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Learning Through Immersive Visualization

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Abstract

This dissertation focuses on the design, development, and evaluation of immersive visualization for learning and teaching microbial knowledge in both informal and formal learning settings.

The first study primarily focuses on designing and evaluating a theory-based immersive visualization for facilitating the public audience to learn metagenomics concepts. By documenting the design process, how virtual reality aiding the general public's comprehension of microbial concepts was evaluated by comparing the visualization design with and without theory-based guidelines in immersive space and comparing immersive and non-immersive methods. My proposed learner-environment interaction model within immersive visualization demonstrates the value of leveraging affective processing for knowledge comprehension. Moreover, perceived engagement, immersion, and subjective performance are significantly correlated, while perceived workload remains the same in both interactive and non-interactive immersive visualizations. This study connects the education and visualization domains by integrating interest theory and visualization design principles into educational application design and assessment.

The second study compares Fully immersive (HMD) VR, Desktop VR, and Slides lectures for Food Microbiology Laboratory instruction. First, I designed two VR prototypes to teach Sauerkraut Fermentation by collaborating with microbiology domain experts. I conducted a pilot testing by recurring seven graduate students in Food Microbiology to refine my instructional design process. Then 49 undergraduate students were recruited from a large Food Microbiology laboratory class to experience a Fermentation lecture in three conditions: HMD VR, desktop VR, and slides. Results indicate that the HMD VR-based lecture has promoted students’ long-term retention of conceptual knowledge along with increased perceived presence, motivation, and visual attention, while there is no significant difference in immediate retention among the three instructional methods (HMD VR, desktop VR, and Slides). This research informs learning impacts of self-directed lectures between VR and conventional modes of instruction. In addition, students’ interview responses and study strategies indicate design implications of instructional artifact usage in higher education.

Together, these studies comprehensively understand the affordances and constraints of integrating VR into teaching and learning in science education.

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Introduction

Learning occurs in our everyday lives. One important aspect of learning science is that an individual's development of intelligence is usually associated with environmental conditions (Choi et al., 2014; Ertmer & Newby, 1993; Ogbuehi & Fraser, 2007). Emerging technologies open a door for people to communicate and collaborate with others, as well as to shape the ways how people learn and think by immersing themselves in digital environments. Particularly, as "Metaverse" becomes a buzz word again, Virtual Reality (VR) takes such an immersive experience one step further by enabling people to interact and explore virtual surroundings that mimic one's real-life experiences (Steuer, 1992).

At the same time, educators, researchers, and developers have sought out innovative approaches to using VR to aid individuals' academic success in both formal and informal settings. Although educators value the potential of using VR to enrich one's learning experiences (Chen, 2006; Luo et al., 2021; Radianti et al., 2020), generalizable research on educational VR is still at the beginning stage. VR has long been viewed as a "fun" and "interesting" way to foster one's positive affective perceptions during immersive learning experiences. However, the association between these affective arousals and the learning performance with VR is barely explored. Moreover, there is a gap between VR learning science from the educational community and VR development research in the human-computer interaction (HCI) field. On the one hand, while developers and HCI researchers emphasize the usability of VR applications to perform a particular learning task, the design process of such applications usually is not well articulated in theoretical considerations from the pedagogical perspective (Fragkaki et al., 2019; Takala et al., 2022). On the other hand, educational researchers largely rely on ready-to-use VR applications (e.g., Labster) for general studying content, leading to missing understanding of personalized learning and VR technical development.

To fill this gap, this dissertation presents two studies focusing on the general public's comprehension of the Metagenomic dataset and undergraduate students' retention of Food Microbiology laboratory instruction to examine how learning occurs within and after VR using a self-directed learning approach. Each of the papers investigates issues from various perspectives, and analyzes how people learn, interact with, behave within, and perceive immersive visualization as a customized learning environment. The data sources of this dissertation were collected from an experiment involving 49 undergraduate students and 33 general public learners. The data collection consisted of experimental design, interviews, video recordings, observations, and questionnaires. Data included: (1) a pre-test survey that contained participants' demographic information, (2) knowledge comprehension and retention tests that captured learner's academic achievement, (3) videotaped experimental sessions for detailed coding and analysis of user engagement, communication, and interactions with VR and conventional teaching material, and (4) semi-structured interviews to understand learners' perception of the VR and alternative study materials they interacted with. Table 1 provides an overview of the studies. Each study utilized a different sample of participants, included one or more of the experimental conditions and used a different analytic approach.

Overview of the Dissertation

The intent of this dissertation is to look at how people learn when using VR applications, how they perceive their immersive experiences, and how factors of immersive visualization impact people's cognition, behavior, and perceptions. The structure of this dissertation is as follows. Chapter 1 serves as an introduction to the dissertation. Chapter 2 and Chapter 3 correspond to each study. Chapter 4 presents conclusions.

Study 1 explored how immersive visualization design derived from the proposed learner-interaction model affects the general public audience's data comprehension and affective perceptions compared to non-interactive immersive visualization and infographic.

Table 1. *Overview of each research design.*

	Study 1	***Study 2***
Sample	n = 33	n = 40
Participants	The general public who had no prior experience in Metagenomics.	Undergraduate students enrolled in Food Microbiology laboratory class.
Setting	Lab setting	Lab setting; Undergraduate classroom
Data Sources	Immersive visualization design ● teaching Metagenetic dataset Experimental Design: ● Interactive Immersive visualization ● Non-interactive visualization ● Infographic Interviews ● at the end of each experiment	Immersive visualization design ● teaching Sauerkraut Fermentation Experimental Design: ● HMD VR lecture ● Desktop VR lecture ● PowerPoint Slides Observation ● Videotaped sessions Interviews ● at the end of each experiment
Analytic techniques	T-test; Qualitative analysis	ANOVA; Qualitative analysis

Results from study 1 suggest that properly designed immersive visualization could outperform traditional visualization approach- infographic, and non-interactive immersive visualizations, helping users comprehend the marine Metagenomic dataset. Furthermore, perceived immersion, engagement, and subjective performance are decisive factors in cognitive learning gains. When implementing immersive visualization to aid teaching and learning, these factors should be borne in mind.

In study 2, I focused on VR's educational impacts in a formal learning setting- Food Microbiology laboratory undergraduate education. Students' learning processes, learning outcomes, perceptions, and behavior were examined to compare three teaching artifacts: Fully Immersive VR (HMD VR), Desktop VR, and conventional PowerPoint Slides. Findings identified significant differences in the Food Microbiology Knowledge retention task among the HMD VR, Desktop VR, and PowerPoint Slides. Although students' short-term retention scored similarly across conditions, students' long-term retention score using HMD VR was significantly higher than Desktop VR and Slides groups. Moreover, HMD VR can facilitate students' motivation to better understand concepts by cultivating students' longer visual attention and fostering a higher sense of immersion. These findings imply that rather than investigating HMD VR for students' immediate achievement, further studies should be expanded for an in-depth exploration of HMD VR's long-term impacts on how students' past VR lecture experiences shape their subsequent externalizing and internalizing behaviors during their lab sessions' procedural learning.

In the concluding chapter, I discuss the implications of the findings that emerged across the two studies and future directions.

References

Chen, C. J. (2006). The design, development and evaluation of a virtual reality based learning environment. *Australasian Journal of Educational Technology*, *22*(1). https://doi.org/10.14742/ajet.1306

Choi, H.-H., van Merriënboer, J. J. G., & Paas, F. (2014). Effects of the physical environment on cognitive load and learning: Towards a new model of cognitive load. *Educational Psychology Review*, *26*(2), 225–244.

Ertmer, P. A., & Newby, T. J. (1993). Behaviorism, cognitivism, constructivism: Comparing critical features from an instructional design perspective. *Performance Improvement Quarterly*, *6*(4), 50–72.

Fragkaki, M., Hatzligeroydis, I., Palkova, Z., & Kovas, K. (2019). Instructional Design in Virtual Reality Environments: The case of Palestinian HEIs. *2019 10th International Conference on Information, Intelligence, Systems and Applications (IISA)*, 1–4.

Luo, H., Li, G., Feng, Q., Yang, Y., & Zuo, M. (2021). Virtual reality in K-12 and higher education: A systematic review of the literature from 2000 to 2019. *Journal of Computer Assisted Learning*, *37*(3), 887–901.

Ogbuehi, P. I., & Fraser, B. J. (2007). Learning environment, attitudes and conceptual development associated with innovative strategies in middle-school mathematics. *Learning Environments Research*, *10*(2), 101–114.

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education*, *147*, 103778.

Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. *The Journal of*

Communication, *42*(4), 73–93.

Takala, Malmi, Pugliese, & Takala. (n.d.). Empowering students to create better virtual reality applications: A longitudinal study of a VR capstone course. *Informatics in Education*. https://eric.ed.gov/?id=EJ1117297

From Theory to Practice:

Designing Immersive Visualizations to Facilitate the General Public's Understanding of Marine Metagenomics

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Abstract

To evaluate how virtual reality facilitates the general public's learning, we designed an immersive visualization of a marine ecosystem to facilitate learning the interconnections between genetic expression and microbial behavior. We documented our design process grounded in a theoretical framework from educational and human-computer interaction research. Particularly, we explored if learners' affective perceptions from perceived immersion, subjective performance, and sustained engagement benefit learning in immersive visualization. Then we conducted an experimental study to compare learning effects among interactive immersive visualization, non-interactive immersive visualization, and non-immersive visualization method - infographic. 33 Participants participated in our study. Findings suggest the significance of interaction design considerations from the affective domain when designing immersive educational visualizations. We have found that perceived engagement, immersion, and subjective performance are significantly correlated during users' immersive learning experience. These factors should be considered when designing immersive visualization to be implemented using self-directly learning approach. Our study connects the education and visualization domains by providing important considerations for the design and evaluation of educational VR. Finally, we reflect on lessons learned and call for future studies to explore the affordances of immersive visualization as an educational tool.

Introduction

Technology in education is becoming ever more prevalent with the advancements and ubiquity of modern information and communication devices. With the COVID-19 outbreak impacting 91% of the world's student population (UNESCO, 2020), many schools and universities have shifted towards remote instruction. As online teaching has become a global necessity, developing technologies to support education and communication has become more vital than ever before (Aslan et al., 2019; Fang et al., 2021; Kim & Lim, 2021). Yet, despite the significance, the design and development of educational technologies face multiple challenges. One emerging challenge is the online nature of remote instruction resulting in the loss of social presence and intimacy found in an in-person classroom setting (Veletsianos & Navarrete, 2012; Xue et al., 2021; Zhan & Mei, 2013). Moreover, instructional technology design requires interdisciplinary collaboration from education, computer science, and human-computer interaction (HCI) to carefully design and implement systems, systematically perform evaluation, and ultimately archive the desired pedagogical goal (Petersen et al., 2020; Xie et al., 2019).

Visualization plays a fundamental role in communicating complex data to both domain expert and lay audiences (Munzner, 2014), augmenting human perception (Harold et al., 2016; Ma et al., 2012), directing visual attention (Harold et al., 2016; Healey & Enns, 2012), and facilitating comprehension (Adar & Lee, 2020; Géryk, 2015; Tobiasz et al., 2009). The meaning of visualization for exploration and storytelling is usually drawn from two categories of visualization: infographic and information visualization. While infographic has traditionally made use of illustration to provide visual presentations of complex data involving storytelling as a conventional graphic method, Information visualization applications transformed un-defined data into visual dissemination for exploration (Byrne et al., 2016; Dur, 2014; Munzner, 2014). In recent years, interest in using immersive environments for visualizing data to support users' cognitive processing has kept growing. With education ultimately sharing the same goal of knowledge construction, we see an intrinsic need for developing novel educational visualizations that facilitate teaching and learning in immersive space. While studies have investigated the learning effects of VR, there is still limited research examining how learning outcomes transpire while interacting with virtual environments. In addition, VR designers are susceptible to confounding usability with learning effects, which leads to a misunderstanding of learning outcomes (Radianti et al., 2020). If the design intent is to enable users to comprehend domain knowledge, visualizations design should be drawn from theoretical guidelines in educational research. In this way, VR designers can cater to the specific needs of creating visualizations for educational spaces. Emerging research (Adar & Lee, 2020; Huynh et al., 2020) has begun addressing this deficiency using a learning-based approach. However, research on designing immersive educational visualization and assessing its learning effects is still in its infancy.

Moreover, a wide array of research on immersive learning has involved facilitating laboratory tasks (Dunnagan et al., 2020; Singh et al., 2021; Thees et al., 2020), supporting cognitive outcomes (Lamb et al., 2018; Parong & Mayer, 2021; Thees et al., 2020), and fostering social skills (Bahng et al., 2020; Roswell et al., 2020). However, making sense of datasets from immersive visualization is somewhat understudied. The present study aims to address this gap by examining the potential of immersive visualization in the form of a virtual marine ecosystem that places general public learners within the context of a metagenomics dataset. First, we documented our design process based on theoretical frameworks. Next, we evaluated the instructional benefits, particularly for the interaction affordance within immersive visualization, by allowing learners to feel present in an underwater community when experiencing microbial activities. We argue that a well-designed immersive system can be used to reinforce one's affective processing by interacting within the visualization. Here, affective processing refers to the processing of stimulus on the affective dimension (De Houwer & Hermans, 2001). Therefore, the purpose of this study was to analyze affective factors that significantly influence the level of learning of general public users who used immersive visualization for self-directed learning. We focused on the literature review from educational research, HCI, and visualization studies to do this. We then identified three constructs - perceived immersion, perceived engagement, and subjective performance making up the research model for designing educational immersive visualization.

In summary, our contributions is fourfold: (1) a discussion of identifying affective factors that support knowledge acquisition in immersive environments from both theoretical and empirical interdisciplinary studies, (2) research design components to further guide learning effectiveness studies within immersive space, (3) quantitative experimental results demonstrate the advantages of affective processing design considerations compared to other methods in both immersive and non-immersive settings, and (4) we further explored how factors contribute to positive affective processing and developed design strategies for further research.

Theoretical Background

Research showed that students perceive the interaction within virtual environments to be useful and engaging for facilitating learning (Makransky & Wismer, 2019; Parong & Mayer, 2018, 2021), for acquiring social skills (Huang, 2018; Parsons & Mitchell, 2002), and for emotional triggers (Bahng et al., 2020; Roswell et al., 2020). However, only looking at the integration of technological elements constituting an immersive learning environment is not sufficient for us to explore how learning occurs through interaction between learners and the virtual world. We also want to draw insights from visualization design principles, learners' emotional perspectives, the affordance of VR, and pedagogical guidelines.

Learning in Immersive Visualization: Design, Implementation, and Evaluation

Visualization can be considered a learning approach to educating audiences through perceptual channels. Previous studies explored ways of using visualization to aid learning in scientific reasoning (Hullman et al., 2018; Viégas & Wattenberg, 2007) and narrative comprehension (Figueiras, 2014; Ma et al., 2012). However, the learning processes through immersive visualization need detailed planning and designing beyond perceptual considerations from visualization research, and include pedagogical, curricular, and social primitives to be borne in mind (Byrne et al., 2016). Engagement is an essential element through which the activities to be done and immersive experiences are constructed (Dede, 2009).

In the implementation phase, interaction is significant. However, it is challenging for visualization designers to select the most appropriate interaction technique to teach data and information effectively due to insufficient knowledge of pedagogical guidelines. To what extent the interactivity and visual representations should be implemented is essential for users’ satisfying learning experiences and learning success.

In VR, visualization demonstrates its value beyond the two-dimensional space by enabling spatial reasoning and increased visual realism. These salient characteristics of immersive visualization leveraged more flexibility in ways for educational success. However, many existing studies focus on assessing the effectiveness of cognitive tasks within VR while neglecting users’ learning performance. In this regard, in addition to consider the product of knowledge achievement as the goal for educational visualization evalutions, we also need to understand further how interaction dynamics shape user's affective perceptions (Krčadinac et al., 2012; Leony et al., 2013). In summary, co-evaluation from both affective and cognitive aspects is necessary to design and analyze educational immersive visualization.

Affective Perceptions as an Enabler of Learning

Learners' affective perceptions during the study activity have a significant influence on the learning processes and outcomes (Marta Arguedas et al., 2016; Mayer, 2020; Shephard, 2008). Although affective constructs can be evaluated from different points of view, in order to achieve a specific learning objective, these affective constructs should be consistent with the planned study activities. Therefore, one's affective perception of immersive space needs to be able to facilitate knowledge construction and align with the task workflow in the virtual world (Kartiko et al., 2010.; Makransky & Petersen, 2021; Shin, 2017). A user's feeling of immersion is essential for achievement, along with the perceived engagement within a learning activity and one's positive subjective performance.

To gain a better understanding of what constructs in affective processing might be ascribed to support cognitive tasks, we looked to the *interest theory*, which has been commonly used to investigate motivational constructs of facilitating cognitive processing (for example, see the works of Parong & Mayer, 2021). *Interest theory (Schiefele, 2009)* suggests that learners will work harder if they value the material and interest in the environment. More motivated learners are more likely to put more effort into understanding the material and are more resilient to overcome obstacles (Eccles & Wigfield, 2002; Koulouris et al., 2020; Parong & Mayer, 2018). Furthermore, interest may contribute to high levels of achievement because its facilities efforts during task completion. During a learning task, one's willingness to invest more time and effort in the study materials usually relates to their subjective rating on learning progress, as subject task performance (Imlig-Iten & Petko, 2018; Wigfield & Eccles, 2020). Georgiou and Kyza (2019) found that students' motivation and immersion can predict their conceptual learning gains by examining students' environmental science learning using AR apps. Building on the above work, we argue that considering learners' affective processing from subjective performance, immersion, and engagement is crucial for learning through immersive visualization.

In this regard, recent literature revealed that interactivity could trigger interest to aid pedagogical outcomes in immersive spaces (Bailenson et al., 2008; Roussou & Slater, 2020; Zhang et al., 2019). For example. Chen et al. (2016) explored middle students' interest change in a multi-user virtual environment. They found that the simulated situational interest can be translated into individual interest through VR activities, thus increasing knowledge gains. Schott & Marshall (2018) linked immersion in VR to situational interest. By nurturing students' curiosity to explore freely throughout virtual tourism, their study suggests that being fully immersed in simulated environments could benefit learning outcomes. The aforementioned research showed these situational interests could be implemented by using self-paced learning (Förtsch et al., 2017; Rotgans & Schmidt, 2011; Weiss & Zacher, 2022), exploratory strategies (Dewez et al., 2019; Dohn, 2013), and informational language(Jang et al., 2010).

As established, VR enables users to be engaged in a realistic-looking environment to transfer real-world activities. Scholars find that high levels of immersion (Dede, 2009; Donalek et al., 2014) and augmented visual perceptions (Cummings et al., 2017) in VR are the main factors influencing participants' feelings and emotions. In an environment that mimics real-to-life environments, engagement throughout the activity and the sense of immersion within the space empower users with positive attitudes towards their learning performance. Such attitudes are usually used to measure students' self-reported learning performance. Moreover, research has measured topic interest by means of referring to self-efficacy and value-related valences, such as improved competence beliefs (Lee, 2015; Metallidou & Vlachou, 2010) and growth in persistence (Hilton & Lee, 1988; Tulis & Fulmer, 2013). If one perceives a higher level of subjective task value, one is more likely to perform well in actual activity.

Therefore, a well-designed immersive visualization can be measured by the degree of one’s perceived immersion, subjective performance, and engagement. From this viewpoint, immersive visualization ideally serves as an enjoyable and satisfying learning tool based on a learner-environment interaction perspective and thus aids in amplifying motivation. Ultimately these positive affective processing gains can lead to increased cognitive learning gains of the study material.

Learner-Environment Interaction

An effective learner-environment interaction in immersive visualization requires a lot of thoughtful designs. First, one's perceived immersion differs from the objective description of the 360-degree, fully immersive virtual environment. Perceived immersion refers to a specific and psychological experience completely absorbed or engaged in an activity (Southgate, 2019). Previous studies (Parong & Mayer, 2018; Potapov et al., 2021) examined how VR can be used to simulate the close-to-life experience. However, most of the research simply attributed the increased learning gains in VR due to the inherently immersive nature of virtual environments while failing to examine a user's subjective perceptions of "being there." Analogously, reading a well-written book might not be considered immersive per definition, while the user's perceived immersion with the transpired knowledge might be high. Furthermore, not all interactions help with cognitive information processing using VR. Zhang (2019) explored the impacts of various levels of interactivity on immunology in VR. Although students' engagement increased, they found no significant difference between different interactivity levels on actual learning gains.

These studies indicate that design considerations need to be specifically tailored to explain how and if interactivity supports both affective and cognitive processes. Therefore, we followed the aforementioned pedagogical guidance to design interactions that facilitate perceived immersion, engagement and subjective performance within an immersive space.

