table 2

Threshold Identification for Eye-Tracking Features (Fixations and Saccades)

Events	Conditions for velocity (v)	Conditions for duration (Δ)	Angular difference threshold
Fixations	50°/s > v	80ms < Δ > 600ms.	~2.29°
Saccades	80°/s < v	30ms < Δ > 80ms	-

Table 3

Descriptive Statistics [M ± SD or n (%)] for Demographic Variables and Mean Values on Background Variables Related to Biology, Prior Experience With VR, and Perceived Usefulness of VR in the Three Groups, Randomized to the Learning-Usefulness, Daily-Life-Usefulness, and Control Conditions

Variables	Learning usefulness *n* = 69	Daily-life usefulness *n* = 52	Control *n* = 50	Homogeneity test *p*-value	ANOVA *p*-value
Demographics					
Age	15.5 (0.66)	15.5 (0.70)	15.7 (0.75)	$p = .734$	$p = .376$
Gender[a]					
Female	32 (0.46)	33 (0.63)	22 (0.44)		
Male	37 (0.54)	19 (0.37)	28 (0.56)		
Biology-related variables					
Grades	2.21 (0.76)	2.33 (0.87)	2.38 (0.98)	$p = .115$	$p = .569$
General interest	2.78 (0.77)	3.06 (0.63)	2.81(0.71)	$p = .386$	$p = .086$
Self-concept	3.01 (0.57)	3.05 (0.53)	2.94 (0.64)	$p = .408$	$p = .695$
VR-related variable					
Prior experience	2.11 (0.54)	2.19 (0.49)	2.18(0.50)	$p = .287$	$p = .606$
Manipulation check					
Perceived usefulness of VR	3.54 (0.33)	3.55(0.58)	3.39(0.36)	$p = .850$	$\mathbf{p = .032}$

Note. A one-way ANOVA for background variables related to biology and prior experience with VR was conducted to compare the three groups' mean values. Homogeneity of variance was also assessed using Levene's test to ensure equal variances for each relevant variable, and the *p*-values for each analysis are reported. Values in bold indicate statistically significant results. [a] A Chi-square test (two-tailed) was calculated to assess the distribution of gender in the three conditions, $X^2(2, N = 171) = 4.80, p = .091$.

Table 4

Descriptive Statistics [M ± SD] for Learning Outcomes and Eye-Tracking Variables in the Three Groups, Randomized to the Learning-Usefulness, Daily-Life-Usefulness, and Control Conditions

Variables	**Learning usefulness**	**Daily-life usefulness**	**Control**
Sample size	*n* = 69	*n* = 52	*n* = 50
Students' learning outcomes			
Interest in the virtual lesson	3.53 (0.48)	3.51 (0.53)	3.56 (0.50)
Learning achievement	7.71 (2.66)	7.21 (2.75)	6.70 (2.80)
Fixation-related variables			
Fixation duration (ms)	168.39 (17.20)	159.79 (15.87)	157.33 (16.94)
Fixation number (No.)	966.25 (217.01)	973.52 (209.34)	955.08 (190.20)
Saccade-related variables			
Saccade amplitude (°)	7.55 (1.80)	7.31 (1.32)	6.77 (1.83)
Saccade duration (ms)	47.93 (1.23)	47.87 (1.37)	47.97 (1.00)
Saccade number (No.)	1185.5 (275.24)	1161.44 (246.17)	1129.88 (251.21)
Saccade velocity (°/s)	140.72 (34.70)	146.92 (36.71)	150.94 (36.88)
Pupillometry			
Pupil diameter	1.02(0.11)	0.98(0.13)	1.01(0.13)
Blink-related variables			
Blink rate (No./min)	7.76 (5.80)	8.39 (4.92)	8.53 (5.01)
Blink duration (s)	0.16 (0.02)	0.16 (0.02)	0.16 (0.02)

Note. Values for saccade number and fixation number are the average number of saccades and fixation for the whole experiment. The values for pupil diameter represent the normalized mean values.

Table 5

Summary of Regression Analyses for Students' Eye-Tracking Features, Pupil Diameter, Blinking Behavior, and Learning Outcomes (N = 171)

	Learning usefulness vs. control				**Daily-life usefulness vs. control**				**Learning vs. daily-life-usefulness**			
Variables	**Direct effects**											
	B	***SE***	**β**	***p***	**B**	***SE***	**β**	***p***	**B**	***SE***	**β**	***p***
Learning outcomes												
Interest in the VR lesson	-0.03	0.07	-.03	.631	-0.05	0.09	-.04	.627	-0.01	0.07	-.01	.860
Learning achievement	1.01	0.35	.18	**.004**	0.51	0.29	.09	.080	-.50	.38	-.08	.196
Eye-tracking features												
Fixation number	0.00	0.02	.01	.945	0.01	0.028	.03	.810	0.01	0.02	.03	.810
Fixation duration	0.03	0.01	.31	**< .001**	0.01	0.012	.07	.558	-0.02	0.01	-.22	**.009**
Saccade number	0.02	0.01	.09	.117	0.01	0.013	.06	.360	-0.01	0.01	-.03	.551
Saccade duration	0.00	0.00	-.02	.713	-0.00	0.00	-.04	.404	-0.00	.00	-.03	.408
Saccade amplitude	0.06	0.02	.22	**.007**	0.05	0.02	.18	**.023**	-0.01	0.01	-.03	.451
Saccade velocity	-0.03	0.03	-.12	.248	-0.01	0.03	-.04	.703	0.02	0.02	.07	.179
Mean pupil diameter	0.01	0.00	.08	.069	-0.01	0.01	-.11	.201	-0.02	0.01	-.18	**.013**
Blink rate	-0.09	0.06	-.14	.149	-0.01	0.05	-.01	.874	0.08	0.06	.12	.162
Blink duration	0.00	0.01	.01	.891	0.02	0.01	.13	**.049**	0.01	0.01	.12	**.020**

Note. Values in bold indicate statistically significant results.

Table 6

Correlation Matrix for Students' Eye-Tracking Features, Pupil Diameter, Blinking Behavior, and Learning Outcomes (N = 171)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Learning achievement	1									
Interest in the VR lesson	.05	1								
Fixation number	.10*	.09	1							
Fixation duration	.16*	.10**	.19	1						
Saccade number	.01	.03	.02	-.47***	1					
Saccade duration	-.08*	.01	.01	-.33***	.31***	1				
Saccade amplitude	.22**	.03	.25*	.28***	-.14*	-.22**	1			
Saccade velocity	-.08	.12	-.04	.09	-.07	-.12	.02	1		
Mean pupil diameter	-.06	.08	.00	-.05	.07	.04	-.22	-.01	1	
Blink rate	-.04	-.12	-.13	-.20**	-.27***	.02	-.17***	-.02	.01	1
Blink duration	-.19***	-.15*	-.08	-.16*	-.02	.24***	-.29**	-.00	-.06	.22**

Note. Pearson correlations were computed for all correlations between continuous variables.

* $p < .05$. ** $p < .01$. *** $p < .001$.

Appendix A

1. Aggregation of Eye Measurements

To calculate fixation- and saccade-related measurements, we used the gaze vectors of both eyes. A gaze vector is the approximate direction of a person's view, determined by the orientation and location of the pupil within the eye. This direction is represented as a 3D vector in the local coordinate system. This means that it shows the direction of the gaze in relation to the location and orientation of a person's face, with the pupil as the origin. Therefore, two gaze vectors can be measured for each eye, starting at each pupil and pointing away from the face into the environment. Because both vectors are measured at every time point (around every 30 ms), the gaze vector can be used to detect eye and gaze movement.

1.1 Fixations

To calculate fixations, we used two main indicators, namely, (a) thresholds based on gaze velocity and duration and (b) the gaze similarity of the left and right eyes in terms of their direction and parallelism. In a first step, we detected eye movements as fixation candidates similar to previous work (Agtzidis et al., 2019; Salvucci & Goldberg, 2000) if their gaze velocity was less than 50°/s and the duration of such events was between 80 ms and 600 ms.