Recent literature revealed that learners play an active role in study activity as they construct knowledge by making their own observations (Khan et al., 2018; Limniou et al., 2008; Sundqvist, 2019). In VR, such an exploratory "learning by doing" experience can be facilitated by spatial navigation(Al Zayer et al., 2019). Moreover, previous studies indicated that perceived motivation is crucial in constructing knowledge from environmental representation and self-exploration (Khan et al., 2018; Winterbottom & Blake, 2008; Wu et al., 2013). These findings encouraged us to translate our challenging metagenomics dataset to a more story-rich visual grammar.

Overall, findings from these works shaped our design considerations. By integrating affective aspects in immersive visualization design, visualizing abstract scientific concepts directly helps reduce cognitive load, interaction primes learners' situational interest such as perceived immersion and subjective performance to learn, along with high perceived immersive experience using a self-directed learning method. Figure 1 shows our proposed learner-environment interaction model derived from Mayer and Parong's (2021) affective-cognitive model in immersive space. Understanding how interaction facilitates users' affective perceptions of the environment, activity, and performance is crucial for researchers and practitioners in the field because it connects vision and cognition throughout interaction between oneself and the entire virtual world.

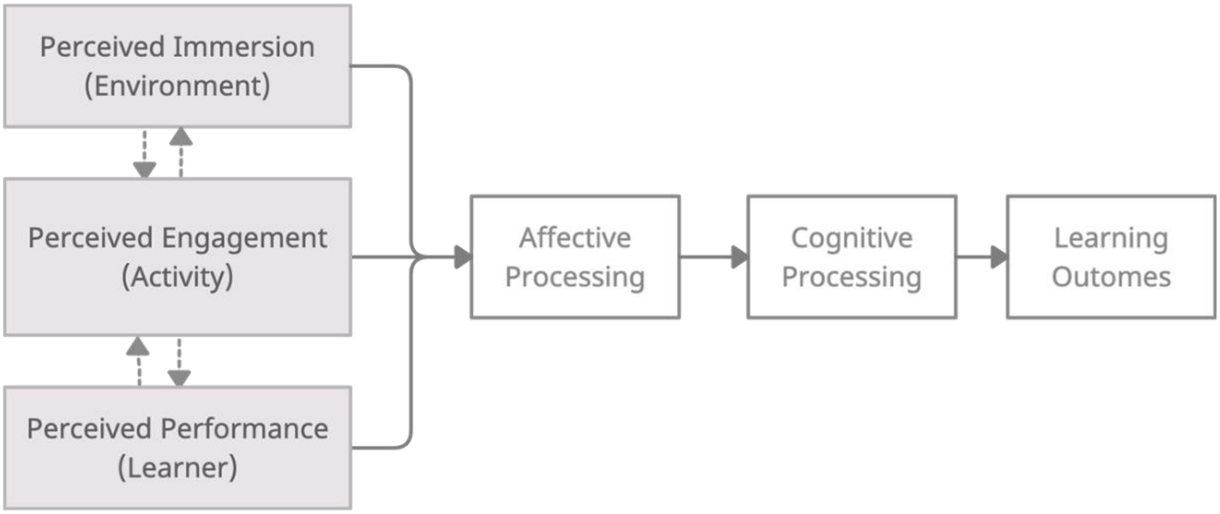


Figure 1. *The proposed learner-environment interaction model.*

Design Criteria

In this initial exploration project, we aimed to help general public users comprehend the basic concepts of a marine microbial ecosystem driven by a metagenomics dataset. Metagenomics plays a central role in every aspect of life on earth, and it links processes like a microbe's activity to the concept of genetic expression. Enabling the general public to understand the fundamentals behind Metagenomics is important for public health, especially in the existing COVID era. However, comprehension of such data requires a lot of cognitive effort and sustained engagement due to a lack of background knowledge (Duarte et al., 2020).

The learning goal of our immersive visualization is to comprehend the information within the dataset at three layers: (1) identifying the time-series properties of each microbe, (2) describing the interplay between microorganism species, and (3) explaining how microbe's behaviors are affected by gene expression. To achieve the above learning objectives, we consulted a microbiology instructor for the learning experience design, and our design team was comprised of an educational researcher, an HCI researcher, and a virtual reality developer.

Although various criteria have been proposed by visualization and HCI research communities to support visualization tasks, we firmly believe interaction design grounded in the learner-environment interaction model should be used to craft engaging, immersive learning experiences after several iterative discussions within the study team. In addition, we reflected the relationship between learner-environment interactions and theories. We thus started with the following three design criteria for *MicroOcean VR*.

In a nutshell, *interest theory* and previous literature in HCI and Educational communities suggested that interaction design should focus on increasing affective processing such as perceived immersion, perceived engagement, and subjective performance. Adding interactions to VR space can trigger situational interest and increase immediate comprehension. Furthermore, these elements should be positively correlated with others to reflect important factors which constitute a learner-environment interaction model using the self-directed learning method. Derived from the above theoretical background, we further grounded our design considerations (DC1-3) to align with learner-environment interaction aspects - learner, environment, and activity.

Environment: Acclimate to the Environment

By transitioning from the real environment to an immersive space, learners who have yet to explore our design need to understand their role within it. *Interest theory* suggested that people should perceive familiarity throughout the direct experience of both learning space and subject matter. HCI research (Dickinson et al., 2021; Harman et al., 2019; Ho, 2017; Soave et al., 2021) suggested that for VR games, interactivity is crucial to facilitate this familiarization process. Interface acquaintance was correlated by Virvou and Katsionis (2008) to a user's notion of what constitutes a "legal move" within a system. Our design thus needed to feature interactions that require low cognitive effort to use while also feeling familiar. As we discussed above, spatial navigation becomes a potential interaction design option then.

Learner: Self-Directed Exploration

Since VR creates a separate space, educational applications can leverage the additional room for informal, self-directed exploration. With Qarareh (2016) showing that among students, learner-centered approaches are favored over teacher-centric learning, the design could invite its users to explore the presented content on their own. As the learner-environment interaction model builds on how perceived affective processing support cognitive processing, our design would encourage autonomous learning and thus only offer soft narrative guidance. Such strategies foster users' confidence and perceived performance. While preserving the domain's complexity by accurately portraying microbial interplay, we made the design choice to reserve most information for deliberate user interaction. To achieve this form of interactive exploration, our interactions must be carefully designed to promote motivational benefits and learning.

Activity: Sustainable Engagement

In an informal, explorative learning setting, it is vital to draw users' attention and to keep them engaged throughout the activity or create a desirable space for users to explore freely. Di Serio et al. (2013) indicated the importance of visual and auditory designs toward students' attentiveness in augmented reality. With *interest theory* accrediting one's willingness to learn happens during the continuous process of the initial experience of situational interest involving intrinsic motivation and perceived satisfaction of the learning process, our design has to both foster engagement through the use of visuals, animations, audio, and interactivity. To elicit an intrinsic desire to explore the space further, these stimuli have to be both automated, related, and continuous.

Immersive Visualization Design

Materials

MicroOcean VR is an interactive educational simulation of an underwater microbial ecosystem derived from the Metagenomics dataset. After several rounds of discussion with the microbiology instructor and educational researcher, our system aimed to create both an authentic and playful environment for studying marine metagenomics. The dataset depicted in *MicroOcean VR* was collected by oceanographers affiliated with the Center for Microbial Oceanography: Research and Education (C-MORE) at the University of Hawaii at Manoa and the Monterey Bay Aquarium Research Institute (MBARI). Through a series of analyses performed on environmental and genomic data gathered from the ocean during 2014-2017(Aylward et al., 2015), scientists were able to collect information on microbes' taxonomy, gene function and expression levels, and the peak of expression. This led them to infer the daily pattern and function of microbes within their ecosystem.

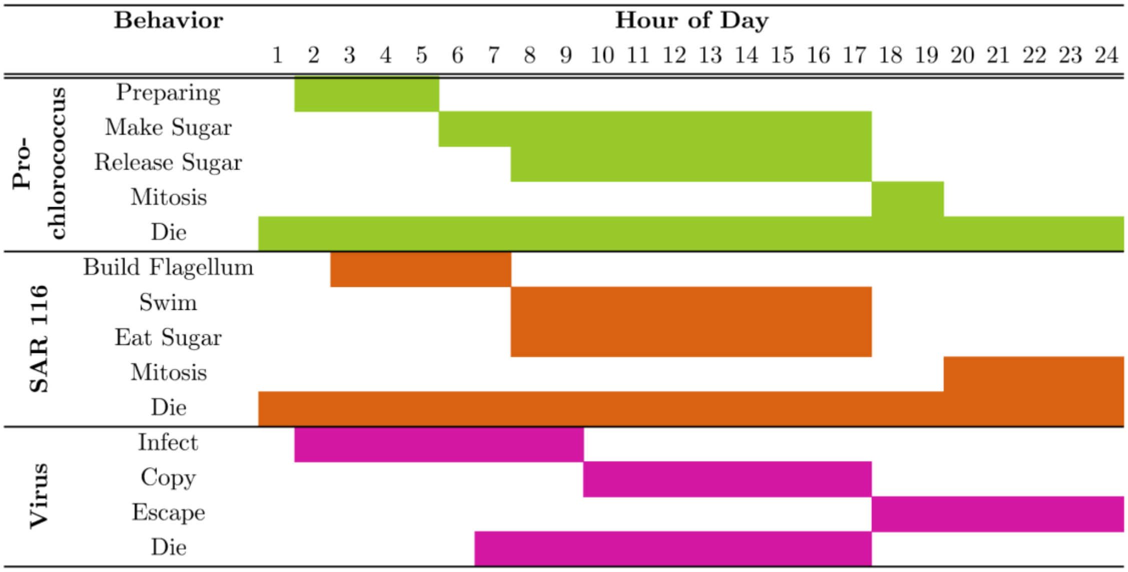
Implementation

Our system was implemented using Unity 2020.2.1f1 with an Oculus Quest VR headset. While a standalone Quest headset renders on its integrated mobile GPU, we connected it via Oculus Link to render the simulation on a local computer. This allowed us to combine the benefits of using a lightweight and affordable headset—affordances especially sought by the education market—with the graphics rendering capabilities of a dedicated GPU. While the system used for development has an Intel i9 9900K, 3.6GHz 8-core processor with 32 GB of RAM, and an NVIDIA GeForce RTX2080 TI GPU, the requirements for running our system are much lower. As detailed in the section below, *MicroOcean VR* also runs on a laptop with average performance specifications.

Simulation Design

MicroOcean VR is built as a cyclic, live simulation of marine microbial ecology. Three microbes—Prochlorococcus, SAR116, and a Cyanophage—were chosen from the dataset to illustrate microbial interplay, which is influenced by environmental factors, their form of reproduction, and their genetic expression. While all microbes share the common goal of procreation for passing on their genetic material, each follows a distinct pattern based on their pre-defined day-night schedule adapted from the dataset, as described in Table 1. Each microbe was assigned a non-scientific name for users to contextualize their functional role within the ecosystem easily.

Table 1. *The hourly activity of microbes derived from the original dataset.*



	Behavior	**Hour of Day**																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Prochlorococcus	Preparing		🟩	🟩	🟩	🟩																			
	Make Sugar						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩							
	Release Sugar								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩							
	Mitosis																		🟩	🟩					
	Die	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
SAR 116	Build Flagellum			🟧	🟧	🟧	🟧	🟧																	
	Swim								🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧							
	Eat Sugar								🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧							
	Mitosis																				🟧	🟧	🟧	🟧	🟧
	Die	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Virus	Infect		🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪															
	Copy										🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪							
	Escape																		🟪	🟪	🟪	🟪	🟪	🟪	🟪
	Die							🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪							

Parameters about the simulation, such as the probability of a particular behavior occurring, are configurable and set to uphold an equilibrium among microbes while their schedule remains accurate to the source dataset. We chose a relatively realistic rendering style because previous studies (Drettakis et al., n.d.; Gao et al., 2021) suggested that realistic representations help engagement efficiency. Microbes are colored 3D versions of their underlying 2D microscopical image. Coloring each distinctly would help users to quickly identify them within an informal setting (DC2). The 3D modeling and rendering are based on anthropomorphism (Dasu et al., 2021) considerations to foster users' sensation of engagement (DC3). To trigger users' awareness of connections between genetic expression and microbe behavior, we designed rotated DNA inside microbes figuratively. The rendering of the underwater environment is integrated with ambient ocean sounds to increase self-motion perception and presence(Soave et al., 2021). We omitted scenery objects in favor of shifting the exposure entirely to the interactive simulation (DC1-3). Figure 2 shows our design process for creating recognizable 3D models that we used in our simulation.

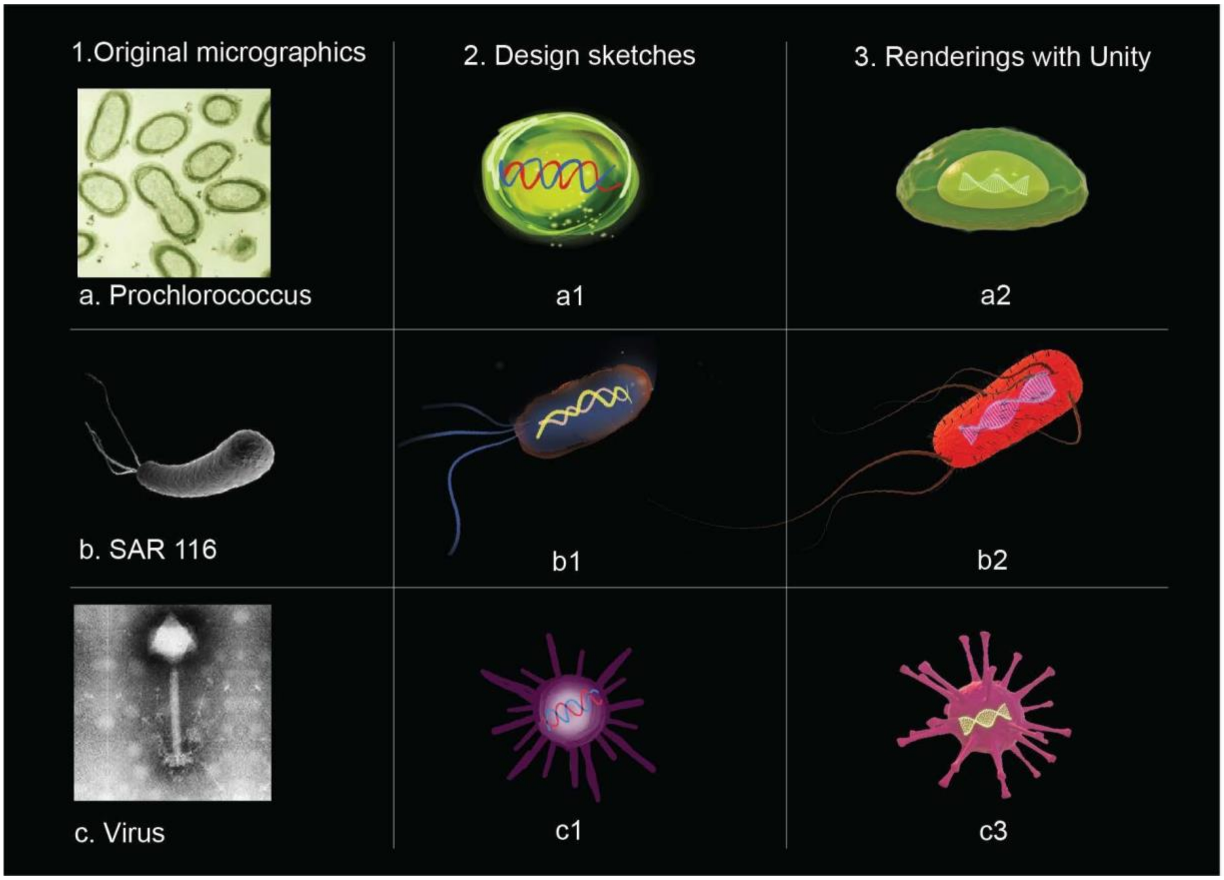


Figure 2. *Design process of the microbes portrayed. Left: the original electron microscope images; Middle: design sketches; Right: renderings within our application.*

Interaction Design

As the primary way of actively engaging with the simulation, meaningful interactions are essential for creating a user-driven learning experience. Therefore, their design has to foster sustained engagement and yet feel familiar to help users transition into an unknown space (DC1-3). We thus offered two intuitive ways of interaction for both navigating and exploring the underwater environment informed by our learner-environment interaction model, as depicted in Figure 3.

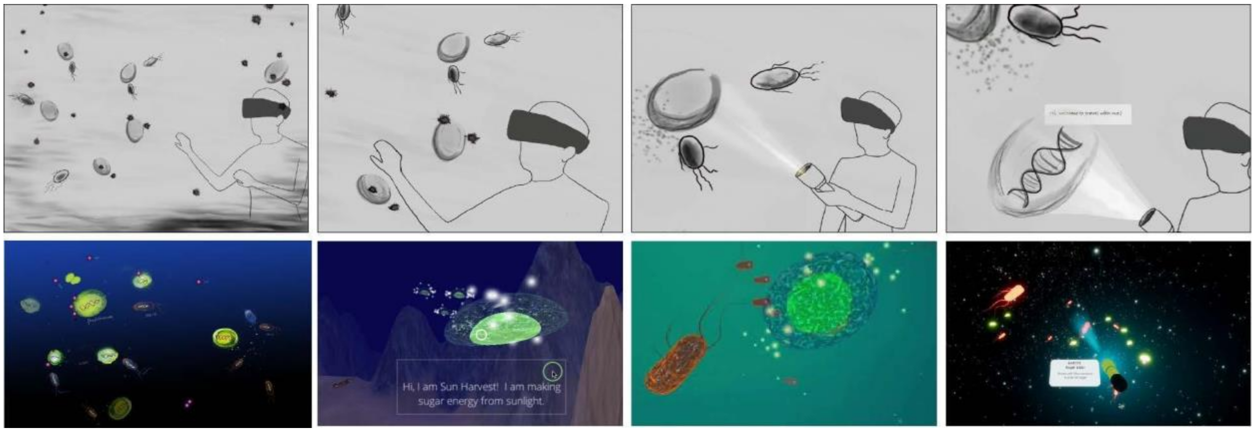


Figure 3. *A sampling of design artifacts, including early storyboards (top), 3D concept design, and progressive prototypes (bottom left to right).*

Diving Spatial navigation is a crucial component of VR interactivity (Al Zayer et al., 2019; Chang, 2017), as it encourages self-directed exploration and sustained engagement in our simulation (DC2-3). Furthermore, Gillies (2016) discussed the importance of movement design in VR for two reasons: it effectively supports the embodied aspects of our cognition and emotions and triggers thoughts and emotions similar to moving in the real world. To navigate the underwater ecosystem, learners would use the handheld controller’s joystick and buttons to move around the scene freely. With movement possible along all three axes, the aim was to give the impression of diving and swimming along with the microbes. Such multi-direction navigation could enable users to observe microbes and microbes' activities from different angles, perceive a sense of environment familiar to them, and trigger curiosity engagement.

Flashlight A flashlight serves as the primary way of exploring our simulated world. Through this metaphor, users are literally able to shine light and reveal hidden information about the learning environment. Neale and Charroll (1997) discussed interface metaphors to transfer knowledge from a known source to an unknown target domain, enabling users to apply specific prior knowledge of the metaphor in an unfamiliar context. As such, the flashlight should be a tool that users intuitively know how to use. Kirsh (2013) explored the use of tools as means of interaction and stressed that using them fundamentally changes our cognition and perception of our environment. With users entering the simulation at midnight amid a gloomy underwater environment, the flashlight would offer them a familiar interface for acclimating themselves to our environment (DC1). When aiming at a microbe, a side panel attached to the flashlight would display its scientific and non-scientific name and a text describing its current behavior, as shown in Figure 4. In addition, the outer shell of each microbe would become transparent, revealing a microbe's DNA, which rotates to figuratively illustrate each behavior's origin in genetic expression when users shine the flashlight on it (DC3). While most general information can be learned by simply observing the environment, detailed animated visuals and text descriptions could be deliberately reserved for interaction to motivate autonomous exploration of the space - which directly supports information processing (DC2). Figure 5 illustrates an overview of a learner exploring *MicroOcean VR* with flashlight interaction.

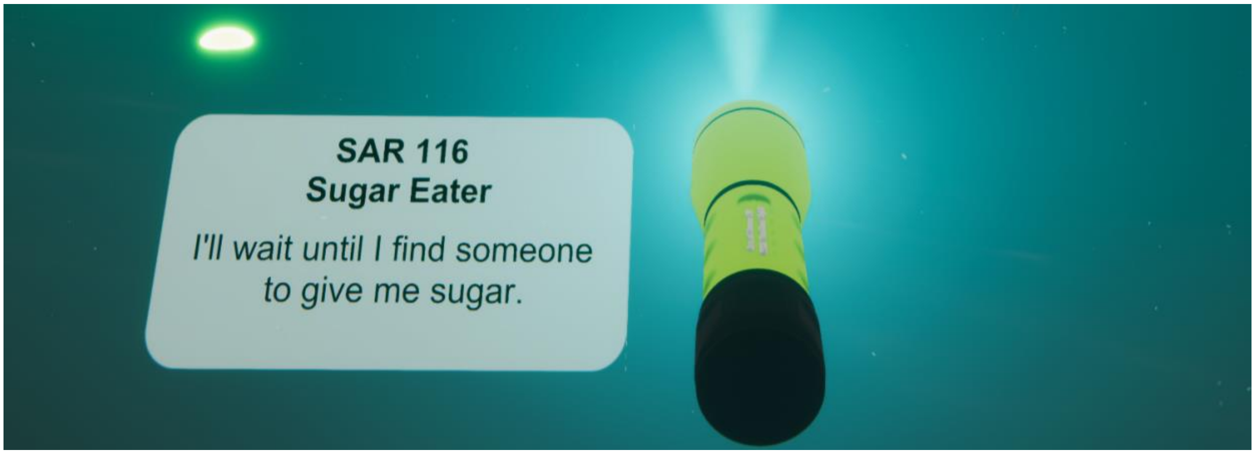


Figure 4. *A flashlight is used as an interface metaphor. When light is shone on a microbe, additional information is displayed, and the microbe reveals its DNA.*

Figure 5. *A learner exploring MicroOcean VR with flashlight interaction.*

Methods

We conducted two experiments to evaluate learning in immersive and non-immersive spaces. In the first experiment, we removed the two interactive elements and created a system automated version as a baseline for comparison. In essence, learners in the baseline condition watched a 360-degree fully immersive movie, whereas learners in the experimental group actively engaged with the immersive space by using the diving and flashlight interaction. In both baseline and experiment conditions, users perceived the same still visuals and text information.

In the second experiment, we used the same visuals and dataset to create an infographic as the conventional visualization method to compare its educational effects with *MicroOcean VR*.

In all studies, learning and motivational outcomes have been taken into account. The method section below provided a summarized version of the method implementation per study. More detailed information on the method and results can be found in separate publications.

Study 1: Interactive Immersive Visualization (*MicroOcean VR*) versus Non-Interactive Immersive Visualization

Figure 6. *Users in the EG interact via flashlight and movement (right), whereas users in the BG remained stationary and interacted by looking at microbes (left).*

Study 1 assessed the effectiveness of immersive visualization applications for teaching Marine Metagenomics concepts (n = 22). In this study, we recruited 22 general public participants from diverse educational backgrounds, and randomly assigned them to interactive immersive visualization (*MicroOcean VR*, as EG) and non-interactive immersive visualization (BG) conditions. To investigate whether adding interactions would lead to additional learning by considering learners' perceived immersion, engagement, and subjective performance, 11 participants were randomly assigned to each group. Figure 6 depicts an example of the experimental session for both the EG and BG group.

Participants

Participants were recruited using word of mouth, flyers, and social media sites. Each participant must have a normal vision to be able to wear VR headsets and perform learning tasks. We recruited a total of 22 participants aged 14 through 48 years (*M* = 29), including eight males and fourteen females. Nineteen had not used VR before this study, and fourteen reported some prior experience. To ensure the validity of learning gains, we only recruited those without prior knowledge about Metagenomics. Recent VR studies started addressing the side effects of fatigue during VR tasks (Masopust et al., 2021). Therefore, we also measured perceived workload during the experiment. A between-subjects design was chosen to ensure each participant experience the learning environment only once.

Procedure and Data Collection

During study 1, each participant filled out a pre-questionnaire to report their demographic information and previous experience with VR at the beginning. Each participant was made aware of the potential adverse effects of VR usage, which include nausea, eye irritations, or disorientation. Then each participant was given a training session of up to 5 minutes to familiarize themselves with the interaction techniques and the virtual environment. After, each participant was randomly assigned to one of the two conditions to perform the task. At the end of each task, participants complete a questionnaire including three dimensions of measurement: (1)affective learning measures - a self-reported rating of learning gains ranging from 1-10; six 7-point Likert scales adapted from Mütterlein (2018) to measure immersion; six 7-point Likert scales adapted from Mottet and Richmond (1998) to measure engagement, (2). six multiple-choice and four open questions based on the learning content to measure cognitive learning gains, (3). five 7-point Likert scales were partially adapted from NASA-TLX (Hart & Staveland, 1988) to measure perceived workload. Answers for these assessments range from 1 on the negative side (not agree at all) to 7 for positive (strongly agree) ratings.

Study 2: Immersive Visualization (*MicroOcean VR*) versus Non-Immersive Visualization (Infographic)

In study 2, an infographic poster was developed using the same text and still visuals to provide marine Metagenomic dataset information compared to the interactive immersive visualization (*MicroOcean VR*). The infographic group (n=11) sat at a desk and looked at an infographic adapted from immersive visualization. All information is shown in front of the user. Participants' interactions with immersive visualization and infographic are depicted in Figure 7.

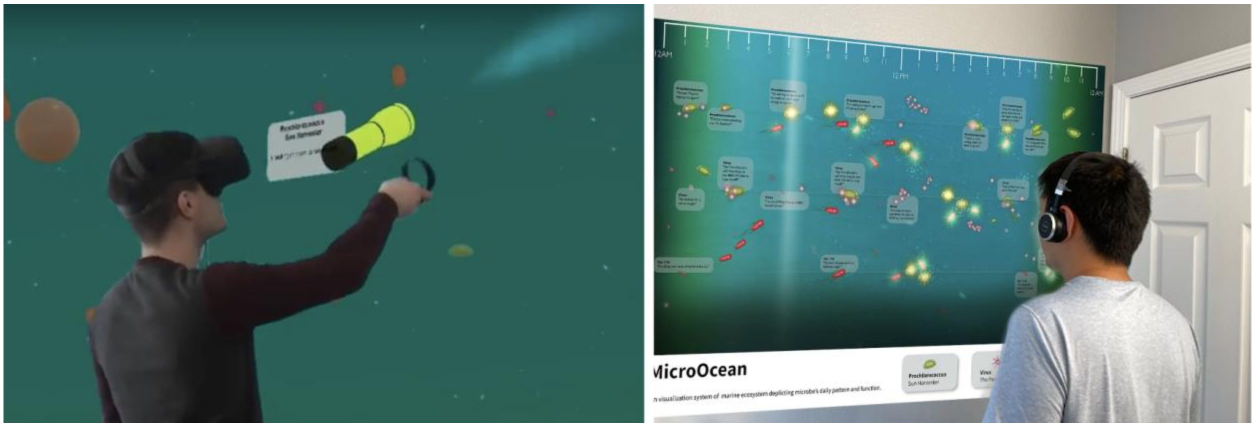


Figure 7. *Learning in immersive visualization -MicroOcean VR (left) versus Learning with an infographic (right).*

Participants

Study 2 participants were recruited through flyers and word of mouth. In total, 11 public participants with normal vision between the ages of 14 to 60 years (*M* = 35) participated in study

2. Five are males, and six are females. Seven participants had not used VR before this study, and four reported some prior VR experience. None of the participants had prior knowledge of Metagenomics. We randomly assigned them to a one-on-one experiment.

Procedure and Data Collection

During study 2, a paper-based infographic was used for participants to perform learning tasks by following the same procedures in study 1. In addition, we invited two participants to test *MicroOCean VR* and shared their opinions after finishing the infographic experiment. On average, a whole session took about 50 minutes.

Results

Study 1: Immersive Visualization (*MicroOcean VR*) versus Non-Immersive Visualization

Affective Learning Gains

Using the proposed learner-environment interaction model, we evaluated affective learning gains from three subjective perceptions: immersion within the environment, engagement through the learning activity, and subjective performance. Two-sample t-test analysis revealed a significant difference in subjective learning performance ($p = 0.01$) between BG and EG. On average, EG group ($M = 8.27$, $SD = 0.96$) perceived 28% higher performance subjectively than BG group ($M = 6.45$, $SD = 1.67$). On average, participants felt more immersed while interacting with the underwater community. We performed a Mann-Whitney's U-test on each rated category as our sample is ordinal and without assumption of normality. Results indicated significant differences between EG and BG for: navigation ($U = 14.5$, $Z = -2.99$, $p = .003$), emotional attachment ($U = 30$, $Z = 1.97$, $p = .04$), curiosity for next scene ($U = 26.5$, $Z = 2.19$, $p = .03$), and "willing to experience VR again" ($U = 28.5$, $Z = 2.07$, $p = .03$). On average, participants in the EG were more engaged with the learning content than in the BG. A Mann-Whitney's U-test indicated significant differences on each rated category for: enjoyment ($U = 23$, $Z = 2.43$, $p = .01$), satisfaction ($U = 26$, $Z = 2.23$, $p = .02$), helpfulness ($U = 18.5$, $Z = 2.72$, $p = .006$), and desire to learn more ($U = 16.5$, $Z = 2.85$, $p = .02$).

Cognitive Learning Gains

We analyzed both six multiple-choice questions (MCQ) and four open-ended questions (OEQ) from 22 participants across two conditions for cognitive learning. For the MCQ, we analyzed the number of correct answers that each participant responded to across 6 MCQs. A two-sample t-test compared the answers from OEQ from each group and found that students in EG provided more complete and detailed responses about each microbe’s behavior. However, two participants in indicated EG group ($M = 8.17$, $p = 1.57$) scored significantly higher ($p = .04$) than the EG group ($M = 8.17$, $SD = 1.57$), resulting in 12 % higher accuracy in the score of MCQ than BG. The OEQ asked students to describe each microbe’s behavior based on what they learned from the VR task. Some BG participants mentioned that they didn’t understand partial information within the VR task (e.g., virus’ daily behavior). These results demonstrated that users indeed achieved a higher level of knowledge comprehension by using the proposed interaction design in the EG condition.

Perceived Workload

Although two-sample t-test indicated there is no significant difference between the average perceived workload in two groups, our U-test on each rated category found significant differences between the two conditions for: physical demand ($U = 24.5$, $Z = 2.33$, $p = .02$) and cumbersomeness ($U = 29.5$, $Z = -2.00$, $p = .004$). This is an interesting finding. Interacting with virtual artifacts using physical movement could lead to fatigue, like the side effects caused by the Gorilla arm problem (Georgiou and Kyaz, 2018). However, our results indicated users didn't perceive increased cumbersomeness and physical demand although they interactivity engaged with the learning content. Furthermore, users in EG even showed a marginally lower rating of physical demand and cumbersomeness than the BG group. We speculated that factors underlying the two interactions might distract attention on physical demand and headset cumbersomeness.

Relationship of Affective Learning Gains

We conducted a regression analysis to examine linear causal relationships among perceived immersion, engagement, and subjective performance within *MicroOcean VR* (EG group). Our results indicate that all these three factors are significantly positively correlated to each other as shown in Table 2. Immersion contributes 72% to learning engagement, subjective performance contributes 61% to immersion, and subjective performance contributes 45% to learning engagement. This result indicates that appropriate pedagogically based interaction design can facilitate affective processing from the above three dimensions based on our learner-environment interaction model.

Table 2. *Association among perceived immersion, engagement, and subjective performance.*

Dependent Variable	Independent Variable	R^2	F	p
Engagement	Immersion	.72	51.59	< .001
Immersion	Subjective performance	.61	31.02	< .001
Subjective performance	Engagement	.45	16.23	< .001

Qualitative Feedback

In the post-study interviews, we asked participants from both groups if they learned anything about the three microbes portrayed in our visualization. We then transcribed all interviews and conducted a thematic analysis (Saldana, 2015). Four themes are derived from multiple passes of coding, which mainly reflect users' perceptions throughout the EG and BG experiment.

From Comprehension to Reflection

Besides our quantitative results revealing that students in EG group exhibited a higher level of knowledge comprehension than BG participants (from both MCQ and OEQ responses), interview also found that our interaction design facilitates comprehension and triggers participants' reflection on their learning experiences. Four participants from the EG reflected their own reasoning and thinking about the VR content with questions and concerns and expressed that they expected a more in-depth portrayal of metagenomics —*"the simulation should] explain why viruses infect Prochlorococcus?" and "how does metagenomics affect our daily life?"*. Below is a selected response describing the simulation.

E006- *"I think I learned that viruses copy themselves. But I wonder why they copy them. If you can continue to make a visualization to show the underlying reasons, that would be interesting!"*

Impacts of Interaction

We also asked participants in the BG if adding additional interactions would have helped them in learning the content. All 11 participants expressed that "adding interactions" would help their learning. They mainly described interactions including ones to "move around," to use "touch controllers," to "select microbes," to "move closer to the place of action," to "change my position" and to "drag microbes." Below is a comment from a participant in the BG.

One participant mentioned she was unsure if adding interaction helped because she felt interactivity was dependent on a learner's personal preferences. Based on this feedback, we identified that BG participants believed adding interaction functions could improve both affective perception and cognitive learning gains.

B003-*"Being able to see different angles and being able to add multiply infected cells at once would be more interesting."*

In addition, all 11 EG participants considered the two interactions help their learning in VR. Six participants expressed it would be helpful to add further interactions, such as "visual cues", "sound", or a "time speed control" for changing the scaled time in the simulation. Selected comments are shown below.

E003-*"Instead of using separate interactions to move horizontally [using a joy stick] and dive vertically [using buttons], if I can swim towards the direction I am looking at, it would be more immersive [...] for me [like swimming/diving the ocean]."*

E005-"If the VR participant [could] control the speed of the time changing, it might be helpful [...] to observe the patterns of microbes' behaviors."

Furthermore, all 22 participants from both groups mentioned that they believe VR is an interesting learning tool. Five out of 11 participants in the EG stated that the dividing interaction helped with their engagement and interest in exploring the underwater community. Three participants from both groups mentioned that the flashlight guided them to navigate the entire story. Below are several selected responses.

E008-*"I like it [dividing]. It does give me [a better] understanding of the space I was in. It definitely increased my engagement, my intention."*

E009-"I think moving around helped me [familiarize] and [gain] control overseeing and interacting. This is cool!"

These responses on learning effects suggested that our interaction design provides an active learning experience for most participants. Although prior experience with VR varied, no participant of either group responded that they felt exhausted or disengaged during the immersive learning activity.

Moving beyond Traditional Classrooms

Five out of 22 participants noted that VR's inherent features could address some challenges in a traditional classroom set K-12 STEM education. This feedback highlighted the value of immersive visualization for educational purposes. Four of our participants were middle school and high school students, and they explicitly explained the potential of introducing immersive visualization to the K-12 classrooms.

E012-*"It is hard to tell when looking at the diagram in the textbook how big it is. In VR, you see [it], you can be at that level. It is no longer too small to comprehend because, you know, technology [can be used] to be at that level."*

E001-"I know how big [a] car is, how big [a] house is because I am looking at it, but I don't have that knowledge about [...] cells and virus[es],"

Empathy and Emotional Support during the Pandemic

In addition to affective perception, we asked participants how the immersive experience connected to their personal traits in the context of the current COVID-19 pandemic. Four participants noted that they were emotionally attached to their virtual embodiment and suggested that VR might be an approach to relieve the anxiety and stress of remote learning. This finding indicates that VR can create emotional bonds through storytelling and visual encoding.

E010- *"It is very interesting. I am excited to participate in this VR research... you know, we have been locked down for a long time, and I am just full with my zoom lecture and online* *exams. This VR makes me feel like I was traveling the underwater aquarium, and I feel kind of [an] emotional attachment to the microbes."*

E008- "Yeah, definitely! Because the attention span of engagement is something I personally struggle with, and I have seen other people struggling too. I think it brings many pros to education, especially in the pandemic - All we do is looking at a tiny screen."

Study 2: Interactive Immersive Visualization (*MicroOcean VR*) versus None-Immersive Visualization (Infographic)

In experiment 2, we compared the general public's learning effects in immersive space (EG) and non-immersive space (IG). We found that users exhibit higher affective learning gains using immersive visualization than in an infographic. In addition, immersive visualization users tend to provide much more complete and reflective responses compared with the non-immersive visualization group, while accuracy remains no different.

Affective Learning Gains

A two-sample t-test analysis revealed a significant difference in subjective performance between EG and IG group ($p < .001$). On average, EG group (M = 8.27, SD = 0.96) perceived 107% higher performance subjectively than IG group (M = 4, SE = 1.41). Statistically, participants felt more immersed in EG group compared to IG group in average. Mann-Whitney's U-test on each rated category indicated significant differences between EG and IG for: concentration (U = 4, Z = 3.68, p < .001), forgetting surroundings (U = 29.5, Z = 2, p = .04), emotional attachment (U = 25, Z = 2.3, p = .21), and "willing to experience the material again" (U = 9, Z = 3.35, $p < .001$). In addition, participants felt more engaged in EG (M = 8.27, SD = 0 .96) compared to IG (M = 3.92, SD = 1.18) in most categories. A Mann-Whitney's U-test indicated significant differences on each rated category for: enjoyment (U = 28, Z = 2.10, p

= .03), satisfaction (U = 29, Z = 2.04, p = .02), helpfulness (U = 17, Z = 2.82, p = .005), and desire to learn more (U = 4.5, Z = 3.64, p < .001).

Cognitive Learning Gains

For the MCQ, although no statistically significant difference was found between EG and IG, on average EG group (M = 9.178, SD = 1.57) scored higher than the IG group (M = 7.33, SD = 1.37). This result can be interpreted as EG students achieving 25% higher accuracy in the score of MCQ than IG participants. The OEQ results in the IG group revealed similar results as the BG group, providing less reflective responses when compared with EG participants. Overall, participants in EG provide the most complete and reflective answers.

Qualitative Feedback

We then invited participants to consider whether immersive visualization can help their learning compared to the infographic. Eight out of eleven participants expressed that using immersive visualization to teach seems promising to sustain learner engagement. Two participants mentioned that educational efficiency is highly dependent on the interface and interaction design of the instructional material, so they held a neutral attitude to immersive visualization. One participant firmly believed that an infographic would help a better learning experience than immersive visualization. As she indicated, infographic allows easy access, and learners have a superior ability to store the material.

Two participants then agreed to try out our immersive visualization application, *MicroOCean VR*, and both expressed their excitement and emotional attachment to the immersive visualization. One participant mentioned that the virtual underwater navigation experiences reminded his childhood as he grew up in a coastal city. Another participant, as a middle school student, shared that virtually exploring the microbial life cycle triggered her sentimental analog emotions as she perceived the passing of time as an impermanent tiny microorganism. These sharing implied the potential of VR for demonstrating empathy through enriching visuals, aligning with the insights discovered from Fragkaki's study (2020) that VR can be used to increase cognitive empathy when inviting participants to interact through digital avatars in science education.

Discussion

Reflecting on our design process and the insights obtained from the evaluation, we concluded that implementing appropriate interaction design by considering the affective aspects derived from theory not only helps learning outperform in immersive space but also leads to higher levels of comprehension compared with traditional non-immersive learning methods, e.g., an infographic. By carefully considering theories, design elements, technical development, and learning outcome evaluation, our research documentation contributed to scientific evidence of integrating theories in VR application development to guide learning objects, a major pinpoint identified in Radianti et al. (2020)'s recent systematic review.

Our study suggests an association among learner's perceived subjective performance, immersion, and engagement in an interactive immersive learning environment. In other words, these affective indicators should be taken into account when designing and assessing motivational and efficiency outcomes during self-directed immersive learning. This finding echoes a recent investigation from Parong and Mayer (2021), who found that students perceived immersive experience could lead to a positive emotion during their VR-based history learning.

Interaction triggering interest and engagement within VR activity has been well studied. Yet effective interaction facilitating one's perceived immersion and subjective task performance is a new finding from our work. Based on previous findings from Whitehill et al. (2019), who developed a probabilistic model revealing a correlation between learners' subjective learning gains and their actual cognitive outcomes, in our study, such subjective task performance could relate specifically to the learner's perceptions of the environment (perceived immersion) and the learning activity (engagement).

Design Implications

Through the course of this work, we derive insights into the importance of instructional guidance in immersive visualization for facilitating learning. Our study reveals the significant role of situated learning environments and learning motivation in science. We credit this to foundational principles we identified from educational theories. As emerging technologies have been developed to scaffold pedagogical practices, there is a growing need to ascertain what type of taxonomy and theories should be integrated into education to facilitate personalized learning tasks. However, the visualization community has not reached a consensus on defining instructional guidance to support the design and task assessment in immersive space. Adar and Lee (2020; 2021; and 2022) has been highlighted the importance of framing communicative visualization as a learning problem to assess the design intent grounded in Bloom's taxonomy. In documenting our design process of developing an immersive visualization system derived from interest theory, our work supports the importance of using instructional guidance to consistently connect design objectives and task evaluation from both cognitive and affective aspects. We recommend that visualization designers first focus on the underlying theory guidance instead of visualization design intent. We believe that appropriate pedagogically-based interaction design choices can shape an individual's interest to change from immediate situational interest to long-term individual interest.