Next, we computed the angular differences between the gaze vectors of each eye. In order for a person to fixate on an object or specific location in the virtual learning environment, their eyes must be aligned, which results in slightly different directions for each eye due to the distance between them. Accordingly, we calculated fixation when the angle between two gaze vectors was larger than the arccosine (0.999). The magnitude of this value depends on the distance from the object, but it does not depend on the object's location in a person's Field of View (FOV).

By contrast, if a person is focusing on a specific location, the gaze direction of each eye should not be parallel. Because we were interested in knowing when a person was concentrating on a specific object, we combined the gaze velocity and angular difference variables to compute the period in which the participant was gathering visual information. As stated before, we assumed that these periods of information intake are correlated with learning. Therefore, we applied an empirical angular difference threshold of ~2.29°. If the angle between the eyes was greater than this threshold, we identified them as fixations. This assumption and the angular difference threshold were well-aligned with the accuracy of the integrated eye-tracker (0.5° to 1.1°) that we used during the experiments. Overall, once a set of observations passed these thresholds, they were identified as fixations.

We used the fixations that were detected by applying the aforementioned procedures to calculate the number of fixations for the complete experiment, the number of fixation periods per minute, and the mean fixation durations.

1.2 Saccades

To detect saccades, we applied speed- and duration-based thresholds as proposed by the eye-tracking literature in the VR domain (e.g., Agtzidis et al., 2019). We detected saccades when the gaze velocity was greater than 80°/s and the duration of such movement was between 30 ms and 80 ms. After detecting the saccades, we calculated the mean saccade duration, the saccade amplitude, the saccade velocity, and the overall number of saccades.

1.3 Pupil diameter

We used the mean pupil diameter as the third eye-tracking measurement. This information about the size of each pupil was also automatically assessed and preprocessed by the integrated eye-tracker.

As pupil diameter values can differ from person to person on the basis of biological factors or instant circumstances, before the actual analysis, we applied a median-based divisive baseline correction. To do so, we used a baseline duration of ~1 s based on Mathôt et al.'s

(2018) work for normalization. Once the pupil diameters were normalized, we calculated the mean pupil diameters.

1.4 Blinking behavior

From the pupil information measured by the eye-tracking system, we were also able to identify a person's blink rate and blink duration. To do so, we used the methods proposed in Hershman et al. (2018) and Kret and Sjak-Shie (2019). Because the eye-tracker does not detect blinks separately, we identified the blinks afterward from pupil size information. Therefore, we created a combined pupil diameter variable by taking the mean value of the size of the pupil in each eye.

In general, blinks lead to missing data in the pupil diameter variable because the size of the pupil cannot be detected by the eye-tracker when a person's eye is closed. However, missing values in the pupil diameter variable are due not only to blinking but also potentially from recording problems with the eye-tracker (e.g., due to technical errors). Therefore, a specific type of preprocessing must be used to identify the intervals that were caused by blinking, whereas the other missing data intervals must be rejected.

To achieve this separation, the applied method uses pupil dilation speed as a variable to separate blinks from other error sources (Kret & Sjak-Shie, 2019). Pupil dilation speed is the change in the size of the pupil from one time point to another. Closing and opening the eyes leads to a continuous increase in dilation speed. Right before and right after blinking, the eye-tracker can only detect parts of the pupil, and therefore, pupil size decreases before a blink and increases after it. In comparison, pupil size artifacts caused by detection errors lead to a larger increase in pupil dilation speed, resulting in spikes in the size of the pupil. Therefore, we set a threshold for the dilation speed and removed the intervals with spikes.

To get a more sensitive measure of dilation speed, we first increased the number of frames per second. Between two existing time points, we interpolated the pupil size for two additional time points with a third-order polynomial interpolation. This allowed us to identify changes in pupil size more accurately. Then, "the dilation speed at each sample […] is calculated as the maximum absolute normalized change relative to either the preceding or the succeeding sample" (Kret & Sjak-Shie, 2019, p. 1338).

$$d'^{[i]} = \max\left(\left|\frac{d[i]-d[i-1]}{t[i]-t[i-1]}\right|, \left|\frac{d[i+1]-d[i]}{t[i+1]-t[i]}\right|\right).$$

$$d'^{[i]} = max\left(\left|\frac{d[i]-d[i-1]}{t[i]-t[i-1]}\right|, \left|\frac{d[i+1]-d[i]}{t[i+1]-t[i]}\right|\right)$$

Where d[i] is a pupil size series with a corresponding timestamp t[i].

We set the threshold for dilation speed by using the median absolute deviation (MAD), calculated as:

$$MAD = median\left(\left|d'^{[i]} - median(d')\right|\right) \quad (2)$$

$$Threshold = median(d') + n \cdot MAD \quad (3)$$

We set the constant n to 30. To remove the spikes caused by detection errors, we considered intervals of missing data as blinks only when the pupil size before and after the interval contained values that were below the mean pupil size. Then, we set the starting point of the blink interval to the first value of the dilation speed that was above the calculated threshold and the end of the blink to the last point above the threshold, with a period of at least one missing pupil size data point in between.

After that, we considered only intervals that were larger than 0.1 s and smaller than 0.4 s to capture the range of human blink duration set by the Harvard Database of Useful Biological Numbers (2022).

With these remaining intervals, we calculated blink duration as the average length of the intervals and blink rate as the average number of blink intervals per minute.

6

GENERAL DISCUSSION

6 General Discussion

The use of immersive VR in science education has drastically increased in the last two decades as VR has become more affordable and capable, offering students unique opportunities to experience learning content and play an active role in the learning process. However, despite VR's unique affordances and embedded motivational and hedonic factors—that are supposed to increase students' intrinsic motivation, interest in, and engagement with the learning content—its effectiveness as a learning tool lags behind its potential and expectations. Among the reasons often advanced for this lack of effectiveness are the insufficient pedagogical and motivational support in VR and the embedded hedonic elements that can also distract students from their learning goals and increase their cognitive load. Most current attempts to improve VR's effectiveness are not always practical. In addition, they are primarily based on cognitive theories (e.g., CLT and CTML), which have been criticized for their failure to specify the role of motivation in the cognitive processing of learning content in multimedia (Astleitner et al., 2006; Astleitner & Wiesner, 2004; Brünken et al., 2010; R. E. Mayer, 2014). At the same time, it has been proposed that motivation and cognition are linked, and integrating motivation into learning instructions can facilitate effective cognitive processing (Astleitner, 2018; Astleitner et al., 2006; Astleitner & Wiesner, 2004); this approach is referred to in this dissertation as the integrative approach. Therefore, this dissertation aims to integrate motivational support into virtual learning simulations to increase VR's effectiveness in science education.

Based on the CTML and empirical research on motivation (e.g., TAM, EVT, and the integrative approach), I propose that integrating motivational support into virtual simulations as part of the learning instructions can foster students' positive attitudes toward learning with VR, help them to stay focused on their learning goals, and, more importantly, facilitate their processing of the learning content. Notably, generative processing is fundamental for effective learning: it involves selecting relevant informational elements (avoiding distractions), building mental and structural relationships between these elements, and integrating them into prior knowledge. According to CTML, generative processing is caused by students' motivation (Mayer, 2022). To operationalize motivation and vary motivational support in VR, I relied on TAM and EVT, which also highlight the role of motivation in learning. On the one hand, TAM posits that perceived usefulness plays a fundamental role in learning with multimedia because it increases students' acceptance of the learning tool, which in turn affects their learning outcomes. However, most studies on TAM do not use experimental designs to test the effects of different levels of perceived usefulness on acceptance nor account for the impact of acceptance on students' learning achievement.

On the other hand, EVT provides a large body of research showing how to increase students' motivation in traditional classroom settings by conducting parsimonious but effective usefulness interventions that facilitate learning. Therefore, combining the strengths of the two theories provides a solid basis for conducting the usefulness interventions involving students' perception of VR as a learning tool. The usefulness interventions were integrated into the virtual learning simulation as a form of motivational support that was expected to enhance students' learning outcomes.

Accordingly, this dissertation pursued three main objectives: First, it tested whether integrating classical usefulness interventions into a virtual learning environment could also enhance VR's effectiveness. More concretely, this dissertation assessed how such parsimonious interventions affect students' presence, interest in the virtual lesson, and learning achievement. Second, this dissertation investigated the assumptions of the TAM; that is, whether students' acceptance of VR as a learning tool can be increased through usefulness interventions and whether acceptance subsequently affects students' outcomes. More concretely, this dissertation tested how students' acceptance is related to their presence, perceived learning, and learning performance. Third, this dissertation tested how integrating motivational support in VR affected students' visual attention and cognitive processing of the lesson content. Simply put, this dissertation examined whether integrating usefulness interventions into the virtual learning simulation led to better processing of the learning content (assessed through eye movements) and tested how students' eye movements were related to their learning outcomes.

These three main objectives were addressed in three studies (see Chapters 3, 4, and 5). In these studies, we applied an experimental approach and used multimodal methods (e.g., self-report paper-pencil tests, questionnaires in VR, knowledge tests, and eye-tracking analysis). In the present section, I will first summarize the main research findings of these three studies (Section 6.1). Then, I will discuss this dissertation's significance and theoretical contributions (Section 6.2) and highlight its practical and educational contributions (Section 6.3). In addition, I will acknowledge the strengths and limitations of the present dissertation (Section 6.4) and make recommendations for future research in this field (Section 6.5). Finally, I will present an overall conclusion (Section 6.6).

6.1 Empirical contributions

Regarding the first objective, namely whether traditional classroom interventions based on EVT could also enhance VR's effectiveness in science education, this dissertation provides the following findings (Study 1): first, the results showed that both usefulness interventions (learning usefulness and daily-life usefulness) were capable of increasing students' perceived usefulness of VR as a learning tool. Second, students who benefited from the interventions tended to report lower presence in VR but had better learning performance compared to those who did not receive any motivational support in VR. Third, the results also revealed that students' presence in VR was positively associated with situational interest but was not related to their learning achievement. Similarly, there was no relationship between situational interest and learning achievement.

The second objective was to assess the role of acceptance—in terms of intention to use VR—in students' learning experience in VR and learning performance. Particularly, this dissertation tested whether students' acceptance of VR as a learning tool can be increased through usefulness interventions and whether acceptance subsequently facilitates students' learning experience in VR (e.g., presence) and enhances learning (Study 2). The results showed that only the specific usefulness intervention (learning usefulness intervention) led to a higher acceptance of VR as a learning tool, suggesting that the specificity of the priming intervention may play an important role in fostering students' acceptance of VR as a learning tool. Moreover, structural equation modeling indicated that students' acceptance led to higher presence in VR, which was positively associated with perceived learning but negatively with learning achievement. The results also showed that induced acceptance positively affected perceived learning but did not affect learning achievement. Finally, when controlling for the effect of acceptance and presence, the findings showed that students who did not receive any usefulness intervention reported higher perceived learning, but in reality, they had worse learning performance than those who received the learning usefulness intervention.

With respect to the third objective, namely to investigate how integrating motivational interventions into immersive learning affects students' cognitive processing of the lesson content, the empirical contributions are threefold: first, using an eye-tracking-based approach confirmed previous research (Liaw & Huang, 2013; Makransky & Lilleholt, 2018; Song et al., 2021) suggesting that students' perceived usefulness of VR positively affects their learning experience in VR. Second, it supported the assumption that integrating motivational support into VR can help students process the learning content better. Students who received the learning usefulness intervention had higher average saccade amplitude and fixation duration than those who did not. Third, saccade amplitude and fixation duration—which are involved in selecting and processing visual information, respectively—were positively related to learning achievement.

6.2 Theoretical contributions

In line with previous research arguing in favor of the integrative approach—integrating motivation into cognitive theories of multimedia learning (Astleitner, 2018; Astleitner et al., 2006; Astleitner & Wiesner, 2004), this dissertation shows how the integration of motivational support into virtual learning simulations can be beneficial for learning. First, this dissertation shows how established classroom motivation interventions from the EVT can be applied to learning with VR. Second, it supports the assumptions from TAM by showing how the acceptance of VR as a learning tool can be experimentally increased and how acceptance, in turn, affects students' learning experience in VR and learning outcomes. Most importantly, it reveals, in accordance with the CTML, how such motivational support can facilitate effective processing of the learning content in VR and enhance students' learning achievement. Accordingly, this dissertation provides important insights regarding the role of motivation in learning, more specifically, how integrating motivational support into VR influences students' perceptions, attitudes, cognitive processing, and learning outcomes. Thereby, the dissertation makes substantial contributions to the educational and psychological field of research regarding the use of VR in education. I will discuss these contributions from the perspective of the CTML and the integrative approach (integration of motivation into cognitive theories), the TAM, and EVT in this section.

Fundamental prerequisites for effective learning in VR: perceived usefulness, acceptance, and goal orientation

Virtual learning simulations, like edutainment content in general, positively affect students' motivation, which can facilitate learning (W. Huang et al., 2022; Klingenberg et al., 2020; Makransky & Mayer, 2022); paradoxically, motivation can also hinder learning due to overstimulation and distractions (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2021). The fundamental issue in learning with VR—which offers unique affordances and entails embedded hedonic and motivational elements—is how to create the appropriate conditions for effective learning. Using insights from the integrative approach and EVT, the three studies integrate either a specific video priming intervention (VR is useful for learning) or a more general priming intervention (VR is useful in daily life) into the virtual learning simulations as part of the learning instruction. The studies found that this parsimonious approach led to higher perceived usefulness of VR as a learning tool, greater acceptance of VR, and affected students' learning outcomes. Therefore, the empirical evidence of this dissertation suggests that integrating motivational support into VR implicitly guides students toward the instructional objectives, putting students in the appropriate mindset for learning. This has overreaching effects on their perception (perceived usefulness and acceptance), metacognition (attitude and judgment), goal-oriented behavior and cognition (assessed through eye movements), and learning outcomes.

Previous research on EVT has established that usefulness interventions have major impacts on students' motivational factors, achievement-related behavior (self-concept, effort, persistence, etc.), and learning outcomes in traditional classroom settings (Anderman et al., 2001; Brisson et al., 2017; Eccles et al., 1983). This dissertation provides evidence suggesting that such interventions can also enhance students' learning experience and foster their processing of the learning content in VR. In this regard, the analysis of the eye-tracking data reveals that the learning usefulness intervention led to higher average saccade amplitude (involved in visual task selection) and higher fixation duration (involved in the processing of visual information). Both average saccade amplitude and fixation duration were positively related to learning achievement. From a metacognitive perspective, the priming interventions may have prompted students to think about the learning objectives, facilitating goal-oriented VR actions. Previous research has shown that such priming interventions can trigger information-seeking behavior (Savolainen, 2012) and goal-oriented behavior (Chen et al., 2020; Latham & Locke, 2018; Latham & Seijts, 2016). Therefore, by indirectly emphasizing the learning goals, the learning usefulness intervention created a learning context in which students prioritize the processing of task-relevant visual information (Ford et al., 2010; Van der Heijden, 1992). Consequently, the learning usefulness intervention led to better processing of the learning content in VR.