Limitations

Though the findings are promising, our study has a few limitations. First, the current study only investigates the interaction impacts on learning. We acknowledge that other elements (e.g., different visual styles, immersive and non-immersive learning modes) might yield other results. Therefore, further work is necessary to explore systematic learning evaluation from all aspects of design considerations. Furthermore, the encumbrance of wearing an HMD during the testing session might influence our study results. Several participants expressed that the headset is heavy and makes them feel uncomfortable. A part of the reason might be due to participants wearing face masks and disposable eyeglasses due to COVID-19 safety protocols. If the experiment lasts longer, the hardware setup might increase users' perceived fatigue. Thus, this variable might affect the internal validity of learner engagement. Lastly, the limited sample size was also an issue. A large-scale evaluation in k-12 and higher education classrooms would perhaps allow an in-depth understanding of VR learning technologies in HCI.

Conclusions

Overall, the evaluation results showed that our system (*MicroOcean VR*) facilitates participants' comprehension of specific scientific concepts derived from the data while enabling users to engage with the learning activity, be immersed within the virtual environment, and perceive a high subjective task performance. We outlined our design implications drawn from the investigation and saw value in further research for studying the impacts of theory-based visualization on education. Future work could benefit from more extensive user studies with specific demographic groups, such as middle school students. That way, findings could be better generalized in both fields of education and HCI.

References

Adar, E., & Lee, E. (2020). Communicative Visualizations as a Learning Problem. *IEEE Transactions on Visualization and Computer Graphics*, *PP*. https://doi.org/10.1109/TVCG.2020.3030375

Al Zayer, M., Adhanom, I. B., MacNeilage, P., & Folmer, E. (2019). The Effect of Field-of-View Restriction on Sex Bias in VR Sickness and Spatial Navigation Performance. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–12.

Aylward, F. O., Eppley, J. M., Smith, J. M., Chavez, F. P., Scholin, C. A., & DeLong, E. F. (2015). Microbial community transcriptional networks are conserved in three domains at ocean basin scales. In *Proceedings of the National Academy of Sciences* (Vol. 112, Issue 17, pp. 5443–5448). https://doi.org/10.1073/pnas.1502883112

Bahng, S., Kelly, R. M., & McCormack, J. (2020). Reflexive VR Storytelling Design Beyond Immersion: Facilitating Self-Reflection on Death and Loneliness. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 1–13.

Bailenson, J., Patel, K., Nielsen, A., Bajscy, R., Jung, S.-H., & Kurillo, G. (2008). The Effect of Interactivity on Learning Physical Actions in Virtual Reality. *Media Psychology*, *11*(3), 354–376.

Byrne, L., Angus, D., & Wiles, J. (2016). Acquired Codes of Meaning in Data Visualization and Infographics: Beyond Perceptual Primitives. *IEEE Transactions on Visualization and Computer Graphics*, *22*(1), 509–518.

Chang, J. S.-K. (2017). Tangible and Virtual Interactions for Supporting Spatial Cognition. *Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems*, 382–383.

Chen, J. A., Tutwiler, M. S., Metcalf, S. J., Kamarainen, A., Grotzer, T., & Dede, C. (2016). A multi-user virtual environment to support students' self-efficacy and interest in science: A latent growth model analysis. *Learning and Instruction*, *41*, 11–22.

Cummings, J., Scheltens, P., McKeith, I., Blesa, R., Harrison, J. E., Bertolucci, P. H. F., Rockwood, K., Wilkinson, D., Wijker, W., Bennett, D. A., & Others. (2017). Effect size analyses of Souvenaid in patients with Alzheimer's disease. *Journal of Alzheimer's Disease: JAD*, *55*(3), 1131–1139.

Dasu, K., Ma, K.-L., Ma, J., & Frazier, J. (2021). Sea of Genes: A Reflection on Visualising Metagenomic Data for Museums. *IEEE Transactions on Visualization and Computer Graphics*, *27*(2), 935–945.

Dede, C. (2009). Immersive interfaces for engagement and learning. *Science*, *323*(5910), 66–69.

De Houwer, J., & Hermans, D. (2001). Automatic affective processing. *Cognition and Emotion*, *15*(2), 113–114.

Dewez, D., Fribourg, R., Argelaguet, F., Hoyet, L., Mestre, D., Slater, M., & Lécuyer, A. (2019). Influence of Personality Traits and Body Awareness on the Sense of Embodiment in Virtual Reality. *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 123–134.

Dickinson, P., Jones, A., Christian, W., Westerside, A., Mulloy, F., Gerling, K., Hicks, K., Wilson, L., & Parke, A. (2021). Experiencing Simulated Confrontations in Virtual Reality. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 1–10.

Dohn, N. B. (2013). Situational Interest in Engineering Design Activities. *International Journal of Science Education*, *35*(12), 2057–2078.

Donalek, C., Djorgovski, S. G., Cioc, A., Wang, A., Zhang, J., Lawler, E., Yeh, S., Mahabal, A., Graham, M., Drake, A., Davidoff, S., Norris, J. S., & Longo, G. (2014). Immersive and collaborative data visualization using virtual reality platforms. *2014 IEEE International Conference on Big Data (Big Data)*, 609–614.

Drettakis, Roussou, & Reche. (n.d.). Design and evaluation of a real-world virtual environment for architecture and urban planning. *: Teleoperators and Virtual …*. https://direct.mit.edu/pvar/article-abstract/16/3/318/18687

Duarte, A. S. R., Stärk, K. D. C., Munk, P., Leekitcharoenphon, P., Bossers, A., Luiken, R., Sarrazin, S., Lukjancenko, O., Pamp, S. J., Bortolaia, V., Nissen, J. N., Kirstahler, P., Van Gompel, L., Poulsen, C. S., Kaas, R. S., Hellmér, M., Hansen, R. B., Gomez, V. M., & Hald, T. (2020). Addressing Learning Needs on the Use of Metagenomics in Antimicrobial Resistance Surveillance. In *Frontiers in Public Health* (Vol. 8). https://doi.org/10.3389/fpubh.2020.00038

Dunnagan, C. L., Dannenberg, D. A., Cuales, M. P., Earnest, A. D., Gurnsey, R. M., & Gallardo-Williams, M. T. (2020). Production and Evaluation of a Realistic Immersive Virtual Reality Organic Chemistry Laboratory Experience: Infrared Spectroscopy. *Journal of Chemical Education*, *97*(1), 258–262.

Dur, B. I. U. (2014). Data Visualization and Infographics In Visual Communication Design Education at The Age of Information. *Jahresbericht* , *3*(5), 39–50.

Eccles, J. S., & Wigfield, A. (2002). Motivational beliefs, values, and goals. *Annual Review of Psychology*, *53*, 109–132.

Figueiras, A. (2014). How to Tell Stories Using Visualization. *2014 18th International Conference on Information Visualisation*, 18–18.

Förtsch, C., Werner, S., Dorfner, T., von Kotzebue, L., & Neuhaus, B. J. (2017). Effects of cognitive activation in biology lessons on students’ situational interest and achievement. *Research in Science Education*, *47*(3), 559–578.

Fragkaki, M., Mystakidis, S., Hatzilygeroudis, I., Kovas, K., Palkova, Z., Salah, Z., Hamed, G., Khalilia, W. M., & Ewais, A. (2020). TPACK INSTRUCTIONAL DESIGN MODEL IN VIRTUAL REALITY FOR DEEPER LEARNING IN SCIENCE AND HIGHER EDUCATION: FROM “APATHY” TO “EMPATHY.” *EDULEARN20 Proceedings*, 3286–3292.

Fuller, U., Johnson, C. G., Ahoniemi, T., Cukierman, D., Hernán-Losada, I., Jackova, J., Lahtinen, E., Lewis, T. L., Thompson, D. M., Riedesel, C., & Thompson, E. (2007). Developing a computer science-specific learning taxonomy. *SIGCSE Bull.*, *39*(4), 152–170.

Gao, H., Bozkir, E., Hasenbein, L., Hahn, J.-U., Göllner, R., & Kasneci, E. (2021). Digital Transformations of Classrooms in Virtual Reality. Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, 1–10.

Georgiou, Y., & Kyza, E. A. (2018). Relations between student motivation, immersion and learning outcomes in location-based augmented reality settings. *Computers in Human Behavior*, *89*, 173-181.

Gillies, M. (2016). What is Movement Interaction in Virtual Reality for? In *Proceedings of the 3rd International Symposium on Movement and Computing*. https://doi.org/10.1145/2948910.2948951

Harman, J., Brown, R., Johnson, D., & Turkay, S. (2019). The Role of Visual Detail during Situated Memory Recall within a Virtual Reality Environment. *Proceedings of the 31st Australian Conference on Human-Computer-Interaction*, 138–148.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In P. A. Hancock & N. Meshkati (Eds.), *Advances in Psychology* (Vol. 52, pp. 139–183). North-Holland.

Hilton, T. L., & Lee, V. E. (1988). Student Interest and Persistence in Science: Changes in the Educational Pipeline in the Last Decade. *The Journal of Higher Education*, *59*(5), 510–526.

Ho, J. C. F. (2017). Practice in Reality for Virtual Reality Games: Making Players Familiar and Confident with a Game. *Human-Computer Interaction - INTERACT 2017*, 147–162.

Huang, W. (2018). Evaluating the Effectiveness of Head-Mounted Display Virtual Reality (HMD VR) Environment on Students' Learning for a Virtual Collaborative Engineering Assembly Task. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 827–829.

Hullman, J., Qiao, X., Correll, M., Kale, A., & Kay, M. (2018). In Pursuit of Error: A Survey of Uncertainty Visualization Evaluation. *IEEE Transactions on Visualization and Computer Graphics*. https://doi.org/10.1109/TVCG.2018.2864889

Imlig-Iten, N., & Petko, D. (2018). Comparing serious games and educational simulations: Effects on enjoyment, deep thinking, interest and cognitive learning gains. Simulation & Gaming, 49(4), 401-422.

Jang, H., Reeve, J., & Deci, E. L. (2010). Engaging students in learning activities: It is not autonomy support or structure but autonomy support and structure. *Journal of Educational Psychology*, *102*(3), 588–600.

Kartiko, Kavakli, & Cheng. (n.d.). Learning science in a virtual reality application: The impacts of animated-virtual actors' visual complexity. *Computers & Education*. https://www.sciencedirect.com/science/article/pii/S0360131510001053?casa_token=MfHXfrv4IocAAAAA:RGDILKqSsPcrRAZ2a40VcX6XBJt1l6r0seEUXTe4Ex3dhi9XutonubOJw

6bV5p0Tbi1buVUw6g

Khan, M., Trujano, F., & Maes, P. (2018). Mathland: Constructionist Mathematical Learning in the Real World Using Immersive Mixed Reality. *Immersive Learning Research Network*, 133–147.

Kirsh, D. (2013). Embodied cognition and the magical future of interaction design. *ACM Trans. Comput.-Hum. Interact.*, *20*(1), 1–30.

Klein, Klein, Moon, & Hoffman. (2006). Making Sense of Sensemaking 2: A Macrocognitive Model. In *IEEE Intelligent Systems* (Vol. 21, Issue 5, pp. 88–92). https://doi.org/10.1109/mis.2006.100

Koulouris, J., Jeffery, Z., Best, J., O'Neill, E., & Lutteroth, C. (2020, April 21). Me vs. Super(wo)man: Effects of customization and identification in a VR exergame. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20: CHI Conference on Human Factors in Computing Systems, Honolulu HI USA. https://doi.org/10.1145/3313831.3376661

Krčadinac, U., Jovanović, J., & Devedžić, V. (2012). Visualizing the Affective Structure of Students Interaction. *Hybrid Learning*, 23–34.

Lamb, R., Antonenko, P., Etopio, E., & Seccia, A. (2018). Comparison of virtual reality and hands on activities in science education via functional near infrared spectroscopy. *Computers & Education*, *124*, 14–26.

Lee, C.-Y. (2015). Changes in self-efficacy and task value in online learning. *Distance Education*, *36*(1), 59–79.

Leony, D., Muñoz-Merino, P. J., Pardo, A., & Delgado Kloos, C. (2013). Provision of awareness of learners' emotions through visualizations in a computer interaction-based environment.

Expert Systems with Applications, *40*(13), 5093–5100.

Limniou, M., Roberts, D., & Papadopoulos, N. (2008). Full immersive virtual environment CAVETM in chemistry education. *Computers & Education*, *51*(2), 584–593.

Ma, K.-L., Liao, I., Frazier, J., Hauser, H., & Kostis, H.-N. (2012). Scientific storytelling using visualization. *IEEE Computer Graphics and Applications*, *32*(1), 12–19.

Makransky, G., & Petersen, G. B. (2021). The Cognitive Affective Model of Immersive Learning (CAMIL): a Theoretical Research-Based Model of Learning in Immersive Virtual Reality. *Educational Psychology Review*, *33*(3), 937–958.

Makransky, G., & Wismer, P. (2019). A gender matching effect in learning with pedagogical agents in an immersive virtual reality science simulation. *Journal of Computer*. https://onlinelibrary.wiley.com/doi/abs/10.1111/jcal.12335

Marta Arguedas, Thanasis Daradoumis, & Fatos Xhafa. (2016). Analyzing How Emotion Awareness Influences Students' Motivation, Engagement, Self-Regulation and Learning Outcome. *Journal of Educational Technology & Society*, *19*(2), 87–103.

Masopust, L. M., Bauer, D., Yao, S., & Ma, K.-L. (2021). A Comparison of the Fatigue Progression of Eye-Tracked and Motion-Controlled Interaction in Immersive Space. *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 460–469.

Mayer. (2020). Searching for the role of emotions in e-learning. *Learning and Instruction*. https://www.sciencedirect.com/science/article/pii/S095947521930324X?casa_token=air5bH9MFw0AAAAA:n-BPqKv1zImdiVyDzJLJqRqHUSO0qzWAxownlm_LwLnDYAwBkkU0qQy5XWIpzk5WEdhk5e4-BA

Metallidou, P., & Vlachou, A. (2010). Children's self-regulated learning profile in language and mathematics: The role of task value beliefs. *Psychology in the Schools*, *47*(8), 776–788.

Mottet, T. P., & Richmond, V. P. (1998). Newer is not necessarily better a reexamination of affective learning measurement. *Communication Research Reports: CRR*, *15*(4), 370–378.

Munzner, T. (2014). *Visualization Analysis and Design*. CRC Press.

Mütterlein. (n.d.). The three pillars of virtual reality? Investigating the roles of immersion, presence, and interactivity. *Proceedings of the 51st Hawaii*. https://scholarspace.manoa.hawaii.edu/handle/10125/50061

Neale, D. C., & Carroll, J. M. (1997). Chapter 20 - The Role of Metaphors in User Interface Design. In M. G. Helander, T. K. Landauer, & P. V. Prabhu (Eds.), *Handbook of Human-Computer Interaction (Second Edition)* (pp. 441–462). North-Holland.

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. *Journal of Educational Psychology*, *110*(6), 785–797.

Parong, J., & Mayer, R. E. (2021a). Cognitive and affective processes for learning science in immersive virtual reality. *Journal of Computer Assisted Learning*, *37*(1), 226–241.

Parong, J., & Mayer, R. E. (2021b). Learning about history in immersive virtual reality: does immersion facilitate learning? *Educational Technology Research and Development: ETR & D*, *69*(3), 1433–1451.

Parsons, S., & Mitchell, P. (2002). The potential of virtual reality in social skills training for people with autistic spectrum disorders. *Journal of Intellectual Disability Research: JIDR*, *46*(Pt 5), 430–443.

Potapov, K., Vasalou, A., Lee, V., & Marshall, P. (2021). What do Teens Make of Personal Informatics? In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3411764.3445239

Qarareh, A. O. (2016). The effect of using the constructivist learning model in teaching science on the achievement and scientific thinking of 8th grade students. *International Education Studies*, *9*(7), 178.

Qian, Y., & Lehman, J. (2017). Students' misconceptions and other difficulties in introductory programming. *ACM Transactions on Computing Education*, *18*(1), 1–24.

Roswell, R. O., Cogburn, C. D., Tocco, J., Martinez, J., Bangeranye, C., Bailenson, J. N., Wright, M., Mieres, J. H., & Smith, L. (2020). Cultivating Empathy Through Virtual Reality: Advancing Conversations About Racism, Inequity, and Climate in Medicine. *Academic Medicine: Journal of the Association of American Medical Colleges*, *95*(12), 1882–1886.

Rotgans, J. I., & Schmidt, H. G. (2011). Situational interest and academic achievement in the active-learning classroom. *Learning and Instruction*, *21*(1), 58–67.

Roussou, M., & Slater, M. (2020). Comparison of the effect of interactive versus passive virtual reality learning activities in evoking and sustaining conceptual change. *IEEE Transactions on Emerging Topics in Computing*, *8*(1), 233–244.

Saldana, J. (2015). *The Coding Manual for Qualitative Researchers*. SAGE.

Schiefele. (2009). Situational and individual interest. *Handbook of Motivation at School*. https://doi.org/10.4324/9780203879498-16/situational-individual-interest-ulrich-schiefele

Schott, C., & Marshall, S. (2018). Virtual reality and situated experiential education: A conceptualization and exploratory trial. *Journal of Computer Assisted Learning*, *34*(6), 843–852.

Self, B. P., Miller, R. L., Kean, A., Moore, T. J., Ogletree, T., & Schreiber, F. (2008). Important student misconceptions in mechanics and thermal science: Identification using Model-

Eliciting Activities. *2008 38th Annual Frontiers in Education Conference*, S2G – 1–S2G – 6.

Shephard, K. (2008). Higher education for sustainability: seeking affective learning outcomes. *International Journal of Sustainability in Higher Education*, *9*(1), 87–98.

Shin, D.-H. (2017). The role of affordance in the experience of virtual reality learning: Technological and affective affordances in virtual reality. *Telematics and Informatics*, *34*(8), 1826–1836.

Singh, G., Mantri, A., Sharma, O., & Kaur, R. (2021). Virtual reality learning environment for enhancing electronics engineering laboratory experience. *Computer Applications in Engineering Education*, *29*(1), 229–243.

Soave, F., Padma Kumar, A., Bryan-Kinns, N., & Farkhatdinov, I. (2021). Exploring Terminology for Perception of Motion in Virtual Reality. *Designing Interactive Systems Conference 2021*, 171–179.

Southgate, E. (2019). Virtual Reality for Deeper Learning: An Exemplar from High School Science. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 1633–1639.

Sundqvist. (n.d.). Commercial-off-the-shelf games in the digital wild and L2 learner vocabulary. *Language Learning & Technology*. https://scholarspace.manoa.hawaii.edu/handle/10125/44674

Thees, M., Kapp, S., Strzys, M. P., Beil, F., Lukowicz, P., & Kuhn, J. (2020). Effects of augmented reality on learning and cognitive load in university physics laboratory courses. *Computers in Human Behavior*, *108*, 106316.

Tulis, M., & Fulmer, S. M. (2013). Students’ motivational and emotional experiences and their relationship to persistence during academic challenge in mathematics and reading. *Learning and Individual Differences*, *27*, 35–46.

Viégas, F. B., & Wattenberg, M. (2007). Artistic Data Visualization: Beyond Visual Analytics. *Online Communities and Social Computing*, 182–191.

Virvou, M., & Katsionis, G. (2008). On the usability and likeability of virtual reality games for education: The case of VR-ENGAGE. *Computers & Education*, *50*(1), 154–178.

Vogel, J. J., Greenwood-Ericksen, A., Cannon-Bowers, J., & Bowers, C. A. (2006). Using Virtual Reality with and without Gaming Attributes for Academic Achievement. *Journal of Research on Technology in Education*, *39*(1), 105–118.

Weiss, M., & Zacher, H. (2022). Why and when does voice lead to increased job engagement? The role of perceived voice appreciation and emotional stability. In Journal of Vocational Behavior (Vol. 132, p. 103662). https://doi.org/10.1016/j.jvb.2021.103662

Wigfield, A., & Eccles, J. S. (2020). 35 years of research on students' subjective task values and motivation: A look back and a look forward. In Advances in motivation science (Vol. 7, pp. 161-198). Elsevier.

Winterbottom, C., & Blake, E. (2008). Constructivism, virtual reality and tools to support design. Proceedings of the 7th ACM Conference on Designing Interactive Systems, 230–239.

Whitehill, J., Aguerrebere, C., & Hylak, B. (2019). Do Learners Know What's Good for Them? Crowdsourcing Subjective Ratings of OERs to Predict Learning Gains. International Educational Data Mining Society.