Although hedonic elements in a given learning tool can also influence students' acceptance of such tools (Dimitrijević & Devedžić, 2021; Estriegana et al., 2019; van der Heijden, 2004), research on TAM has indicated that perceived usefulness is the most important and reliable predictor of students' acceptance (Ma & Liu, 2004; Yousafzai et al., 2007a, 2007b). According to TAM, acceptance is a prerequisite for effective learning with multimedia (Davis, 2011; Merchant et al., 2014); it creates the condition for students to engage with the learning content. The results of this dissertation provide some evidence for this assumption, showing that acceptance had a significant effect on presence. Another recent study also showed a positive relationship between acceptance and presence (Plotzky et al., 2021). Expressly, this dissertation indicated that priming students to perceive VR as useful for learning led to higher acceptance, which subsequently enhanced their perceived presence in VR. However, the empirical evidence raises more questions than answers when it comes to the effect of acceptance on learning outcomes. Acceptance had a positive effect on perceived learning (affective outcome) but was not associated with learning achievement (cognitive outcome). The surprising lack of research on the effects of acceptance on learning performance makes it difficult to interpret these results. Since acceptance—also characterized as behavioral intention—implies the intention to use VR for learning purposes, I propose that acceptance increases students' willingness to engage with the lesson content in VR, which can lead to regular usage for learning purposes (Juarez Collazo et al., 2014; Larmuseau et al., 2018; Turner et al., 2010); if this premise is correct, then the possible effects of acceptance on students' learning performance will mostly manifest over time. This could explain why that acceptance only partially affected students' learning experience in learning in VR.

Relationship between motivation and cognition

The assumption that integrating motivational support into VR can enhance its effectiveness is based on the premise that motivation and cognition are linked (Astleitner & Wiesner, 2004; Finn, 2020; Pintrich, 2003) and that students need pedagogical support to take full advantage of VR (Mayer et al., 2022). Learning with VR can be very motivating and engaging because of its affordances and hedonic characteristics. At the same time, maximizing learning in VR requires students to be engaged in the learning process and avoid possible distractions due to hedonic factors. On the one hand, it has been argued that hedonic factors in VR can induce positive emotions, which increase motivation, thus facilitating learning (Makransky, Borre‐Gude, et al., 2019; Makransky & Lilleholt, 2018; Tang et al., 2022). On the other hand, those same hedonic factors can be distracting and cause overstimulation, which can lead to cognitive overload, hindering learning (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2018, 2020). Consequently, interventions to support students' learning goals become a balancing act between the experience and enjoyment of the learning process and the motivation to learn. The empirical evidence of this dissertation suggests that priming students to perceive VR as useful for learning or daily life constitutes adequate motivational support that subtly makes the learning goals more salient and indirectly reminds them why they are in the virtual learning environment in the first place. Such motivational support affects both their affective and cognitive learning outcomes.

Motivation support and affective processing in VR

The findings of this dissertation indicate that providing students with motivational support reduced their perceived presence in VR and led to lower perceived learning. At first glance, these results seem counter-intuitive, but a deeper analysis of how human factors (e.g., emotion and perception) can also affect presence and perceived learning and how this kind of intervention can influence affective processing could help explain these results.

Perceived presence in VR

Presence is an essential prerequisite for immersive learning because it involves a sense of emotional involvement (Huang et al., 2019; Witmer et al., 2005) in the virtual learning environment: it allows students to feel physically there in the virtual learning environment (Held & Durlach, 1992; IJsselsteijn & Riva, 2003; Minsky, 1980b), which could facilitate their engagement with the learning content (Claman, 2015; Vrellis et al., 2016). The literature is consistent in the assertion that a higher level of immersion leads to a greater sense of presence in VR (Cummings & Bailenson, 2015; Makransky & Lilleholt, 2018; Makransky & Mayer, 2022; Makransky, Terkildsen, et al., 2019). Different factors (e.g., control, sensory fidelity, high-quality interface, vividness, interactivity, etc.) have been presented to facilitate presence in the virtual learning environment (Cummings & Bailenson, 2015; Slater & Usoh, 1993; Witmer & Singer, 1998). In this same line, it has been proposed that immersion and interactivity in VR lead to greater presence, which has positive effects on various motivational hedonic factors in VR (Makransky & Petersen, 2021; Petersen et al., 2022). However, very little attention has been given to the impact of students' attitudes, emotions, or goals on their perception of presence in the learning environment. In this regard, Avram et al. (2014) argued that in addition to these interface and control factors, learners' characteristics can further help understand the concept of presence in VR.

With regard to the effect of students' characteristics on presence, Avram et al. (2014) showed that negative expectations regarding the virtual session led to lower perceived presence. The authors cleverly manipulated expectations by having an accomplice comment negatively about his virtual experience while he was in VR next to the participant. This further supports the idea that priming students before a learning session in VR could influence their whole experience. Accordingly, the empirical results from this dissertation showed that priming students to perceive VR as useful for learning reduced their perceived presence in VR but increased their learning achievement. It is worth noting that these interventions reduced presence but did not completely shut down students' emotional involvement and situational interest, as the results showed that students across all conditions reported a considerable level of presence and interest in the virtual lesson (a mean above the scale midpoint). In addition, there was no difference between the different conditions in terms of interest in the virtual lesson.

Using eye-tracking data, the results of this dissertation provide additional details showing that the interventions helped students be more selective with regard to which stimuli they paid attention to, leading them to process the learning content more effectively. These results are in line with those of a meta-analysis on learning with serious games (Wouters et al., 2013). The authors found that serious games were more effective than conventional instructional methods but did not have a higher motivational appeal, which, based on the hedonic value of these games, should be higher. Similar to the added-value approach, the results also showed that students learned much better with serious games when additional learning strategies were added to them. Analog to Wouters et al. (2013) explanation for reduced motivation in serious games, motivational support and other learning prompts that aim to help students focus on the learning goals may undermine the entertainment aspect of the virtual learning simulations, thus reducing students' perceived presence.

Reducing the level of presence could have been beneficial for learning, as the results showed that presence was positively related to interest and perceived learning but was not (or negatively) associated with actual learning. However, this result should be interpreted with caution, for the current empirical literature is still inconsistent in this regard (Ahn et al., 2022; Krassmann et al., 2019; Morélot et al., 2021). Since presence is fundamental for learning in immersive VR and too much presence can be overstimulating and hinder learning, it seems that an optimal level of presence is necessary for presence to impact learning positively. Therefore, it could be that there is a quadratic relationship between presence and learning achievement: very low and very high levels of presence could lead to lower learning performance, and an optimal range (medium to high) could increase learning performance.

Perceived learning and actual learning

Another interesting finding of this dissertation is the opposite effects of the interventions on students' perceived learning and actual learning. When controlling for the effects of presence and acceptance, the dissertation found that students who received the priming interventions in VR reported lower perceived learning but learned more than those who did not. Stated differently, students who did not receive the priming interventions believed they had learned more but had lower learning achievement. It seems like being in the virtual learning environment and being able to interact with the learning content are enough for students who did not benefit from the motivational support to perceive a high level of learning performance. These results suggest that the interventions created the appropriate learning context that made the learning goals more salient and the hedonic aspects of learning with VR less predominant.

This has major consequences on students' effort to process the learning content (exemplified by the eye-tracking data), their learning performance, and their metacognition and judgment about their learning performance (perceived learning and actual learning).

In accordance with the present results, previous studies have demonstrated that students' engagement and mental effort in the learning materials led to lower perceived learning (Deslauriers et al., 2019; Van Sickle, 2016). For instance, Barzilai and Blau (2014) showed that adding an external scaffold before a game-based learning scenario about financial-mathematical real-world problems (i.e., balancing cost and price in an online restaurant game) reduced learners' perceived learning. Similarly, Deslauriers et al. (2019) found that students in passive learning environments learned less but reported higher perceived learning than their counterparts in active learning environments. It has also been shown that when students perceived a learning strategy to be more effortful, they also perceived it as less effective and were less likely to use it (Kirk-Johnson et al., 2019; Macaluso et al., 2022), even if this learning strategy was actually more effective (Macaluso et al., 2022). Such inaccurate learning judgments are referred to as the misinterpreted-effort hypothesis regarding students' self-regulated learning strategies (Kirk-Johnson et al., 2019). This posits that learners based their perception of the effectiveness of a learning strategy on the mental effort they exerted (Kirk-Johnson et al., 2019). It seems that the mismatch observed in this dissertation regarding students' judgment of their perceived learning and actual learning results from students exploring the learning environment without adequate guidance and motivational support.