Wu, H.-K., Lee, S. W.-Y., Chang, H.-Y., & Liang, J.-C. (2013). Current status, opportunities and challenges of augmented reality in education. *Computers & Education*, *62*, 41–49.

Zhang, L., Bowman, D. A., & Jones, C. N. (2019). Exploring Effects of Interactivity on Learning with Interactive Storytelling in Immersive Virtual Reality. *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*, 1–8.

From Artifacts to Outcomes:

Comparison of Fully Immersive VR, Desktop VR, and Slides Lectures for Food Microbiology Laboratory Instruction

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Abstract

Laboratory lectures can be challenging due to students' low motivation to learn abstract scientific concepts and low retention rate. To address this issue, we designed a virtual reality-based lecture on the topic of fermentation and compared its instructional effectiveness with lectures using PowerPoint slides and Desktop VR. Grounded in the theory of distributed cognition and motivational theories, our study examined how learning happens in each condition from students' learning outcomes, behaviors, and perceptions.

Our result indicated that VR could facilitate students' motivation to better understand concepts by cultivating students' longer visual attention and fostering a higher sense of perceived immersion. Although all three instructional artifacts showed no significant difference when evaluating students' short-term knowledge retention ($p > .05$), students enrolled in the fully immersive VR group had the highest long-term knowledge retention scores ($p < .05$). We reflect on the findings' implications and provide instructional design ideas for using emerging technologies to support students' laboratory learning experience.

Introduction

In recent years, scholars have investigated how VR enhances learning in various disciplines, including Earth science (Petersen et al., 2020), Physics (Pirker et al., 2019), Anatomy (Parong & Mayer, 2018), Language (Cheng et al., 2017; York et al., 2021), and Culture (H.-L. Fu et al., 2020; Ji et al., 2021). However, a comprehensive investigation into the instructional effectiveness of VR on undergraduate Food Microbiology education has yet to be done. Food Microbiology is a critical scientific study of microbes, which play a vital role in all life on earth. In Food Microbiology undergraduate education, students need to comprehend fundamental concepts about the food chain in microbial worlds, which is necessary to understand the essence of life on earth. However, processes of learning microbiology are difficult due to low retention of scientific literacy skills (Anderson et al., 2020; Cottone & Yoon, 2020) and lack of sustained attention to conceptual learning among students (Merkel & ASM Task Force on Curriculum Guidelines for Undergraduate Microbiology, 2012).

As a result, educators and researchers have been using emerging technologies to address this concern. Both visualization and VR have been integrated into technology-based learning approaches to facilitate authentic scientific knowledge transmission (Pirker et al., 2019) and promote students' learning interests (Parong & Mayer, 2018; Southgate, 2019). Based on the theory of distributed cognition (Hutchins, 1991), educational technologies can serve as an extension of the human mind, supporting an individual's sense-making. As one of the most promising tools across various technologies, VR encourages learning by isolating users from the physical world and facilitating high levels of immersion and interactivity in the virtual world (El Beheiry et al., 2019; Hodgson et al., 2019). However, how learning happens through these interactive haptic simulations (e.g., sensor gloves and hand controllers) and augmented visual perceptions (e.g., 360-degree visual displays) within immersive visualization is still unclear. Most existing VR studies assess learning outcomes using error rate (Ahlberg et al., 2007; Knierim et al., 2018), task completion time (Buttussi & Chittaro, 2018; Snyder et al., 2011), and questionnaires (Buttussi & Chittaro, 2018; Dehesa et al., 2020; York et al., 2021) in lab setting. Although these findings show that VR can provide immediate learning gains, they do not identify which factors, from such computer-mediated environments to one's individual cognition, contribute to improved learning attainments during the VR experience.

Moreover, while research has demonstrated increased learning outcomes and positive learning experiences in immersive environments, scholars have not yet investigated the impact of increased motivation on students' learning performance in the field of microbiology. As mentioned earlier, teaching microbiology can be challenging due to students' low motivation to learn abstract scientific concepts and low retention rate. PowerPoint slides are commonly used in current Food Microbiology laboratory instruction in undergraduate education, as depicted in Figure 1. To address these existing learning barriers in microbiology undergraduate education, technology integration in classrooms should improve immediate learning attainment and cultivate students' motivation to learn. Last but not least, a theoretical framework derived from learning science to guide designing immersive visualization is still lacking. There is an urgent need to examine the effectiveness of data-driven learning approaches in VR due to the current lack of empirical evidence in this field. Also, educational researchers can implement immersive visualization based on appropriate pedagogical guidance to better understand, discover, and analyze learning behaviors.

Figure 1. *Teaching with slides for laboratory lecture in classroom (left) versus students' laboratory experiments (right).*

In this study, we present a VR application as a self-directed learning approach to study how students memorize Food Microbiology lectures. Using this tool, students' learning processes, outcomes, motivation, and perceptions were investigated. The self-directed VR lecture was adapted to two conventional learning materials - PowerPoint slides and a Desktop VR. This study utilized achievement tests (retention), self-report measures (perceived immersion and motivation), and implicit measures (visual attention) to comprehensively examine students' learning process as well as the process of human-computer interaction throughout different instructional artifacts. In addition, interviews were conducted to understand students' perceptions of learning with each artifact. Our research design is guided by the theory of distributed cognition and motivational theories.

This study builds on existing research about educational VR and online learning. With the rapid development of emerging technologies, a comprehensive investigation into students' learning experience during and after VR lessons, coupled with students' perceptions of their engagement with VR, will provide evidence-based insights and directions for future research. Specifically, this study contributes to the following areas of scholarly interest: (1) Empirical information about the learning impacts of self-directed lessons across VR and conventional modes of instruction, (2) expanded understanding of the learning process and learners' perceptions through their immersive experiences, and (3) summary of design and research implications of selected instructional artifacts usage in higher education. Two questions were asked:

1. How does learning occur among different instructional artifacts (HMD VR vs. Desktop VR vs. Slides) in self-directed learning?
    a. Sub-question 1: What are the differences in the perceived immersion, visual attention, short-term retention, long-term retention, and motivation among HMD VR, Desktop VR, and Slides?
    b. Sub-question 2: How do different elements contribute to students' cognitive processing when learning from different instructional artifacts?
2. How do students perceive their learning experiences from the three instructional artifacts?

Literature Review

The purpose of this literature review is to provide background information on educational VR for understanding existing research in the field.

VR and Education

Currently, there are mainly two types of VR. One is non-immersive VR, and the other one is immersive VR. Non-immersive VR enables users to perceive a believable experience similar to real life while staying connected with their physical surroundings. For example, Desktop VR allows users to experience their physical surroundings and an artificial three-dimensional environment via interaction with virtual items on the web. Fully immersive VR, also known as HMD VR, typically uses specific hardware (e.g., head-mounted devices, wall displays, wireless controllers, etc.) that completely isolates users from their physical world for a fully immersive experience. Examples of fully immersive VR include HTC VIVI and Oculus Rift headsets, which offer high rendering graphics and enriched interactions. With more affordable devices being developed, VR applications have become an even more active field of interest for educational research. Applications within the educational domain have included subjects as diverse as medicine, biology, history, sociology, and language sciences (Truchly et al., 2018).

Many studies have shown that students demonstrated greater satisfaction and engagement when interacting with visually augmented virtual objects in VR space. Both satisfaction and engagement can be considered motivational constructs. Satisfaction (subjective perception of pleasing feeling) can serve as a source of motivation and engagement (focused experience) as it reflects one's actual feeling of being motivated. Full immersive VR enables learners to enter, navigate, manipulate, and interact with virtual three-dimensional (3D) objects and thus leads to an enjoyable experience (Dunnagan et al., 2020; X. Fu et al., 2020; Garcia et al., 2019) and emotional involvement during the task (Allcoat & von Mühlenen, 2018; Bernal & Maes, 2017; L. Zhang et al., 2019). Dede (2009) 's research demonstrated three benefits ofVR: could enhance learning by allowing multiple perspectives, situated learning, and knowledge transfer. Topics within this paper that pertain to learning science broadly include immersion, presence, interactivity, and spatial reasoning. These topics provided a guide for immersive learning researchers to explore the potential of virtual reality in the educational context. As Dede stated, "When evaluation is based on the success of learning as a preparation for future learning, researchers measure transfer by focusing on extended performances where students' learn how to learn' in a rich environment and then solve related problems in real-world contexts." (p. 67).

Later, Mei & Sheng (2011) tested situated learning by using a virtual hospital system for medical students to practice human organ anatomy. Their findings suggested that VR can stimulate learner motivation towards medicine while helping learners practice their clinical skills in an authentic context. This study, along with others showing how VR promotes students' learning interests- an essential motivational construct, provided an excellent basis for understanding applying situated learning in VR and its effects on motivation (Markowitz et al., 2018; Parong & Mayer, 2018; Petersen et al., 2020).

These studies indicated that VR has the potential to aid learning in various respects. However, there is still limited research examining how learning transpires within immersive space. Instead of solely evaluating learning outcomes, it is important to explore more and key mechanisms operating within immersive space, such as the learning process and affective benefits. Before we can claim whether learning gains are attributable to the VR context as a whole, studies that comprehensively explore the process of knowledge construction within an immersive space are required to better understand the key components driving learning.

Immersion in VR

Engaging with VR enables users to enter into an immersive state, making users feel as if they have been in a real-life scenario, which is difficult to achieve from traditional “desktop” visualization tools. This realistic mental involvement is mainly due to the unique characteristics of VR that simulate full immersion, provide high-quality rendering, and offer advanced interactions. Studies have discussed how immersion aids learning in virtual environments (J. A. Chen et al., 2016; North et al., 2004; Parong & Mayer, 2018). Chen et al. (2016) used latent growth model analysis to explore how middle school students’ self-efficacy and interest changed throughout their learning experiences from a VR application - Ecosystems Multi-User Virtual

Environment (EcoMUVE). The researchers found that the triggered situational interest translated to individual interest throughout the perceived realistic environment in VR. North et al. (2004) conducted an empirical study showing that immersive visualization increases learners' understanding of computer science concepts. Parong and Mayer (2018) conducted a comparative study on non-immersive space and immersive space to examine students' learning efficacy in Cell biology. The results showed that providing immersion in VR may promote students' situational interest and engagement.

Findings from these works revealed immersion serves as a significant factor affecting user experience in VR space. Understanding how immersion impacts learning experiences and study outcomes is vital for VR researchers because it can guide experimental design and assessment methods.

Food Microbiology Instruction

Literature has investigated how VR supports students' academic achievement in physics (Loftin et al., 1993), geography (Zhao et al., 2020), and chemistry (Georgiou et al., 2007). However, studies on VR usage in teaching Food Microbiology are very limited and primarily focus on specific biology content and its immediate learning gains. In Food Microbiology laboratory instruction, both declarative and procedural knowledge is very important for students entering the workforce (Pleitner et al., 2014). However, laboratory lectures are sometimes not offered in the same setting as laboratory experiments. Instead, students may have their lectures in a traditional classroom and then move to a different location for the laboratory exercise part. Those laboratory exercises can sometimes take several days. In this case, longer knowledge retention is critical for students as they must complete precise procedures required for that particular laboratory exercise based on their knowledge retention. Existing studies suggested the

VR's potential for triggering students' critical thinking (Merchant et al., 2014), deep learning (Truchly et al., 2018), and scientific reasoning (Truchly et al., 2018; Zhao et al., 2020) through immersive knowledge-oriented activities. However, as seen above, studies examining VR's impacts on students' retention ability and motivation are still underexplored. Therefore, there is an urgent need to investigate how immersive visualization facilitates students' short-term, long-term knowledge retention and motivation throughout their learning with laboratory lectures.

Visualization Aids Education

Visualization is defined as the representation of a dataset for improving the efficiency of carrying out particular tasks (Munzner, 2014). The primary purpose of visualization is to gain insights into an information space via storytelling and exploration (M. Chen et al., 2009). Visualization has been widely used for communicating complex data to both domain experts and lay audiences by augmenting human perception (Harold et al., 2016; Ma et al., 2012a), directing visual attention (Harold et al., 2016; Healey & Enns, 2012), and facilitating comprehension (Adar & Lee, 2020; Géryk, 2015; van Wijk, 2006).

Several studies in the visualization community have explored the interconnections between visualization design and educational practices (J. C. Roberts et al., 2018; Ruchikachorn & Mueller, 2015). Roberts et al. (2018) adapted active and project-based learning strategies in their exploratory visualization system. Students can use the system to analyze problems and explore unknown relationships in a creative way. Ruchikachorn and Mueller (2015) proposed a framework for teaching unfamiliar visualization through analogy to a familiar visualization. By testing the lay audience's understanding of time series data, this learning by analogy approach demonstrated its value in bridging language barriers using visuals to support the teaching process.

Another affordance of visualization is its unique characteristic - telling stories with data. Narratives convey messages and improve comprehension. Gershon & Page (2001) claimed that storytelling is an effective way to convey information through visualization because it requires storytellers not only to be familiar with technologies but also to understand the movie culture and the character interactions. Moreover, previous studies indicate the usage of narrative storytelling can motivate learning and engagement (Dasu et al., 2021; Huynh et al., 2020; L. Zhang et al., 2019).

Compared with traditional desktop-based visualization, a higher field of view in VR leads to better performance when users navigate the story world. VR has been defined as a narrative medium that is predominated by interaction (Bahng et al., 2020), and the narrative role-play experience in VR has been demonstrated to lead to empathy (Dyer et al., 2018; D. Shin, 2018) and embodied cognition (Seo et al., 2017; D. Shin, 2018). Moreover, VR provides a spatial capacity for users to explore multiple-dimensional data quicker and with more engagement. There are two major affordances of immersive visualization that surpass desktop-based visualization: real-time exploration and rich spatial, in-depth cues (van Dam et al., 2000). Previous studies have shown that immersive visualization can make abstract scientific concepts more accessible and allow exploration from first-person perspective by placing users directly within the 3D visual-spatial data space (Buttussi & Chittaro, 2018; Khan et al., 2018; Markowitz et al., 2018). Kwon et al. (2016) demonstrated that participants tend to answer difficult questions using less time in immersive graph visualization than 2D graph visualization. Mazur et al. (2004) designed an immersive visualization to evaluate how movement, gesture, and verbal explanation impact engineering students' understanding of fluid dynamics. They found that gestures and verbalization can support generative learning articulation.

The above literature indicates an inherent connection between visualization and learning science. This claim aligns with Liu et al. (2008)'s argument that an effective visualization should serve as an extended human mind to amplify cognition. Coupled with a virtual environment, immersive visualization shows its potential to distribute the cognitive load more effectively compared with other types of technological tools. While the theory of distributed cognition (DCog) has been proposed as a visualization framework, limited empirical studies were conducted to test this idea. Immersive visualization linked affordances of virtual space together with visual awareness, revealing its potential for leveraging learning from the cognitive domain.

Theoretical Framework

The benefits of VR in Food Microbiology education have not yet been fully leveraged or investigated. To date, minimal research exists about the impacts of VR on students' motivation and knowledge retention, and the learning process during and after VR in Food Microbiology undergraduate education. While educational researchers acknowledge the benefits of using VR for learning success, present immersive tools are often not based on customized learning content and lack dedicated pedagogical guidelines for application design (Johnston et al., 2018). These ready-to-use educational VR applications cannot dynamically configure their specialized cognitive properties to extend the human mind to meet specific learning objectives. Hutchins's distributed cognition theory (DCog) has been demonstrated to account for the human-computer interaction phenomenon - visual representation is a form of external cognition, and interaction facilitates cognitive tasks (Hollan et al., 2000). With regard to motivational theories (Shirey & Reynolds, 1988; Schiefele, 2009; Deci & Ryan, 2008), scholars proposed that knowledge acquisition can be deepened by intrinsic motivation to enjoy the activity and engage with the learning materials. For example, *interest theory* (Shirey & Reynolds, 1988) reveals that situational interest can be an essential intrinsic motivator to learn. From this perspective, students will work harder if they value the study materials. *Self-determination theory* (Deci & Ryan, 2008) discusses how people develop their intrinsic and extrinsic motivation based on the satisfaction of their psychological needs. These motivational theories are conceived well and extensively applied to educational technologies. Therefore, taking DCog and motivational theories together, these ideas form the basis of the present study's conceptual framework.

It is important to review each separately to investigate how these two theoretical frameworks link together to guide the research design. First, a review of DCog will focus on the nature of how learning happens throughout distributed systems between the human and the learning environment. Second, several motivational theories, including *self-determination theory* and *interest theory* have examined how positive affective constructs correlate with academic achievement in computer-assisted learning environments. Relevant for complimentary reasons, reviews of both distributed cognition and motivational theories will clarify the relationship between authentic knowledge transmission and features of instructional media.

Distributed Cognition (DCog)

First proposed by Hutchins in 1997, distributed cognition holds that cognition is more of an emergent property of interaction than a property of the human mind. Hutchins and his colleagues conducted a study of a navy ship and demonstrated how cognitive tasks of ship navigation involve cooperation between people and the artifacts on the ship (Button, 1997). Later, Hutchins and other scholars (Hollan et al., 2000; Zhang & Patel, 2006; Kirsh, 2006) extended the scope of DCog, suggesting that human cognition and action can derive from the environment, the representation of artifacts, social and physical interaction, culture, history, space, and time.

In 2000, Hutchins and his colleagues proposed the concept of a “distributed cognitive system,” which was widely applied in human-computer interaction (Hollan et al., 2000). Its main argument is that designers of human-computer interaction systems should consider manipulating graphic representations and interactions as forms of external cognition of humans and that these visual representations and interactions can impact cognitive tasks such as reasoning and thinking. Based on this argument, learning through a computer-mediated system is an embodied activity across oneself and the world. The visualization uses computer-supported, symbolic, and metaphorical visuals to represent data and information for learners. Representation and interaction are two major components of information visualization, serving as an external representation of the human mind for carrying out cognitive decisions (Hutchins, 1991; Liu et al., 2008). Scholars have studied how information is processed through interaction between learners and the structures in their environment (Alač & Hutchins, 2004; Barab & Plucker, 2002). In VR space, this information processing can be deepened by increased immersion and spatial navigation. Here immersion refers to the perception of “being there” in the artificial world, and spatial navigation in VR refers to teleportation from users' first-person perspective. High levels of immersion in VR mimic learning material and learning environments that people are familiar and encultured with (Dyer et al., 2018; Wendrich, 2011). Virtual spatial navigation triggers interaction between the knowledge domain and the learner, leading to an experiential learning experience (J. W. Roberts, 2012). Meanwhile, the interaction is facilitated by both visual perception and gesture in the physical world, and the 360-degree virtual reality scene amplifies learners’ visual perceptions. Thus, the cognitive process in VR occurs across its distributed heterogeneous systems that combine embodiment, space, culture, and virtual artifacts. Compared with traditional instructional media such as PowerPoint slides and desktop applications, VR has great potential for supporting an extended cognition derived from the DCog.

Although DCog does not account for whether one technology is better than another, understanding how representation and interaction differ among various media types can address how learning compares across different computer-mediated learning environments.

We listed each instructional artifact’s features that facilitate learning in four categories described in Table 1: representation, interaction, learning process, and environment. Systematic analysis of these features will suggest how learning is distributed between learners and different instructional artifacts.

Based on the categorization in Table 1, we analyzed variables that account for representation and interaction differences among the varying instructional artifacts. From this table, three variables are chosen to examine differences among the three learning environments: immersion (accounting for visual-spatial interaction and visual representation), screen time (accounting for visual interaction), and learners' behavior and perceptions (accounting for physical interaction through gesture, movement, verbal, and other behaviors). With this understanding of DCog's mechanisms, evaluating immersion, attention, and learners' behavior and perceptions allow us to understand how learning happens during VR and how retention is distributed through representation and interaction in different learning environments.