The empirical evidence of this study also seems to give some merit to the warnings that edutainment can inadvertently give students the impression of learning (Okan, 2003; Resnick, 2004). Immersed in the learning environment, students can interact with the content of the lesson and enjoy the learning experience, which could create a sense of fluency (Carpenter et al., 2013). Fluency is the subjective perception of how easy or difficult it is for one to process information (Oppenheimer, 2008). A higher sense of fluency can lead to inaccurate judgment of one’s learning performance (Carpenter et al., 2013; Oppenheimer, 2008). Concretely, without proper guidance and motivational support in VR, students may have a greater sense of *fluency* and, as a result, may become overconfident in their level of understanding and therefore become more likely to put less effort in processing the learning material (Bjork, 1994; Dunlosky & Rawson, 2012). Such *fluency* may in turn negatively affect students' learning outcomes (Bjork, 1999; Koriat & Bjork, 2005; Renkl, 1999). The interventions conducted in this dissertation helped students focus on the instructional objectives and engage in appropriate processing; thus, the hedonic elements in the learning environment did not seem to distract them from their learning goals (Makransky & Lilleholt, 2018), nor did they provoke a sense of fluency (Carpenter et al., 2013) that could lead to the illusion of learning (Koriat & Bjork, 2005).

Motivational support and attentional behavior and cognitive processing in VR

Empirical results based on EVT (Eccles et al., 1983; Eccles & Wigfield, 2020) showed that usefulness interventions typically affect students' achievement-related behavior from a macro perspective (e.g., educational choice, persistence, and engagement). The results provide evidence that these interventions also affect students' cognition (from a micro perspective; Eccles & Wigfield, 2020), thus indicating a positive link between motivational support and effective processing in VR. Using eye-tracking data, this dissertation also reveals how priming students to perceive VR as useful for learning affects their attentional behavior and cognitive processing in the virtual learning environment. Concretely, students who received the learning usefulness intervention had higher average saccade amplitude and fixation duration. In addition, the results indicated that eye-tracking features that are involved in active processing (fixation duration, fixation number, and saccade amplitude) were positively associated with learning performance. However, blink duration, associated with higher cognitive load and task difficulty (Appel et al., 2021; Cho, 2021; Irwin & Thomas, 2010), was negatively related to learning achievement. Therefore, these results support the motivational assumption from the CTML, which states that students' motivation can enhance cognitive processing in multimedia (R. E. Mayer, 2014; Mayer, 2022), and offer further evidence for the effectiveness of eye-tracking methods to assess learning in VR (Clay et al., 2019; Rappa et al., 2019).

Other researchers have also argued that effective learning with multimedia requires adequate educational support (Fowler, 2015; Makransky et al., 2021; Mayer et al., 2022; Scheiter & Eitel, 2015). In this regard, different methods have been used to enhance learning in multimedia. For instance, signaling (Lemarié et al., 2008; Scheiter & Eitel, 2015) and annotations (Vogt et al., 2021) draw students toward learning by highlighting learning-relevant information. By providing motivational support in VR, this dissertation accomplishes a similar objective: whereas signaling or annotations use external prompts to focus students' attention, this dissertation uses priming, a more psychological approach, prompting students to engage in meta-cognitive processes by being aware of VR's usefulness for learning and staying focused on the learning goals. Such motivational support can facilitate effective processing in multimedia learning tools such as VR that can be both motivating and distracting. According to CTML (R. E. Mayer, 2014; Mayer, 2022), effective processing entails the reduction of extraneous processing (due to seductive details, distractions or suboptimal instruction), and engagement in essential and generative processing (selecting the relevant information, mentally organizing it and integrating it into prior knowledge).

Analysis of the eye-tracking data suggests two possible ways that integrating motivational support into VR facilitates effective processing in VR. First, higher saccade amplitude suggests deliberated choices; according to Tatler et al. (2006), saccade amplitude is involved in identifying and selecting relevant information. Therefore, students who were primed to perceive VR as useful for learning were more selective about the virtual elements they elected to pay attention to. As a result, they had significantly higher learning achievement. These results mirror those of Kickmeier-Rust et al. (2011), who showed that students who were more selective (indicated by higher saccade amplitude) also learned better. Second, a higher average fixation duration suggests that students deliberately spent more time on visual content, as most of the processing of visual information happens during fixations (Privitera & Stark, 2000). As a consequence, visual lesson content is acquired during fixation (Hoffman, 1999). The empirical evidence supports this assumption, showing that average fixation duration was positively related to learning achievement. Taken together, the data support the notion that integrating motivational support into the virtual learning simulation helped students be more selective and focused in processing the learning. This is because priming interventions that highlight VR's usefulness for learning can foster information-seeking and goal-oriented behavior in the virtual learning environment (Chen et al., 2020; Latham & Locke, 2018; Latham & Seijts, 2016; Savolainen, 2012), facilitating effective processing of learning content.

6.3 Practical and educational contributions

From a pedagogical perspective, the current literature suggests that most of the presently available virtual simulations are inadequately designed, with very little input from educational psychologists and researchers, and are not always based on established learning theories (Fowler, 2015; Radianti et al., 2020). In addition, the hedonic elements can increase students' motivation but also distract them from their learning goals, primarily because of a lack of appropriate guidance and motivational support in these virtual learning simulations (Chen et al., 2005; Fowler, 2015). Moreover, effective use of VR in education requires adequate support for teachers in order to aim them in selecting virtual simulations and preparing students for learning with VR (Chen et al., 2005; Fowler, 2015; Hamilton et al., 2020). Against this backdrop, the present dissertation provides important insights showing possible ways for educators to support their students and potentially increase their learning outcomes.

To increase VR's effectiveness, students need to be pedagogically prepared, guided, and supported, mainly because, in most cases, students will immerse themselves in the virtual learning simulations and start to explore, which could lead to distractions and overstimulation, resulting in poor learning performance (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2021). Contrary to traditional classrooms, where teachers can intervene (i.e., through appropriate classroom management and cognitive activation) to help students shift their attention to their learning goals and foster engagement in the learning content (e.g., classroom management; Fauth et al., 2020; Göllner et al., 2020; Klieme et al., 2006), students are often *left alone* during the learning session in VR (very few collaborative VR lessons are presently available). In this regard, Mulders et al. (2020) suggested that unnecessary interactions in virtual learning simulations should be reduced, and students should be offered pre-training to familiarize themselves with basic concepts related to the lesson content and to inform themselves about the tool. A recent study has also shown that students' awareness of the presence of seductive details in multimedia alone can help increase their learning performance (Bender et al., 2021).

By using classical usefulness interventions, this dissertation also shows that integrating motivation support into VR can be achieved through short priming videos that inform students about the usefulness of VR for learning or daily life. Correspondently, educators could also profit from the insights of this dissertation, suggesting that a specific usefulness intervention may be more effective than a more general intervention. Priming students to perceive VR as a useful tool for learning probably prompts them to be aware of the instructional goals; this assumption fits well with goal theory and goal-orientation theory, which suggest that priming interventions can facilitate goal-oriented behavior (Chen et al., 2020; Latham & Locke, 2018; Latham & Seijts, 2016; Savolainen, 2012). Therefore, students who received the learning usefulness intervention seemed to be more focused, more selective about the visual stimuli they paid attention to, and more capable of processing the learning content in the virtual learning environment. As adequate resources and support for educators to implement VR in their teaching are scarce, this dissertation argues that educators could adopt similar usefulness interventions to help students remain focused on the learning objectives. Based on the empirical evidence presented in this dissertation, this approach is parsimonious and effective. Therefore, this dissertation advocates that, before using VR in science education, educators ensure that students are prepared pedagogically and aware of the affordances of VR—and how VR can facilitate effective learning.

6.4 Strengths and limitations

This dissertation applied an experimental approach in its three studies and used multimodal methods (e.g., self-report paper-pencil tests, knowledge tests, and eye-tracking analysis) to test the assumption that integrating motivational support into the virtual learning environment can enhance students' learning outcomes. Although these studies provide important insights regarding the role of motivation in learning with VR, contribute significantly to the different fields of research (CTML, TAM, and EVT), and have practical implications, they also have some limitations. In this section, I will discuss the strengths and limitations of this dissertation. Concerning the strengths, I will discuss the experimental approach and its contributions to the three theories, the use of multimodal methods, and the practicability of the method used to support students' motivation in VR. Regarding the limitations of this dissertation, I will discuss the homogeneity of the sample used in these studies, the types of knowledge considered, and key variables that are implied but were not assessed.

Strengths of this dissertation

The framing and the experimental approach

This dissertation frames the use of virtual reality in edutainment contexts with two key characteristics (affordances and hedonic elements), which allows me to show how the hedonic aspect of VR can motivate students but also impair their learning (Makransky et al., 2021; Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2020, 2021). This also allows for pinpointing the utilitarian aspect of learning with VR and conducting interventions to reinforce this aspect by applying established motivational interventions. Based on CTML (Mayer, 2022), students' motivation is fundamental for effective processing of the learning content (selection, organization, and integration). However, integrating motivational support into VR requires a careful strategy because motivational elements can also distract and increase students' cognitive load, thus hindering effective learning (R. E. Mayer, 2014; Mayer, 2022). To manipulate motivation, this dissertation relies on the EVT, which, contrary to TAM, provides different methods and strategies to conduct usefulness interventions generally in traditional classroom settings.

With the support of a professional speaker, we created two short priming videos—a specific usefulness intervention (VR is useful for learning) and a more general usefulness intervention (VR is useful in daily life)—which were integrated into the virtual learning simulation as part of the instruction before the learning session. This allowed us to successfully integrate motivational support into VR without overwhelming the students, stopping the flow of the virtual lesson, or making them aware of the intervention. Prior to the main data collection, which was conducted in ten different German high schools (academic track), the priming videos were tested with a convenience sample (first-year college students) in order to assure that they met the purpose of the studies. Finally, a power analysis was conducted to ensure that at least a minimum sample size was secured to test the assumptions presented in the studies.

This experimental approach has far-reaching implications for the CTML, the EVT, and the TAM. First, it shows how motivational support positively affects students' processing in VR (supporting the motivational assumption of the CTML). Second, it supports the idea that established classroom usefulness interventions can be adapted for VR, and such interventions can also increase students' learning outcomes. Moreover, it shows support for the micro assumption of the AVT, now named SEVT (Eccles & Wigfield, 2020). Third, it supports the assumption of TAM that perceived usefulness is a strong predictor of acceptance. To the best of my knowledge, this is the first study to conduct a usefulness intervention in order to test this assumption.

Multimodal methods

To test the assumption that integrating motivational support into VR will enhance students' learning outcomes, a variety of methods were used, including self-reported pre-and posttests, integrated questionnaires in VR, eye-tracking data, and a knowledge test. Below, I discuss briefly how each method was implemented and how the combination of all of these methods allowed a better interpretation of the findings of this dissertation.

First, as is commonly the case, the self-report pretest gave information about students' background, prior experience with VR, and interest and self-concept in biology. The posttest provided information about students' experience in VR. Second, the integration of three different scales (perceived usefulness for learning, acceptance of VR as a learning tool, and perceived presence) in the VR questionnaire was very innovative and required the technical support of my colleagues. Students' perceived usefulness of VR and acceptance of VR as a learning tool were assessed directly after the manipulation and before the lesson to make sure that the learning experience and the difficulty of the lesson did not affect students' perceptions of VR as a learning tool. Moreover, it was assumed that it was more appropriate to measure presence directly after the lesson—when students were still in the virtual learning environment—than to wait until after the lesson and use a paper-pencil test. To answer questions in VR, students used the VR controller. Third, these studies used a modern VR headset with integrated eye trackers that are able to capture students' eye movements, blinking behavior, and pupil dilatation; these variables are linked to cognitive processing during learning (Bicknell et al., 2020; König et al., 2016; Nikolaev et al., 2014; Rayner, 2009; Rayner & Kliegl, 2012; Zagermann et al., 2016, 2018) and can be used to infer students' attention, selection of relevant visual information, and processing of the learning content. Fourth, the knowledge test used in this dissertation was previously tested and used in research by Parong and Mayer (2018).

Each of these methods measured specific aspects and had their own justifications. However, the main strength of the dissertation in this regard is the combination of these different methods, together helping to better assess how integrating motivation into VR affects students' perceptions, metacognition, cognitive processing of the learning content, and their learning outcomes. Hence, the multimodal methods helped to better understand how the interventions enhance VR's effectiveness.

Practicability

The findings of this dissertation suggest that the usefulness interventions had significant positive effects on students' perception, processing of the learning content, and learning performance, thus enhancing learning. The methods used are very effective, practical, and easy to implement. Other researchers can reproduce the findings of these studies by applying the same parsimonious approach provided they can secure the technical support (production of high-quality priming videos with professional speakers and integration of the videos and questionnaires into VR with the help of computer programmers). Given the lack of pedagogical support in the currently available virtual simulations (Chen et al., 2005; Fowler, 2015), schools and teachers who are presently using VR for teaching can apply the insights gained from these studies. Even if they do not have the capacity to manipulate the virtual learning simulations, I would encourage teachers to make sure that their students are pedagogically prepared and aware of VR's features, affordances, and usefulness for learning before learning with VR.

Limitations of this dissertation

The sample used in this study

A sufficient number of participants (N=196) from the 10th grade (German academic-track schools) took part in these studies. Although the sample size was relatively large and there was some variability in the data because they were collected in ten different schools from different cities, the data used in the studies are from students with similar profiles (same grade and same academic track). Consequently, analyses of the data collected in the pretest revealed that the sample was relatively homogeneous. For instance, the participants did not differ in their prior experience with VR nor their affinity for biology (e.g., interest and self-concept in biology). This homogeneous sample has some advantages; for example, it made it easier to assess the effectiveness of the interventions. At the same time, it made it impossible to infer how such interventions would affect students with different levels of interest, prior knowledge, or experience with VR. It is well-documented that students' characteristics (e.g., prior knowledge, motivation, self-concept) also affect their learning outcomes, thus potentially moderating the effect of learning interventions on learning performance (Fiorella & Mayer, 2021; Paas & Kester, 2006; Plass et al., 2009; Song et al., 2016). For instance, prior knowledge can facilitate essential processing—the cognitive processing required to make sense of the learning content (Fiorella & Mayer, 2021; R. E. Mayer, 2014; Mayer, 2022). Furthermore, a recent study suggests that applying annotation in a virtual learning simulation did have an impact on students' learning outcomes, but only helped students with lower intrinsic motivation learn better (Vogt et al., 2021). Accordingly, annotations seemed to have a compensatory effect for lack of motivation. Based on these empirical findings, it can be speculated that the interventions tested in this dissertation could be even more beneficial for students with low motivation or with low self-regulation capacity because of the embedded hedonic elements.