Table 1. *Comparing HMD VR, Desktop VR, and Slides by Media Features.*

	Feature	**HMD VR**	**Desktop VR**	**Slides**
Representation	Static visuals	✓	✓	✓
	Animated visuals	✓	✓	
	360° visuals and video	✓	✓	
Interaction	Physical interaction (haptic)	✓	✓	✓
	Head tracking (360° visual perception)	✓		
	Virtual spatial navigation	✓	✓	
Learning process	Active learning (knowledge is triggered by interaction)	✓	✓	
	Passively learning (knowledge is fully represented)		✓	✓
Environment	Fully immersive	✓		

Motivational Theories

Scholars suggested that high levels of immersion (Dede, 2009; Narayan et al., 2005) and augmented visual perceptions (Gao et al., 2021) in VR are the main factors influencing participants’ affect such as engagement and enjoyment. According to both *interest theory* (Shirey & Reynolds, 1988) and *self-determination theory* (Deci & Ryan, 2008), Learners are intrinsically motivated if their psychological needs are fulfilled. If one perceives the study activity and process to be internally satisfying, one would become self-determined and put more effort onto the learning materials. Furthermore, students are resilient in overcoming obstacles to learning (Eccles & Wigfield, 2002; Koulouris et al., 2020; Parong & Mayer, 2018). The immersive nature of VR may draw learners' interest, and the interaction between them and the study content may sustain their engagement with the learning activities. Levels of engagement can be measured through a user's affective constructs, such as attitude towards the content and the satisfaction of the learning experience. Ryan et al. (2006) have presented several studies on video game playing. They found that the sense of immersion in participants’ gaming experiences is associated with players perceived competence and autonomy to predict players’ satisfaction needs. Huang et al. (2019) sought to understand the role of motivation in virtual tourism. They suggested that interactive activities relating to participants’ psychological needs are essential to interstage motivational dynamics in a virtual learning environment. By virtue of VR's immersion and interactivity, specialized designed educational systems could contribute towards an enhanced learning experience with the corresponding motivational component promoting positive learning outcomes. Therefore, when integrating virtual learning content to standard educational context, motivation should be enhanced compared to that of conventional instructional media. Moreover, motivation increases are predicted to support continuous cognitive outcomes after VR experiences.

Thus, by reviewing motivational theories and DCog together, and using a customized immersive visualization as the learning material, the immediate retention of the concepts in the VR group is predicted to be higher than in the Desktop VR group and Slides group. Moreover, the perceived immersion and the time spent on each lesson are expected to account for the difference in retention. Lastly, students in two VR groups are predicted to achieve higher levels of motivation and retention than the students learning from conventional instructional media. The conceptual framework of this research design is illustrated in Figure 2.

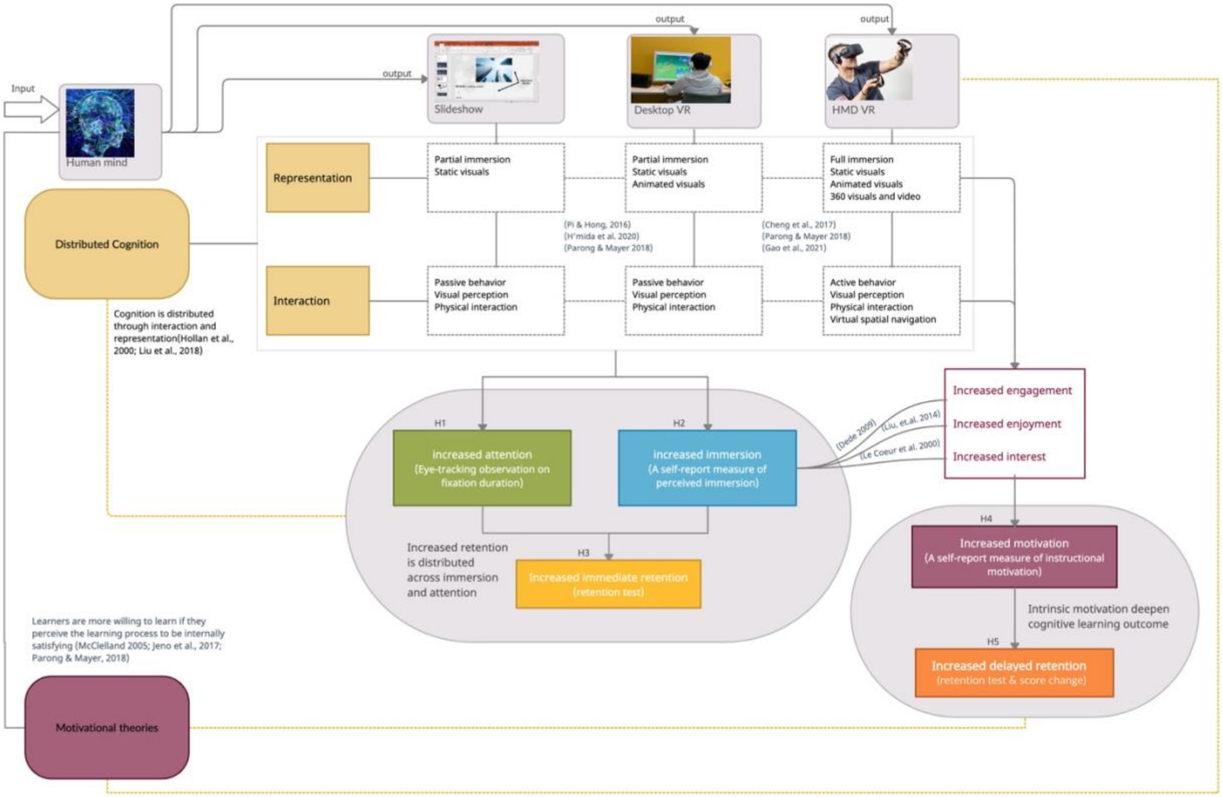


Figure 2. *Conceptual Framework of the Research Design.*

Several studies indicated that sustained attention can be operationalized as reading time and screen time (Fisher et al., 2014; Montagni et al., 2016; Shirey & Reynolds, 1988). On this basis, a longer duration of screen time can predict a more motivated perception. Moreover, perceived immersion as a subjective rating has been demonstrated to be correlated with a higher level of enjoyment, confidence, and positive attitudes. Meanwhile, *self-determination theory* posits that students would be more motivated to learn if their needs are met for autonomy and relatedness. Autonomy suggests that one will try hard in schoolwork if the learning material is linked to personal interest. Thus, according to these two motivational theories and previous empirical findings, we predict that students in HMD VR group will be more motivated to learn than students in Desktop VR and PowerPoint slides conditions.

In this study, we applied DCog and motivational theories to a self-directed learning experiment using three types of instructional artifacts. By expanding the focus of analysis beyond an individual's learning outcomes (immediate retention and delayed retention) to students' perceived immersion, visual attention, and motivation, DCog and motivational theories enable us to illustrate important aspects of immersive VR's role in Food Microbiology laboratory instruction.

Co-Design

To further understand how VR facilitates students' learning from a learner-centered approach, we launched co-design approaches (De Michell & Gupta, 1997; Steen et al., 2011) with relevant stakeholders to uncover further concrete design goals and design strategies for the VR curriculum.

Design Stakeholders

Our co-design team is composed of two VR engineer developers, one Food Microbiology professor who has been teaching the class for decades, two graduate students from the Food Microbiology department, and an education & HCI researcher.

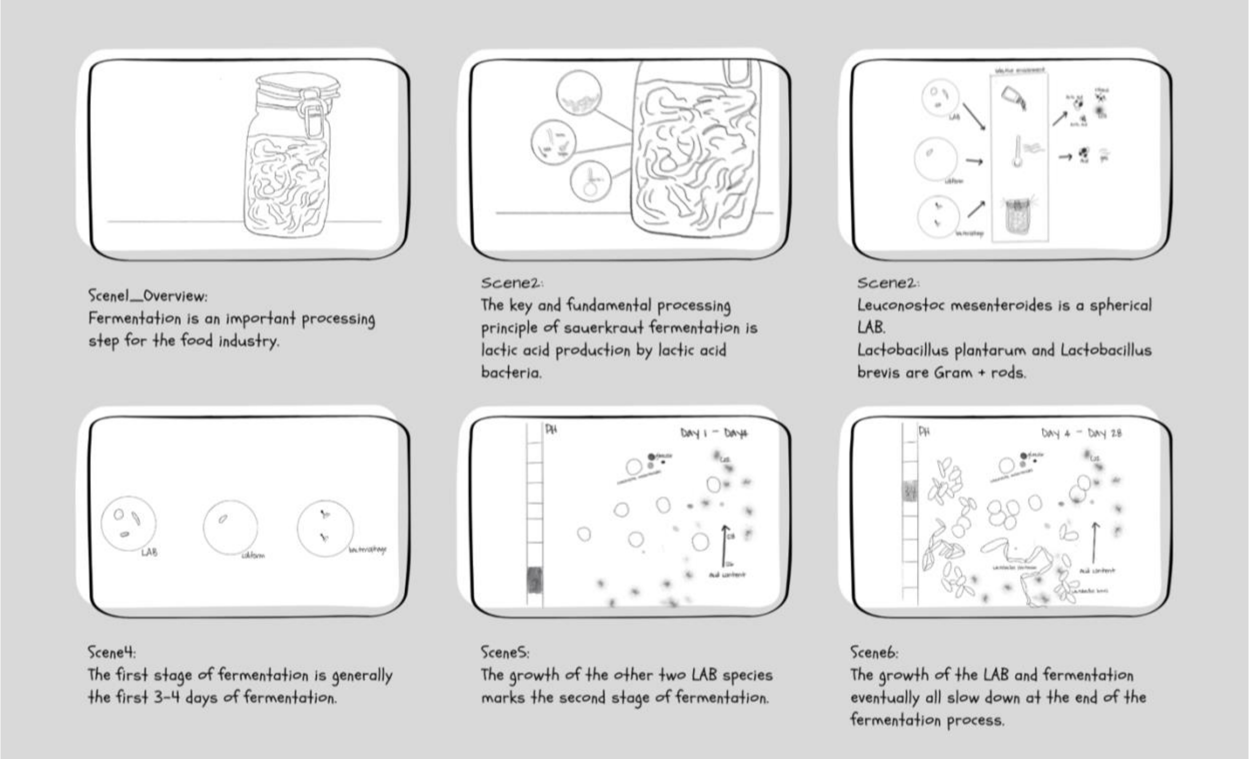
The Process

The co-design sessions were conducted remotely via Zoom at the end of 2021 to decide on appropriate instructional material for immersive visualization. After interviewing the instructor and several rounds of initial discussions, we chose The Fitness of Sauerkraut Fermentation as a learning material for the user study. The Fitness of Sauerkraut Fermentation is a mandatory curriculum module for USA undergraduate Food Microbiology laboratory classes.

The lectures mainly teach the principles and process of fermentation, such as the roles of salt, cabbage, fermentation jar, and temperature in a kitchen. It also discusses how different microorganisms' populations changed throughout fermentation and process. Usually, the lecture uses a classic fermentation curve chart that summarizes various microorganisms' populations, pH value changes, and other environmental factors for the 27-30 days fermented process. And then, in the later hands-on fermentation lab, students will make their own sauerkraut fermentation and observe microbial populations based on the lecture learning. Although the lecture is an indispensable part of the fermentation lab class, it is challenging for students to memorize complex terminologies, procedures, and microbial properties within 20- 30 minutes.

The co-design team met several times for the instructional design and finalized the structure of the Fermentation VR lecture. Two primary components of the lecture are the learning objective: The first component teaches the fermentation principles through a virtual kitchen setting so that students can virtually "enter" a kitchen to navigate each required ingredient for sauerkraut fermentation preparation. The research team modeled 3D objects of the kitchen environment so that a corresponding fermentation principle will display when students interact with an object on the counter. The second section teaches microorganisms' properties, fermentation curve, and the pH value changes through microorganisms' fermentation process in 30 days on average. In this scenario, we created a virtual microbial world to show each microbe's actual population changes and color-encoded the background to show pH values based on the pH scale. Students can interact with microbes using hand controllers to visualize their properties, fermentation chart, and pH values.

We presented our design idea with a set of low-fidelity storyboards. We then asked the Food Microbiology instructor and students to share their insights about the storyboards. We walked them through the workflow of the storyboard scenarios and invited them to identify design barriers and propose new interface strategies from a learner-centered perspective. Figure 3 shows an example storyboard during our design process. After several discussions within the research team, the final prototype is expected to comprise animated visuals, text descriptions, and audio narration.



Scene1_Overview:
Fermentation is an important processing step for the food industry.

Scene2:
The key and fundamental processing principle of sauerkraut fermentation is lactic acid production by lactic acid bacteria.

Scene2:
Leuconostoc mesenteroides is a spherical LAB.
Lactobacillus plantarum and Lactobacillus brevis are Gram + rods.

Scene4:
The first stage of fermentation is generally the first 3-4 days of fermentation.

Scene5:
The growth of the other two LAB species marks the second stage of fermentation.

Scene6:
The growth of the LAB and fermentation eventually all slow down at the end of the fermentation process.

Figure 3. *An example of a storyboards developed during co-design process.*

Two Prototypes Variations

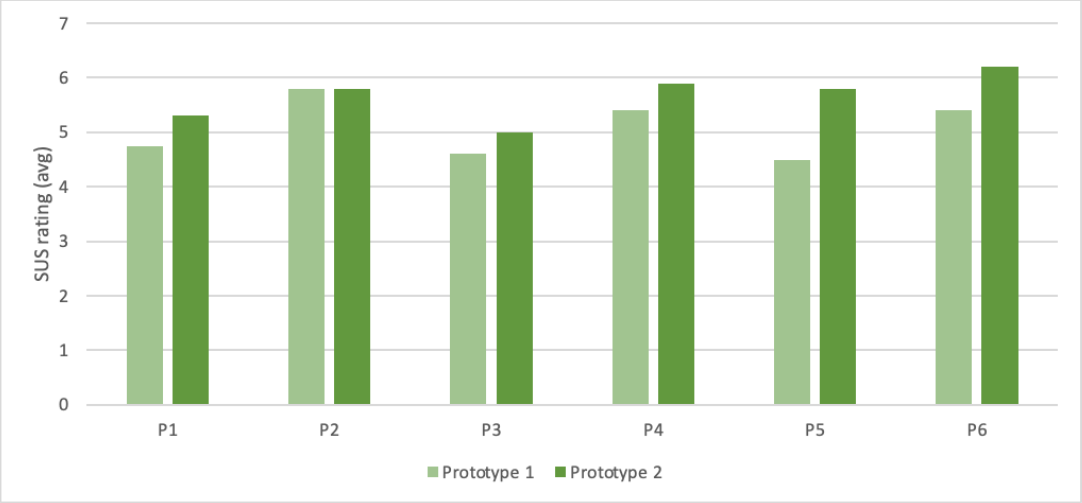
The co-design approach guided us to create two variations of prototypes based on stakeholders' opinions. In particular, the variation is derived from whether students should be guided to learn or be given more freedom to explore materials in an immersive space (Löcken et al., 2019; L. Zhang, 2022). Because each type of VR application has certain benefits, two prototypes were created for pilot testing. Prototype 1 is an automated visualization system that visualizes microbes' population changes every 20 seconds so that users can be immersed within the VR application to observe information changes every 20 seconds without interacting with the VR content. Meanwhile, users still have options to use a hand controller to select a particular microbe to look at the fermentation curve and read the property information. The prototype 2 is a user-driven visualization that allows users to have more choices to explore the fermentation process. We added "previous" and "next" buttons to enable users to select a particular fermentation day for further exploration. An example of the two prototypes is shown in Figure 4.

Figure 4. *System automated prototype (left) versus user-driven prototype (right).*

Pilot Study

We recruited 6 Microbiology students to test the two prototypes on a between-subjects design basis. Among the participants, three were male, and three were female; 4 have no prior VR experiences, and 2 have light VR experiences. The pilot study lasted 1.5 hours for each participant and was conducted in a lab setting. Each session follows the procedures: 1). brief introduction and VR training session (~ 10 minutes), testing prototype 1 (~20 minutes), testing prototype 2 (~20 minutes), filling a questionnaire (~20 minutes), and participating in a follow-up interview (~20 minutes). The questionnaire implemented System Usability Scale (SUS) (Peres et al., 2013) to evaluate the usability of two prototypes. During the follow-up interview, we also invited students to share their feeling about the prototype and their suggestions regarding design updates.

Table 2. *Total number of participants rating the usability of Prototype 1 and Prototype 2.*



Findings

All pilot testing participants preferred prototype 2, which gives users more flexibility to make interactivity choices. Table 2 shows the statistical comparison ($p = 0.02$, $SD = 0.43$) between two prototypes on usability.

Design Strategies

The pilot study not only guided us to make decisions on the existing prototypes we created but also provided valuable feedback on our design choice for the next interaction regarding improving the students' learning experiences. We used an inductive process to analyze interviews with participants and identified the following design strategies from students' perspectives. We then applied these strategies to our application design update.

- Balance the boundary between learning and play. While all participants mentioned they prefer more flexibility to interact with applications, they also emphasized the importance of using moderate interaction with study materials to avoid potential confusion.
- Support students' learning preferences to assist their information processing. Prior research reveals that visual, auditory, and kinesthetic are the three most common mediums in which students absorb information from lectures (Gilakjani, 2012; Ibrahim & Hussein, 2016). Our interview with pilot study participants also indicates their preference for both auditory and visual learning.
- Ensure text is explicitly in an immersive space. All participants mentioned text is still the main channel for them to absorb information in VR space. Therefore, it is crucial to ensure all text displays are clearly shown in students' view when using hand controllers to interact with VR content.

Fermentation VR

System Overview

Following these design strategies throughout a co-design process, we designed and implemented Fermentation VR, an immersive visualization application for teaching fermentation principles and processes in the Food Microbiology laboratory class. Fermentation VR presents several features that immerse students in a Food microbial-related virtual space in exploring and learning fermentation ingredients, environments, microorganisms, procedures, and processes.

Figure 5. *Interface scenarios. Left: lecture introduction; Middle: Kitchen scene for fermentation preparation; Right: Microbial scene for fermentation processing.*

As is shown ins Figure 5, Fermentation VR consists of three scenes: (1) an introduction to the VR lecture content, (2) a kitchen scene that allows students to explore different ingredients for fermentation preparation, and (3) a microbial-view scene from the view of a fermentation jar to visualize the fermentation process.

Implementation of HMD VR, Desktop VR, and Slides

After the VR lesson was developed for HMD VR implementation, identical learning materials were adapted into Desktop VR and PowerPoint slide formats. The Desktop VR lecture uses the same animated and interactive visuals as the HMD VR lecture, and students sit in front of a computer to interact with learning materials using a mouse. The slides lesson uses screenshots from the VR lesson. All three types of learning materials are self-paced. To ensure experimental validity, every lesson in each condition last approximately 20 minutes.

User Study

Experimental Design

Our user study used a three-condition between-subject experimental design, where participants were randomly assigned to one of the three conditions:

- **HMD group**: participants stood in the center of the tracking area, wore an Oculus Quest HMD with a display resolution of 1920×3664 pixels, and held one hand controller to experience the HMD VR based fermentation lecture. The immersive experience was rendered Oculus browser.
- **DKP group**: Participants were seated at a desk. A Mac laptop was positioned in front of the participant in the tracking area. Individuals wore headphones and used the mouse and keyboard to interact with the desktop application. The lecture was developed using an A-frame Web VR application (Takac, 2020). The learning materials in the desk application are the same as the HMD VR application and the slides.
- **SLS group**: Participants were seated at a desk. A Mac laptop was positioned in front of the participant in the tracking area. Individuals wore headphones and used the mouse and keyboard to interact with the PowerPoint slides. The lecture includes 19 pages of slides, and the learning materials is the same as the Desktop VR and HMD VR.

Participants

The study took place at a large-sized USA university over five weeks of data collection during the Spring quarter of 2022. A total number of N = 49 undergraduate students enrolled in this Food Microbiology laboratory class participated in our research. They were randomly assigned to the HMD (n = 17; 12% male; 22% female; age: *M* = 23; *SD* = 4.58), DKP (n = 16; 10% male; 22% female; age: *M* = 22; *SD* = 1.05), and SLS (n = 16; 12% male; 20% female; age: *M* = 22; *SD* = 3.03) before the start of the fermentation lecture learning.

Overall Procedures

The experiment was a mandatory learning module from an introductory Food Microbiology laboratory course for undergraduate microbiology majors. The course aims to train students in the laboratory methods used in the microbiological analysis of foods, which are critical mechanisms for studying microbial food processing, quality, and safety. We visited participating classrooms to collect consent forms, conducted the user study, and analyzed data from experiments over five weeks, as illustrated in Figure 6.

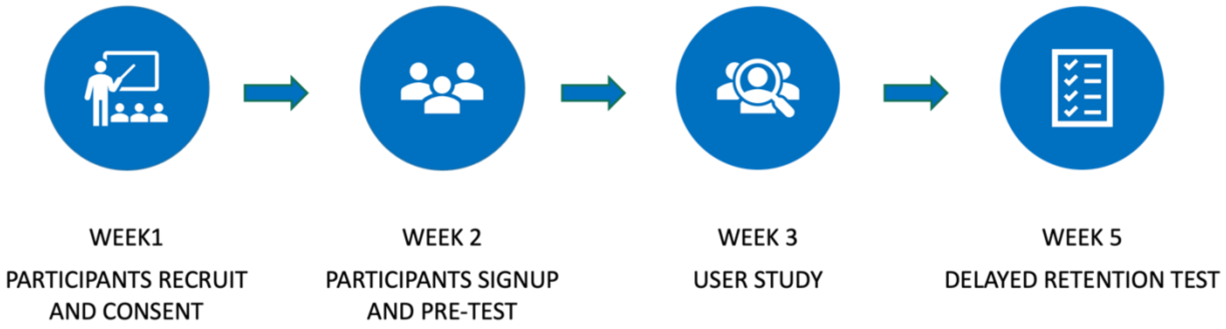


Figure 6. *Project timeline description*.