Types of knowledge considered and the simulation used

Another important limitation of this dissertation lies in the fact that only one type of knowledge was assessed (factual knowledge). With regard to the effect of VR on different types of knowledge, the literature assumes that VR might be more suitable for procedural knowledge and less so for factual or conceptual knowledge (Makransky & Petersen, 2021). This is because the virtual environment offers endless possibilities to train and rehearse procedures (Makransky & Petersen, 2021). In fact, empirical research has revealed that VR is mostly used for practical and procedural knowledge (Radianti et al., 2020). A more recent literature review came to a similar conclusion and showed that most existing studies involving the use of VR for teacher education purposes aimed at fostering procedural knowledge (Y. Huang et al., 2021). How effective VR is in fostering different types of knowledge remains inconclusive. Cromley et al. (2023) found that VR enhanced learning and had significant effects on factual knowledge, conceptual knowledge, and transfer learning outcomes, whereas Howard (2018) showed that it had significant effects on procedural skills but not on factual knowledge when compared to other non-immersive learning tools.

Different learning strategies have been applied to increase learning in VR (Howard & Lee, 2019; Mayer et al., 2022; Meyer et al., 2019; Parong & Mayer, 2018). In a similar fashion, the empirical evidence of this dissertation suggests that motivational support increases learning and reduces presence. Since presence was negatively related to learning achievement (factual knowledge), reducing presence seems to facilitate learning. However, presence might be especially important for procedural knowledge, as VR can facilitate training and rehearsal; presence can increase different affective and cognitive factors, which enhances procedural knowledge (Makransky & Petersen, 2021). A recent study (Morélot et al., 2021) indicated that immersion enhanced procedural but not conceptual learning. In addition, the authors found that presence or the interaction between presence and immersion had no effect on procedural and conceptual learning (Morélot et al., 2021). This reignites the debate regarding the effect of presence on learning achievement. In this regard, the results of the studies making up this dissertation suggest that too much presence could be detrimental to factual learning, but does not contribute to the discussion concerning the effect of presence on procedural and conceptual learning.

With regard to learning content, the three studies used the same virtual simulation—the Body VR—which was technically modified to integrate motivational support as part of the instructions and included the scales on students' perception and acceptance of VR as a learning tool and perceived presence. Although the simulation has been tested multiple times and was used previously by different researchers (Guan et al., 2022; Loureiro Krassmann et al., 2020; Parong & Mayer, 2018), using another virtual learning simulation with different instructions and school subjects would have strengthened the generalizability of the findings. Data collection for these studies was conducted during the COVID-19 pandemic, which made it time-consuming and left very little room for the technical adaptation of new virtual learning simulations and the recruitment of a considerable number of new participants.

Learning was also limited to a single session. Even though most of the current studies on VR use a single session with a much smaller sample size, it would have been interesting to test whether the effects of the usefulness interventions on students' learning outcomes would change over time, especially when it comes to the effects of acceptance on affective and cognitive learning outcomes. Acceptance can be understood in terms of the user's intention to use VR (Davis, 1989; Davis, 2011; Granić, 2022a, 2022b; Granić & Marangunić, 2019), which implies a certain continuity in its use as a learning tool. Nevertheless, the results showed that particularly the learning usefulness intervention led to a higher acceptance of VR as a learning tool. Additionally, the results revealed that acceptance was strongly related to presence and positively associated with perceived learning, but was not associated with learning achievement. I propose that acceptance fosters the right attitude that enables students to engage with the learning materials (exemplified by its effect on students' presence in VR), which gives them the feeling of learning (perceived learning); however, it seems that the effect of acceptance on learning achievement will only manifest after students have used the virtual learning simulation multiple times. In other words, acceptance can create the necessary conditions to learn with VR, but students still need to be pedagogically supported and have the opportunity to learn repeatedly with VR in order to have higher learning achievement.

Key variables that are implied but were not assessed

The relationship between motivational support and students' learning outcomes was assessed directly through a knowledge test and indirectly via students' eye movements. With regard to the eye movement variables, the results showed that the interventions increased average saccade amplitude (which is involved in the selection of relevant visual information) and fixation duration (which is involved in the processing of information), which are positively related to students' learning achievement. Although students' cognitive load was implied through the analysis of their eye movements, blink behavior, and pupil dilation, it is unfortunate that the present studies could not account directly for the effect of cognitive load on their learning achievement. This was due to the fact that the adaptation of the scale (Klepsch et al., 2017) used in this dissertation to assess cognitive load showed poor reliability (Cronbach's alpha under.5); therefore, it was entirely discarded from these studies. However, it remains perfectly valid to use the eye-tracking method to assess students' cognitive processing of the learning content and to infer the level of cognitive load experienced during learning (Chen et al., 2011; Jacob & Karn, 2003; Mikhailenko et al., 2022; Scheiter & Eitel, 2017). Nevertheless, it would also be interesting to map out how the interventions affect external, intrinsic, and germane processing.

Metacognition and self-regulated learning

Two other concepts that are implied in these studies but were not explicitly accounted for are metacognition and self-regulated learning. The assumption that integrating motivational support into VR facilitates effective processing of the learning content mirrors the premises of the integrative approach and of CATLM, which was designed to include motivational and metacognitive factors in CTML and CLT (R. E. Mayer, 2014; Moreno & Mayer, 2007). The empirical evidence showing that simply priming students to perceive VR as useful for learning influenced their perception and acceptance of VR as a learning tool and their behavior in VR (eye movements) suggests they might have internalized the information on a metacognitive level. As a result, they seemed to be more aware, focused on their learning goals, and paid less attention to the hedonic experience of learning with VR.

According to Serra and Metcalfe (2009), metacognition involves one or more of the following cognitive processes: knowledge, monitoring, or control. Awareness of VR's affordances and usefulness for learning should boost students' metacognition, which may be fundamental for effective learning with VR simply because VR, as a learning tool, can be both motivational and distracting. The empirical results from this dissertation also indicate that metacognitive processes could have been at play, as metacognition increases with reflection (Gibson et al., 2016; Serra & Metcalfe, 2009). Namely, students who did not receive any motivational support in VR reported higher perceived learning than those who did, but had lower learning performance. It is likely that the interactivity and the hedonic experience predisposed students to feelings of fluency (Bjork, 1994; Carpenter et al., 2013; Oppenheimer, 2008). Macaluso et al. (2022) argued that such an error in metacognitive monitoring is caused by inaccurate judgment about the learning method. Similarly, the interventions reduced students' presence (without suppressing it), which was negatively related to learning achievement. It would have been interesting to test whether such interventions affected students' self-regulation, which could reduce their presence and their perceived learning but enhance their actual learning. Self-regulation is also essential for effective learning in VR (Makransky & Petersen, 2021; Sakdavong et al., 2019). Moreover, previous studies show a positive relationship between metacognition and self-regulation; that is, strategies to improve students' metacognition also improve their self-regulated learning (Azevedo, 2010; Azevedo & Cromley, 2004; Zhao et al., 2023).

In summation, providing students with relevant information about VR's usefulness for learning—by highlighting its affordances—is similar to an intervention to increase students' metacognition. The results from the three studies, as well as the above discussion, suggest how these results could also be linked to the metacognition and self-regulation literature. Assessing these two variables would have been a further significant contribution, bringing the cognitive theories and metacognitive research together.

6.5 Future research

The discussion of the empirical evidence, theoretical implications, and strengths and limitations of this dissertation leads to a set of implications for future research, both in terms of what can be built on top of these studies and what can be improved. Concretely, I will discuss the integration of motivational support into VR and its possible impact on cognitive processing and cognitive load, the effect of presence on learning with VR, and the relationship between acceptance and presence and students' learning outcomes.