Upon approval by the Institutional Review Board, the primary researcher participated in the Food Microbiology Laboratory lecture class to debrief the project and recruit participants at the beginning of the quarter. After students provided consent to participate in the study, each was scheduled individually with the primary researcher for their assigned self-directed fermentation lecture in a lab setting. The breakdown of demographic information for each of the three groups is described in Table 3.

Before the experiment session, the participant provided their demographic information and general perspectives on educational VR in all conditions. In addition, participants' prior knowledge of Sauerkraut Fermentation was examined using a pre-test comprising identical questions as post-tests 1 and 2.

Table 3. *D*emographics.

Sample demographics (N. 49).

Characteristics	HMD VR (percent)	Desktop VR (percent)	Slides(percent)	**Total (percent)**
Gender				
Female	11 (22%)	11 (22%)	10 (20%)	32 (65%)
Male	6 (12%)	5 (10%)	6 (12%)	17 (35%)
Ethnicity				
African American/Black	0	0	0	0
American Indian/Native American	0	0	0	0
Asian American/Asian	12 (24%)	10 (20%)	13 (27%)	35 (71%)
Chicano/Latino	1 (2%)	2 (4%)	0	3 (6%)
Pacific Islander	0	0	0	0
White/European-American	4 (8%)	4 (8%)	3 (6%)	11 (22%)
Average age	23	22	22	22

During the experiment day, a training session was provided at the beginning for each participant to familiarize themselves with the functions of VR headsets and controllers. Then each participant was randomly assigned to experience either the immersive or non-immersive experiences. In addition, participants were informed that they were free to take a break during the experimental lecture due to self-directed learning principles. After completing the lecture, participants filled out post-test 1 to measure their immediate retention of the learning gains. Then they answered a self-report questionnaire, including perceived immersion, instructional motivation, VR features, system usability, and learning outcomes. In the end, each participant was interviewed to reflect on their learning experiences and perceptions of HMD VR, Desktop VR, and Slides. Figure 7 illustrates how each condition was experimented per session.

Figure 7. *Three experimental conditions (From left to right: HMD VR, Desktop VR, and Slides)*

A delayed retention test (post-test 2) was given over one week of the experiments via Qualtrics survey software. After students completed post-test 1, all students completed a set of experimental fermentation tasks in a laboratory during the class attendance time. During the hands-on laboratory, students need to apply what they learned from the experimental lecture to their actual fermentation experiments to ferment sauerkraut for around 1 hour.

Experiment Measurements

Background Information

A survey was used to collect background information on students' demographics and their prior VR experience. To reduce the confounding effects of the novelty of the VR technology, the research team offered two Google cardboard headsets to the participants at the beginning of the class to ensure there were no significant differences between students' prior user experiences of VR. In addition, students' prior knowledge of formational principles and processing was measured by a pre-test using the same content from post-test 1 and post-test 2.

Retention Test

Students' knowledge of the fermentation principles and processing after the self-directed experimental lecture was measured by a post-test including 8 items of multiple-choice questions.

The instructor of the class initially developed this retention test and then revised it based on the discussion between the instructor and the research team.

Visual Attention

Screen time refers to the amount of time spent using a device with a screen. Previous literature (Montagni et al., 2016) indicated that screen time is positively associated with an individual's self-perceived levels of visual attention. In a self-directed learning environment, assessing the total amount of time participants spent on the screen help to explore how visual representations distribute students' cognitive load and attention among different instructional artifacts.

Perceived Immersion

Students' perceived immersion was measured via an adapted version of the immersion measurement from Mütterlein (2018). The scale consists of 6 Likert scale questions.

Instructional Motivation

Students' instructional motivation in different experimental groups was investigated using Instructional Materials Motivation Survey (IMMS) developed by Kelly (2010), which consists of 9 statements concerning students' motivation for the instructional materials.

Student's Perception of Instructional Artifacts

Semi-structured interviews were used to deeply understand students’ perceptions of using VR compared to traditional slides lectures. Interview questions are mainly focused on asking students to reflect on their user and learning experiences with artifacts, the benefits and drawbacks of the artifacts, learning strategies used along with the learning process, and their suggestions for further improvements.

Results

The following sections describe the analyses concerning the variables of retention test, self-reported immersion and instructional motivation, visual attention, and students' perceptions of using HMD VR, Desktop VR, and Slides.

Table 4. *Mean comparison on pre-test, post-test 1, post-test 2, visual attention, perceived immersion, instructional motivation, and score change over time (one week).*

Variables	*Conditions*	*M*	*SD*	*F*	*P*	*η2*
Pre-test retention score (7 is the full points)	HMD VR	2.24	1.16	0.01	0.99	0.00
	Desktop VR	2.25	1.27			
	Slides	2.19	1.29			
Visual attention (seconds)	HMD VR	806	121	3.46	0.04*	0.14
	Desktop VR	696	127			
	Slides	708	127			
Perceived immersion (7 is the full points)	HMD VR	4.81	0.49	4.84	0.01*	0.18
	Desktop VR	4.18	1.13			
	Slides	3.66	1.24			
Post-test 1 retention score (7 is the full points)	HMD VR	3.34	0.74	0.54	0.59	0.03
	Desktop VR	3.75	1.08			
	Slides	3.59	1.02			
Instructional motivation (7 is the full points)	HMD VR	5.36	0.68	4.00	0.03*	0.15
	Desktop VR	5.19	0.53			
	Slides	4.73	0.62			
Post-test 2 retention score (7 is the full points)	HMD VR	3.29	0.79	2.31	0.11	0.05
	Desktop VR	2.75	0.99			
	Slides	2.50	1.14			
Retention score change (Negative number refers retention level decrease over 1 week)	HMD VR	-0.04	0.78	3.78	0.03 *	0.15
	Desktop VR	-1.00	1.36			
	Slides	-1.09	1.18			

Analysis of Knowledge Retention

Table 4 shows the relative group-dependent means and standard deviations of the knowledge retention test scores before and after the experiments. Simple intragroup comparisons between the results from pre- and post-test 1 revealed a significant increase (HMD: t = - 3.21; p < .001; DKP: t = - 4.14; p < .001; SLS: t = -3.62; p < .001) of conceptual knowledge for all three groups, but no statistically significant difference (pre-test: F (2, 46) = 0.01; p = .99; post-test 1:F (2, 46) = 0.54; p = .59) among three groups in both pre-test and post-test 1.

From post-test1 to post-test 2, intragroup comparisons indicated a significant decrease (DKP: t = 2.50; p = .01; SLS: t = 3.42; p < .001) of conceptual knowledge for Desktop VR and Slides groups, but no significant difference in HMD VR groups (t = 0.18; p = .42). Although no statistically significant difference (F (2, 46) = 2.31; p = .11) identified among three groups in post-test 2, the retention level changes from post-test 1 to post-test 2 (F (2, 46) = 3.78; p = .03) showed a significant different among three groups.

We then conducted Tukey's HSD Test and Two-Way Repeated Measures ANOVA to further examine this problem. The post-hoc testing in Table 5 revealed that the mean value of HMD was significantly different between HMD and SLS groups (p = .04, 95% C.I. = [0.02, 2.07]).

Table 5. *Knowledge retention score comparison.*

Pairwise	$Xi - Xj$	**Confidence interval**	**P value**	**Result**
HMD: DKP	0.96	-0.07, 1.98	.07	Failed to Reject
HMD: SLS	1.05	0.02, 2.07	.04	Rejected
DKP: SLS	0.09	-0.95, 1.14	.9	Failed to Reject

As illustrated in Table 6, A two-way ANOVA revealed there was not a statistically significant interaction between the effects of time (post-test 1 and post-test 2) and (*F* (2, 97) = 2.23, *p* = .11). Simple main effects analysis showed that time has a statistically significant effect on retention score (*p* = .003). Simple main effects analysis showed that instructional artifacts did have a statistically significant effect on retention scores (*p* = .60).

Table 6. *Two-way ANOVA based retention score comparison.*

Source of variation	**Sum of Squares**	***df***	***MS***	***F***	***p***
Time	11.97	1	11.97	9.49	.003
Artifacts	1.28	2	0.64	0.51	.60
Within groups	5.61	2	2.81	2.23	.11
Error	116.00	92	1.26		
Total	134.88	97			

Analysis of Visual Attention

Observed screen time was used to measure participants' visual attention during self-directed learning in each experiment. A one-way ANOVA analysis indicated a significant group difference in screen time (*F* (2, 46) = 3.46; *p* = .04) among the three groups.

Analysis of Perceived Immersion and Instructional Motivation

To investigate group differences in perceived immersion and instructional motivation, a one-way ANOVA analysis was performed. As is shown in Figure 8, there was a significant group difference in perceived immersion and instructional motivation (immersion: *F* (2, 46) = 4.84; *p* = .01; motivation: *F* (2, 46) = 4.00; *p* = .04) among three groups.

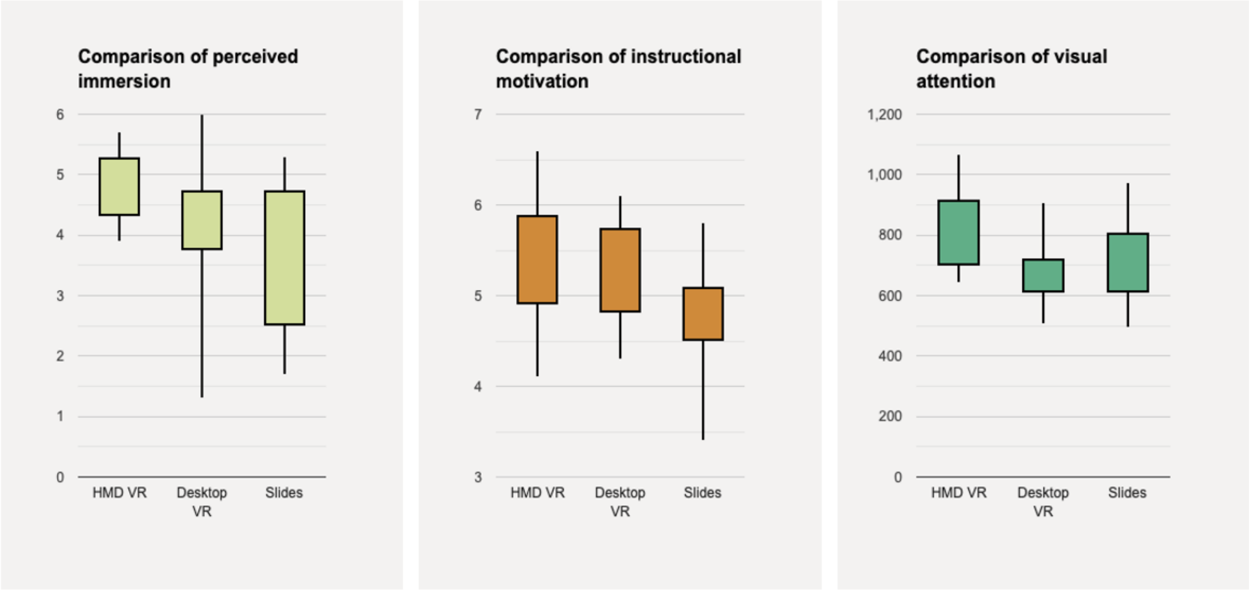


Figure 8. *Comparison of perceived immersion, instructional motivation, and visual attention.*

Analysis of Correlation among Score change, Immersion, Motivation, and Visual Attention

To explore the relationship between immersion, motivation, visual attention (screen time), and score change, the association among all variables was examined using Pearson's correlation analyses. Several significant correlations were found in this study, as are shown in Figure 9 (a), (b), and (c).

First, significant correlations were found between score change and motivation, score change and immersion, immersion and motivation, immersion and visual attention, motivation, and visual attention. There is a significant small-medium positive relationship between score change and immersion, *r* (47) = .36, *p* = .011); as well as score change and motivation, *r* (47) = .30, *p* = .039. Both immersion and motivation, and immersion and visual attention were found to be strongly correlated: immersion and motivation, *r* (47) = .70, *p* < .001), immersion and visual attention, *r* (47) = .55, *p* < .001). Motivation and visual attention were found to be mediumly positive correlated with each other, *r* (47) = .35, *p* = .015). These results of the Pearson correlation indicated that students with higher immersion and motivation tend to better memorize the learning materials during the lecture experiment.

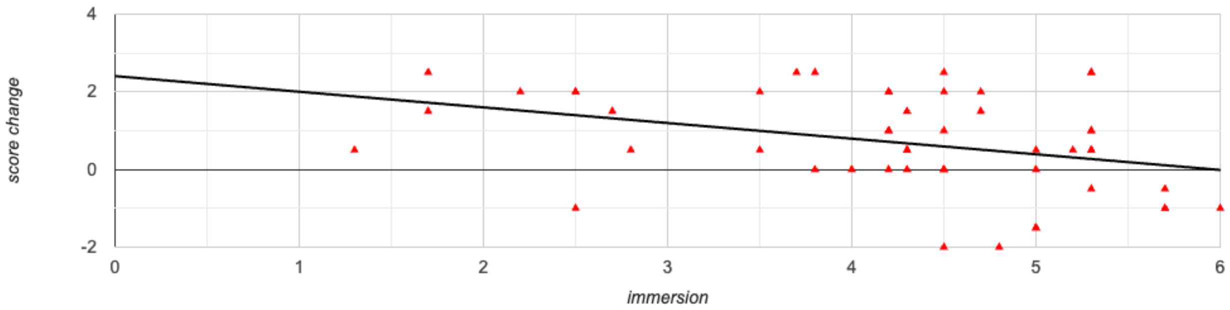


Figure 9 (a). *Association between score change and immersion.*

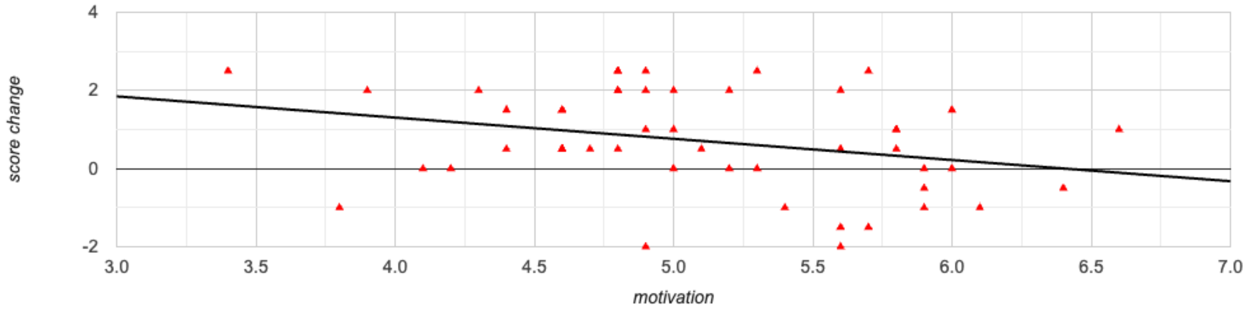


Figure 9 (b). *Association between score change and motivation.*

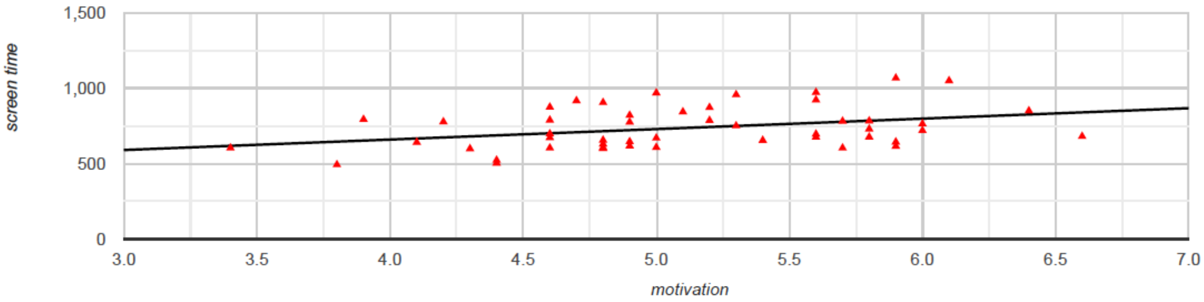


Figure 9 (c). *Association between motivation and visual attention (screen time).*

Analysis of Students' Retention Score Change Over Time

We then analyzed the change in students' retention scores from pre-test to post-test 1 and post-test 2 per question (Q1 to Q7), as is shown in Figure 10. The figure shows no obvious unique patterns reflecting students' retention change from the three tests. However, it is worth noting that most questions (Q1, Q2, Q5, and Q7) have a higher retention rate from post-test 1 to post-test 2 in the HMD group compared to the other two groups. Particularly in Q5, the HMD groups' accuracy rate significantly increased from post-test1 to post-test 2, the Slides group's accuracy rate dropped from post-test 1 to post-test 2, and the Desktop VR group's accuracy remained relatively slow increase from post-test 1 to post-test2. Another interesting finding is that HMD students scored the highest points (0.96) in post-test1 to Q6, which refers to almost every student in the HMD group answering this question correctly, but scores dropped from post-test1 to post-test 2 in all three groups.

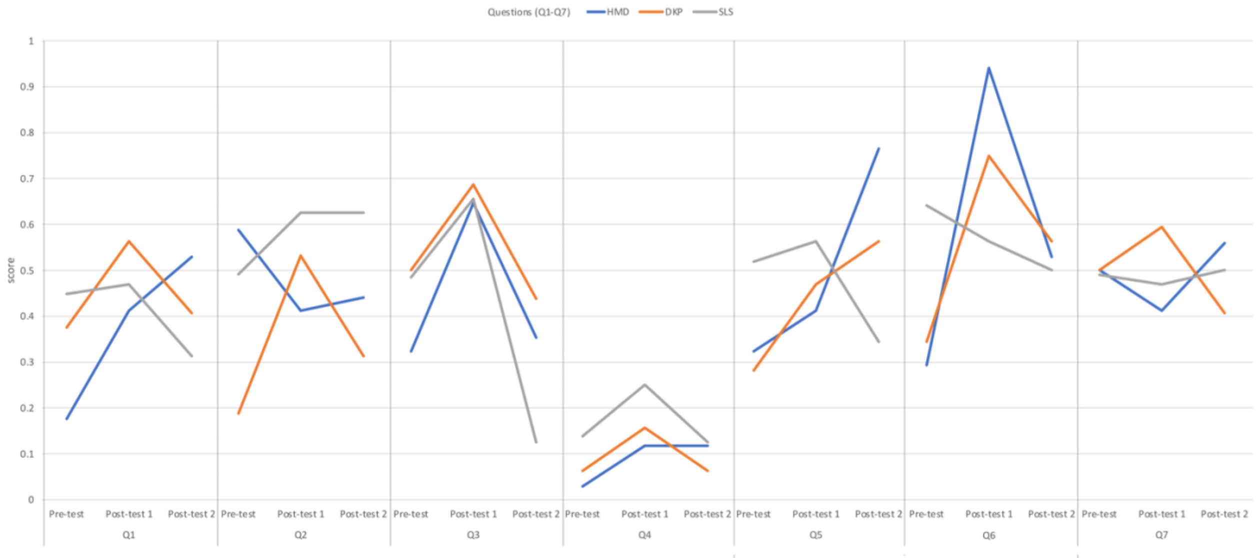


Figure 10. *Comparison of students' retention score in pre-test, post-test 1, and pos-test 2 per question.*

Analysis of Students' Perceptions of Instructional Artifacts

In this section, we report our analysis of students' responses regarding their perceptions of HMD VR, Desktop VR, and Slides during the interview.

Thematic Analysis

Under the guidance of established open coding methods (Belotto, 2018), we performed a thematic analysis through an inductive process on all students' survey responses and interview transcripts. At first, I created a codebook of common themes concerning user experiences, benefits, challenges, and feedback as the first coder. Then another researcher coded the transcripts and survey responses individually based on the initial codebook. We discussed the emergent code through multiple coding passes until reaching a consensus on the themes reflecting students' perspectives. Lastly, we reached a strong agreement in interrater reliability with Cohen's Kappa $\kappa > 0.6$.

How does HMD VR, Desktop VR, and Slides contribute to learning?

In the post-questionnaire, we asked students how features of these instructional artifacts contribute to students' cognitive and affective processing. Figure 11 illustrates students' responses to the usefulness of elements in each instructional artifact for their learning, and Figure 12 shows students' answers to the interestingness of elements in each instructional artifact for their learning. From the questionnaire responses, we found that students in the Slides group feel the text is most valuable, but visuals are most interesting for their learning experiences. In contrast, the Desktop VR group thought the text was most useful, and the virtual environment is most interesting for learning. However, it is interesting that the HMD group thinks visual is most helpful for their learning than text, although they also feel the virtual environment is most interesting for their immersive learning experiences.