Motivational support in VR

To enhance students' learning in VR, this dissertation applied an experimental approach: two video-priming interventions were cleverly integrated into the virtual simulations as part of the learning instruction. This form of motivational support was revealed to be very effective and had significant effects on students' perception, cognition, and even behavior (e.g., eye movements and blinking behavior). In these interventions, students were not told to learn, avoid distractions caused by the embedded hedonic elements, or explicitly reminded of the instructional objectives of the virtual lesson. They were *tricked* into thinking about the usefulness of VR for daily life or for learning; as a result, they came to their own conclusions, which impacted their perception, attitudes, and learning performance. The empirical evidence presented in this study supports the idea that the usefulness interventions prompted a certain reflexive and internalization process. However, an important question that arises from these empirical results is whether this (external and metacognitive) approach increases students' intrinsic motivation. Previous research tends to support this assumption. For example, Saraff et al. (2020) used the Intrinsic Motivation Inventory (IMI) and showed that metacognitive interventions led to better metacognition in all three components of metacognition and led to a significant increase in intrinsic motivation (including autonomy and self-control, interest, perception of choice, effort, and tension). Future research may assess how a usefulness intervention affects students' metacognition, self-regulation, and intrinsic motivation, how these variables are linked with each other, and subsequently affect students' learning outcomes in VR.

The empirical evidence suggests that the interventions affect students' cognitive processing of the learning content, assessed through the analysis of students' eye movements, blink behavior, pupil dilation, and their impact on learning achievement. According to the CTML, students' motivation has a fundamental impact on germane processing, which is involved in the selection of relevant information, mental representation and building structural relations among the information selected, and the integration of these into prior knowledge

(Mayer, 2009b, 2022). Motivation is also involved in essential processing (Mayer, 2022; Mayer & Pilegard, 2014; Moreno, 2007). A further study with greater focus on the effect of such motivational support on the three types of processing (external, essential, and germane processing) could help to better understand the mechanisms by which such interventions lead to effective processing and meaningful learning.

Role of Presence in learning with VR: a double-edged sword

Motivational support in VR reduced perceived presence, which either showed no relationship with learning or a negative association. Based on this evidence, it seems like the interventions reduced the level of presence—participants, in general, reported above-average levels of presence—which was beneficial for learning. However, the literature is rather inconclusive in this regard. Presence functions like a double-edged sword: presence is essential for learning in VR, but too much presence can impair learning (e.g., overstimulation and distraction from the learning goals). CAMIL (Makransky & Petersen, 2021) proposes that immersion and interactivity increase both presence and agency, which impact learning through affective and cognitive variables (e.g., interest, motivation, self-regulation); however, CAMIL does not make any direct or explicit link between agency and presence. In contrast, this dissertation suggests that there may be a strong link between presence and agency. In accordance with this idea, Herrera et al. (2006) posit that presence is more than the illusion of *being there*; it is about experiencing agency. According to Zahorik and Jenison (1998), presence is closely linked with action in the virtual environment, and "successfully supported action in the environment is a necessary and sufficient condition for presence" (p. 87). Therefore, this dissertation also proposes (Study 1) that different conceptualizations of presence (being agentic vs. being there in VR) can yield different effects on students' academic performance. Future research can investigate these assumptions and help to explain the inconsistent results found in terms of the impact of presence on students' learning achievement.

The assumption that presence in VR is essential for immersive learning, but too high a level of presence can also impair learning, has a fundamental and important implication: it implies that there is an optimal level of presence that is required for maximal learning performance (given that other factors affecting learning in VR stay constant). Accordingly, the present dissertation proposes that there might be a quadratic relationship between presence and learning achievement. Testing this assumption will require manipulating the level of presence (at least at three levels: low, medium, and high); however, such a manipulation is not very easy to perform. So far, most studies intending to manipulate presence used different gadgets that convey different levels of immersion (e.g., Parong et al., 2020). Optimally, the level of presence should be manipulated in the same virtual environment using the same or a similar gadget. One option would be to manipulate participants' interactions and agency. In this regard, Johnson-Glenberg et al. (2021) found a positive relationship between agency and presence. If the debate on VR's effectiveness for learning in science education is to move forward, a better understanding of the relationship between the level of presence and learning achievement needs to be developed.

Relationship between presence and acceptance

The TAM has established itself as the most important theoretical approach to predicting students' attitudes toward new learning tools—notably acceptance in terms of intention to use the learning tool. By showing how students' acceptance can be experimentally increased and how it is related to presence and students' learning outcomes, this dissertation makes a substantial contribution to this field of research. It seems logical that acceptance will have a positive influence on presence, as acceptance creates the necessary conditions for learning in VR. Plotzky et al. (2021) also found a positive relationship between acceptance and presence. However, this dissertation posits there may be a reciprocal relationship between acceptance and presence (see Study 2): Students who expressed greater acceptance of VR might experience higher presence, which facilitates more interactions and learning experience; as a result, presence may in turn reinforce students' acceptance of VR. More experimental research is needed in this field in general, but especially to test this reciprocal assumption.

The empirical evidence also suggests that acceptance has a positive effect on perceived learning (affective outcome) but does not affect learning achievement (cognitive outcome). The mechanisms by which acceptance may affect students' learning performance are still not understood, mostly because acceptance in most studies is considered as the outcome variable to be predicted. Understanding the possible effect of acceptance on learning requires a deep understanding of the role of acceptance as an attitude and psychological construct. According to the model, the primary function of acceptance—also referred to as behavioral intention—is to facilitate usage (Davis, 1989; Juarez Collazo et al., 2014). Although today's students are digital natives, they see VR primarily as an entertaining gadget; the findings of this dissertation suggest that students should be aware of VR's affordances and usefulness, which can increase their acceptance of VR as a learning tool. Past research has indeed shown that greater acceptance significantly increases the likelihood of actual usage, which in turn affects learning (Juarez Collazo et al., 2014; Larmuseau et al., 2018; Zogheib & Daniela, 2021). Therefore, a possible moderator of the effect of acceptance on learning is usage frequency. Does acceptance of VR as a learning tool increase students' willingness to study with VR regularly? Based on the conceptualization of acceptance and its functions, the present dissertation asks whether acceptance and the effect of acceptance on learning achievement only unfold over time, namely, whether acceptance leads to actual usage, which then enhances learning. A second possible moderator is students' engagement in the learning process in VR. If acceptance is assumed to create the primary condition for students to use VR as a learning tool (Davis, 2011; Merchant et al., 2014), then acceptance is likely to facilitate engagement with the learning content. Thus, a second important question is whether acceptance affects students' engagement and presence, which in turn affects learning in VR.

6.6 Conclusion

Massive investments by tech titans like Facebook and Apple are likely to accelerate the growth and popularity of immersive VR as an entertainment device. However, it is less certain whether VR will establish itself as an effective educational instrument. Considering the distinct advantages of VR—the combination of affordances for learning and hedonic elements—it would be beneficial to continue investing time and resources in VR effectiveness research. This includes empirical research on instructional design, motivation, and, in particular, integrating motivational support into the instructional design of virtual learning simulations. In this regard, this dissertation demonstrates the effect of integrating motivational support into VR on its effectiveness. Concretely, the dissertation shows that a brief intervention emphasizing the importance of virtual reality (VR) for daily life or specifically for learning can have significant effects on students' attitudes (perception of VR's usefulness, acceptance of VR as a learning tool), virtual learning experience, cognitive processing of lesson content in VR, and learning outcomes. By using multimodal methods (including modern VR headsets with integrated eye trackers), this dissertation shows how such interventions help students to be more aware of the instructional objectives, select the relevant visual information, and process the learning content effectively. On the other hand, this dissertation also suggests that a lack of motivational or instructional support in VR could cause students to simply enjoy the learning experience, be more susceptible to the negative effects of seductive details, and inaccurately believe that they have learned a great deal.

In essence, this dissertation contributes to our understanding of the relationship between motivation and cognitive processing by demonstrating how the integration of motivational support into a virtual learning simulation can enhance VR's effectiveness in science education. Moreover, it provides substantial insights regarding the necessity and the advantages for students to be pedagogically prepared before learning with VR and shows how educators can apply a simple, parsimonious, but effective method to accomplish that. Therefore, this dissertation contributes to this exciting and dynamic research field and has practical implications for the effective use of VR in science education.

7

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