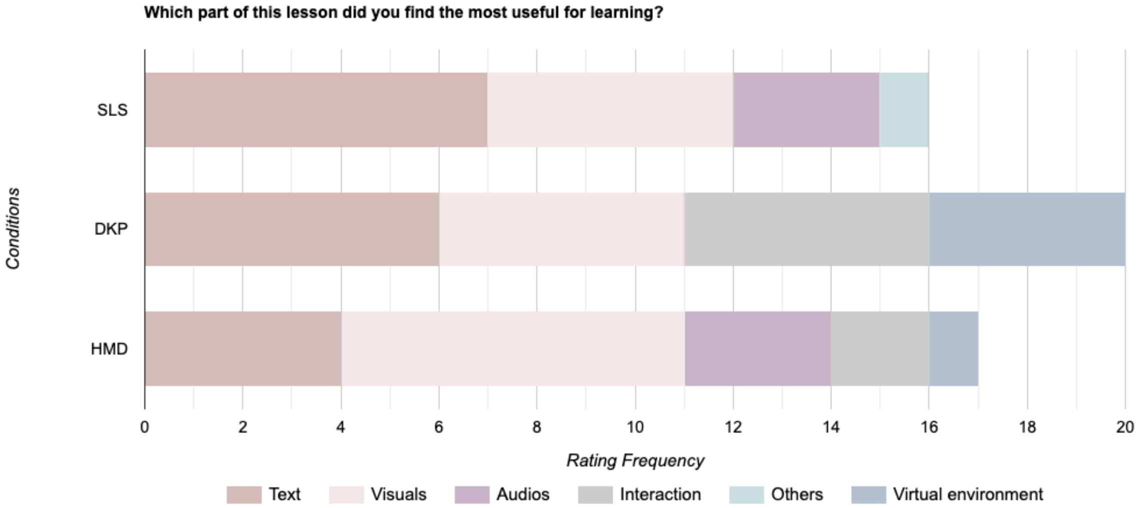


Figure 11. *Students' perceptions of the most useful components in each artifact for learning derived from multiple choice questions during post-test 1.*

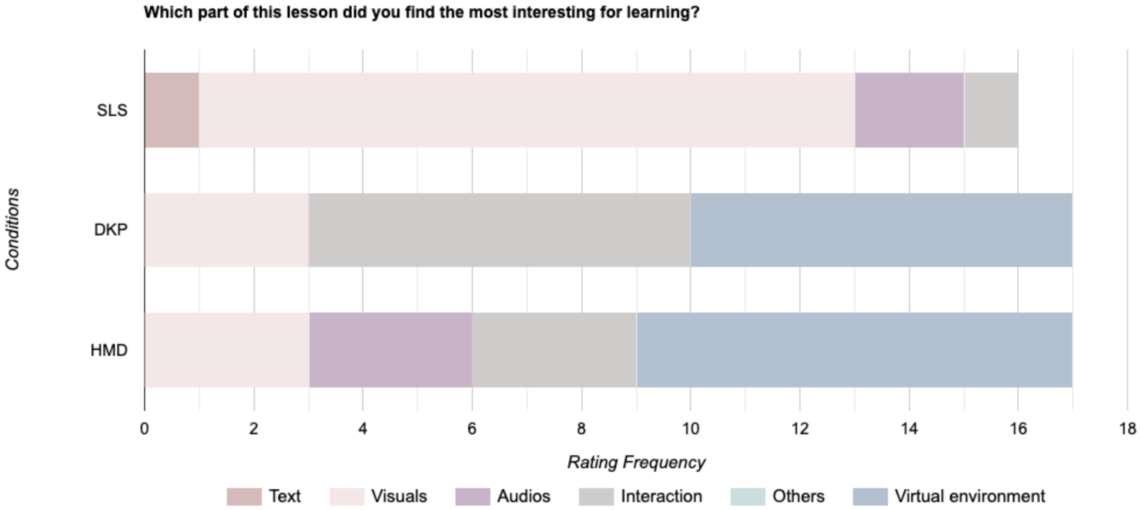


Figure 12. *Students' perceptions of the most interesting components in each artifact for learning derived from multiple choice questions during post-test 1.*

Characteristics of Three Instructional Artifacts

We transcribed the audio for the interviews and then analyzed the transcripts using the Maxqa qualitative analysis software (Kuckartz & Rädiker, 2019). We started with an open coding process by segmenting the transcripts and applying descriptive codes (Merriam & Tisdell, 2015). Next, through an iterative analysis and discussion process, we looked for common features in which students acknowledged the artifacts' helpfulness and refined codes accordingly. After several rounds of discussion, the research team identified the characteristics of each instructional artifact from students' perspectives, as described in Table 7.

We found that 46% of comments shared that “engagement” is the main feature of HMD VR that helps with learning. In comparison, 24% of comments highlighted “features/functionality” and 22% of comments mentioned “visualization” as a key characteristic of HMD VR for educational purposes. According to students’ responses, staying engaged with learning materials in HMD VR is closely related to its enriched visual representations. According to several comments, such engagement makes students “*easy to focus on [study materials]”*. Features of HMD VR refer to the novel immersive experience in the virtual world, which is also closely related to the other two characteristics. Students’ responses reveal that the novel immersive experiences and interactive visuals are the initial factors that trigger students’ interests to continue exploring and thus foster a sense of sustained engagement through their learning experiences. For example, one student mentioned that: *“the process shows the material in pretty different and brand-new ways, the information pops up upon looking at it. I am not quite sure how to express the experiences, but I think in some way it is helping building up understandings of some materials”.*

Table 7. *Summary of artifacts' characteristics helps in learning.*

Characteristics	**Description**	**Example**
Ease of Use	Comments that describe the artifacts as being easy to use, simple, and/or convenient.	*"The benefits of powerpoint slides are that they are easy to use and can be easily done in your own pace where you can go back and forth."*
Features/Functionality	Comments related to the different features or functions that the artifact offered. e.g., immersion for VR, user control for Desktop VR, etc.	*"The unconventional learning method which utilized VR, which is very uncommon. It allows the users to be fully involved in the virtual world that they are in with the materials and actions presented."*
Access	Comments refer to the artifact being accessed or available for everyone to use.	*"The benefits of the slides are easy access for students and faculty and they can be presented to a large audience."*
Compatibility	Comments refer to how compatible the artifact was with another artifact.	*"It (Slides) is straightforwardly related with how we are tested (if we are tested in traditional ways). It is convenient as lecture note for exam review."*
Navigation	Comments about the straightforward navigation or consistency of the artifact.	*"They (Slides) are easy to use and can be easily done in your own pace where you can go back and forth."*

Familiarity	Comments refer to how familiar the artifact users were.	*“Most everyone has a computer and know how to use it”*
Visualization	Comments related to the visuals presented within the artifact.	*“Can recall the information by moving my eyes to where it was in VR, I was able to see the microorganisms very clearly over time.”*
Interact with materials	Comments about the artifact facilitate interaction between the learner and the study material.	*“Because the information pops up upon hovering with a mouse, it's easier to remember than with slides because it isn't monotonous.”*
Information processing	Comments about the use of the artifact to support cognitive processing of learning materials such as remembering, understanding, comprehension.	*“The process show the material in pretty different and brand new ways. I am not quite sure how to express the experiences, but I think in someway it is helping building up understandings of some materials”*
Engagement	Comments about the artifact being useful for promoting student engagement.	*“I think VR is a lot more engaging which helped me keep my focus throughout the lesson. I was also more motivated to learn the material despite not needing to continue.”*

Students' responses to what characteristics of Desktop VR help in learning are similar to their experiences with HMD VR. 37% of comments shared that "Engagement" is the main characteristic of Desktop VR for learning, while 33% of comments featured "interact with materials" and "features/functionality ."Desktop VR features mainly focus on the partial virtual experiences caused by "*drag and rotate the mouse*" and the personalized learning experience caused by "*more user control to select information* ."It is worth noting that "interact with materials" is more frequently mentioned as a beneficial characteristic of Desktop VR by students than "visualization." Although both Desktop VR and HMD VR implemented the same visual contents, our interview results reveal that visual awareness is perceived more clearly when accompanied by high immersive experiences. Recent literature also confirms this finding (Chu et al., 2022; Mania et al., 2006).

When students shared their perceptions of slides, 50% of comments mentioned that the "ease of use" is the main characteristic of slides helps in learning; 44% of comments mentioned "navigation," and 31% of comments mentioned "familiarity." These findings reveal that usability is still essential for system designers and engineers to consider when designing novel educational technologies. Comments about navigation indicate the importance of efficiently accessing study materials in a self-directed learning environment. Moreover, "navigation" and "familiarity" also align with Norman's design principle on Affordance, which depicts the link between things look and how they are used in a user-centered design perspective (Norman, 2010).

Study Strategies

The general study strategies of using HMD VR, Desktop VR, and Slides for self-directed learning differed from interviews with students and observed learning behavior during experiments. For example, Slides participants were observed to tend to skim all slides following a linear presentation sequence to get a quick overview and then jump to a particular slide for further investigation. On the contrary, we observed that Desktop and HMD VR participants tend to navigate applications as a gaming experience through a lens of experiential learning to deepen their cognitive gains. For example, Desktop and HMD VR participants used mouses and controllers to interact with virtual element frequently regardless of whether the virtual object was related to the study materials. These differences are closely related to the characteristics of each instructional artifact and can be used to inform design principles for immersive learning. While the educational affordances of HMD VR are well established in the current research community, it is important to consider learners' classroom routine learning strategies. For example, during our study, when asking students if they would like to choose HMD VR instead of traditional slides for laboratory lectures, most students responded with *"no*" and "*I am not sure*." In addition, while students acknowledged VR's affordances in supporting engagement, many of them expressed that they are still accustomed to PowerPoint slides because this is "*what I usually do for exam preparation.*"

Discussion

Reflecting on our study, results suggest significant differences in retention score changes, students’ perceived immersion, motivation, and visual attention among HMD VR, Desktop VR, and Slides, though we observed similar immediate retention outcomes across all three experimental groups.

Firstly, we recorded students' screen time duration on different instructional artifacts to observe students' visual attention during their self-directed learning experiments. The result indicated that the HMD group had more information processing time than the Desktop VR and Slides participants. During the experiment, we observed that the Desktop VR group and Slides group shifted their attention more frequently compared to the HMD VR group participants. The partial reason might be due to the different unique features in each learning condition. For example, wearing cumbersome head-mounted headsets in HMD VR conditions may cause inconvenience for participants to take off and on devices. On the contrary, Desktop VR and Slides participants can easily and quickly turn their heads towards any directions they would like to focus on beyond the study materials. These results support our **H1 and H2**. Therefore, when designing virtual learning experiences, evaluating users' perceived immersion and visual attention should be taken into account, particularly when understanding immersive learning from the sensation of participants' emotional perceptions.

Our results indicate all three groups scored similarly on their immediate retention tests. Though this result seems to be discordant with **H3**, such non-homogenous results do not reveal a false theoretical conjecture. One possible explanation is that given its dependence upon the heavy head-mounted display and the narrow field of view of 360-degree environment perception, the current form of HMD VR did not provide a satisfactory learning experience. For instance, a few students in HMD VR groups reported motion sickness when experiencing HMD VR. During the interview session, students mentioned that technological access and motion sickness are significant concerns of HMD VR. These negative perceptual and affective perceptions may hinder students’ cognitive performance after experimental instruction. In the future, we need to consider these non-cognitive elements more comprehensively to explore how knowledge construction is distributed across learners, tools, technologies, and environments.

Our study shows consequential effects on students' motivation to learn Sauerkraut Fermentation. As students spent much longer in the HMD VR group, we assume that HMD VR is more attractive and attention-grabbing, which would lead to a continuous interest and curiosity to explore the instructional material. Thus, students' increased curiosity can be translated into motivation to learn the subject, theoretically expected to support **H4**.

Furthermore, we observe a significant difference in retention score change among the three groups. Notably, the HMD group participants scored highest in the delayed retention test and had the smallest score drop from their immediate-delayed retention test comparison. This finding suggests that HMD participants outperformed the other groups regarding their long-term knowledge retention, which supports our **H5.** According to *interest theory*, one's situational interest in a study material can be translated into an individual interest in a long-term learning context (Magner et al., 2014). Thus, increased long-term knowledge retention in the HMD group can be attributed to the participants' increased motivation and immersion. Our findings on the correlation between immersion, motivation, and long-term retention support this claim. Moreover, compared to Desktop VR users using a mouse or keyboard to experience visual changes through abstract navigation, HMD VR users entered their virtual surroundings using the same embodied activities that happened in real life. Therefore, such simulation from fully immersive VR can lead to a higher level of sense of presence during the task.

From correlation analysis, we have found an association among participants' score change and immersion, score change and motivation. This provides HCI and learning sciences researchers with new perspectives to understand VR's learning process and outcomes. Furthermore, we find that visuals are essential for students' knowledge processing in virtual environments instead of text. In contrast, a virtual environment is the most critical element than interactivity to keep students engaged. This information helps researchers determine what environment features they should look at to inform users' learning success and user experience. Lastly, the characteristics identified from each instructional artifact help VR and media developers deal with the increasing complexity of modern interactive systems, which can be used to improve the design in an early stage of the developing process before it is finally implemented. For example, if one wants to train students' social skills, using HMD VR might be more effective than PowerPoint slides and Desktop VR, as it allows students to experience embodied social interactions which mimic their real-life experiences instead of didactic information dissemination.

Design Implications

In our study, we implemented audio narration as an add-on to emphasize the key knowledge points and help students process multimodal information. This design is derived from the cognitive theory of multimedia learning (CTML, Mayer, 2021), which examines the combined visual and verbal presentation's contribution to improving students' academic performance. Our study found that students' learning processes changed when adding audio. For example, Slides participants were observed to tend to spend more time on the individual slide if there was audio added to the written text and pictures. However, it is noteworthy that participants across all three groups did not report any add-on effects from audio narration beyond the visuals and texts, except a few participants expressed their appreciation of the flexible design considerations.

Schmidt-Weigand et al. (2010) found that the distribution of visual attention in digital learning is extensively guided by written text. On this basis, our study adds a new value: the combination of visuals and text largely guides the distribution of visual attention in the virtual learning environment. When participants experience the Desktop VR, visual awareness is less interweaved with text information processing because these visual changes are triggered by relatively abstract navigation interfaces such as mouse-clicking and button-pressing. However, the bodily actions in the fully immersive space allow participants to perceive a higher level of visual awareness using walking and head rotation. These body-specific cues enable participants to foster a sense of embodied access to a virtual kitchen for sauerkraut fermentation preparation and to feel as if they were in a fermentation jar experiencing microbial procedures from a kinesthetic perspective.

Integrating note-taking features into VR lectures is another insight derived from our results. For example, one student shared: *"I am used to taking notes when reading a slide, and it really helps me to reconstruct my understanding… but VR seems incapable of doing this because it is fully immersive."* This reminded us to reflect that the motivation of using slides in educational settings is not only a singular teaching method but also supplemental study materials along with class notes. Furthermore, as an important approach to augmenting an individual's memory, note-taking helps students categorize information as variable and store it in text format for future reference. When integrating notes-taking features in VR applications, students' deep information processing can continue and reach their full potential. Recent research has also shown the positive impacts of notes-taking applications on academic success, in aiding short-term memory (Riche et al., 2017), encouraging individual learning responsibility (Zhu et al., 2013), increasing participants' social interaction quality (Bauer & Koedinger, 2007; Exposito et al., 2017; Gero et al., 2022), and assimilating large information (Nguyen & Liu, 2016; Reimer et al., 2009).

Another design consideration informed from the interview is integrating the non-linear structure of PowerPoint slides into educational VR applications to meet students’ learning needs when using the self-directed learning method. Many students expressed that jumping back and forth to a particular slide helps them better link knowledge pieces into an integrated concept map, which is hard to achieve in desktop and HMD VR. In general, students have the freedom to choose a linear or non-linear learning strategy when using PowerPoint slides for self-directed learning. Students can gradually build up their overview picture of knowledge following a linear presentation sequence. When implementing a non-linear presentation strategy, students can elaborate on relevant knowledge and organize different graphic images by linking words or phrases.

Self-directed learning with technology is based on learners' choice of their preferred personal strategies. Therefore, it is necessary to take the initiative to consider learners' needs. Due to the complexity of the VR learning interface, knowledge cannot be presented in whole at once due to the principles of interaction design. Therefore, in VR, information is usually triggered by interactions between the learner and the explicit learning content. This might lead to learners' negative learning experiences if they were unfamiliar with the interaction techniques during their immersive activity. Previous research reveals that when using PowerPoint slides, directly jumping to a particular slide provides rich leaner-content interaction (D. Zhang et al., 2004) and helps students form concept relationships (Brian Filmer & Md Deni, 2020; Reed, 2006). Therefore, it is crucial to consider navigation style when designing a VR lecture to ensure the design principles would not hinder its expected instructional effectiveness. Insights derived from PowerPoint affordances (e.g., ease of use, direct navigation, and user-friendly control buttons) are able to lead to effective interactivity design between study materials and learners.

Conclusion and Future Research

In this study, we proposed a theoretical framework to evaluate how immersive visualization facilitates knowledge retention grounded in the theory of distributed cognition and motivational theories. We then designed a VR lecture teaching the Fitness of Sauerkraut

Fermentation by following co-design paradigms. We conducted a mixed-method study with Food Microbiology undergraduate students by randomly assigning them into three experimental groups: HMD VR, Desktop VR, and Slides. In particular, students' academic outcomes (e.g., short-term retention and long-term retention outcomes), learning experience data (e.g., immersion, motivation), and behavioral data (e.g., visual attention, observed behavior) were examined. Our findings suggest several design opportunities for education, HCI researchers, and VR developers. Results presented in our study also inform future generations to implement a variety of digital artifacts into customized learning in higher education.

Future research should continue exploring the impacts of different artifact-mediated lectures on related students' hands-on procedural learning. Although our study was conducted in a fundamental Food Microbiology laboratory class, we did not examine the long-term effects of students' lecture learning on their relevant laboratory experimental performances. A follow-up study that explores students' performance during the sauerkraut fermentation lab session is needed to support how learning occurs during and after immersive visualization. To do so, we can develop an in-depth understanding of how declarative knowledge evolved into a procedural learning process.

References

Adar, E., & Lee, E. (2020). Communicative visualizations as a learning problem. *IEEE Transactions on Visualization and Computer Graphics,* 27(2), 946-956. https://doi.org/10.1109/TVCG.2020.3030375

Ahlberg, G., Enochsson, L., Gallagher, A. G., Hedman, L., Hogman, C., McClusky, D. A., 3rd, Ramel, S., Smith, C. D., & Arvidsson, D. (2007). Proficiency-based virtual reality training significantly reduces the error rate for residents during their first 10 laparoscopic cholecystectomies. *American Journal of Surgery, 193*(6), 797–804.

Alač, M., & Hutchins, E. (2004). I See What You Are Saying: Action as Cognition in fMRI Brain Mapping Practice. *Journal of Cognition and Culture*, *4*(3-4), 629–661.

Allcoat, D., & von Mühlenen, A. (2018). Learning in virtual reality: Effects on performance, emotion and engagement. *Research in Learning Technology*, *26*. https://doi.org/10.25304/rlt.v26.2140

Anderson, A. E., Justement, L. B., & Bruns, H. A. (2020). Using real-world examples of the COVID-19 pandemic to increase student confidence in their scientific literacy skills. *Biochemistry and Molecular Biology Education: A Bimonthly Publication of the International Union of Biochemistry and Molecular Biology, 48*(6), 678–684.

Bahng, S., Kelly, R. M., & McCormack, J. (2020). Reflexive VR Storytelling Design Beyond Immersion: Facilitating Self-Reflection on Death and Loneliness. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 1–13.

Barab, S. A., & Plucker, J. A. (2002). Smart People or Smart Contexts? Cognition, Ability, and

Talent Development in an Age of Situated Approaches to Knowing and Learning. *Educational Psychologist*, *37*(3), 165–182.

Bauer, A., & Koedinger, K. R. (2007). Selection-based note-taking applications. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 981–990.

Belotto, M. J. (2018). Data Analysis Methods for Qualitative Research: Managing the Challenges of Coding, Interrater Reliability, and Thematic Analysis. *The Qualitative Report; Fort Lauderdale*, *23*(11), 2622–2633.

Bernal, G., & Maes, P. (2017). Emotional Beasts: Visually Expressing Emotions through Avatars in VR. *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, 2395–2402.

Brian Filmer, A., & Md Deni, A. R. (2020). Powering Up Interactivity in the Use of PowerPoint within an Educational Context. *2020 The 4th International Conference on Education and Multimedia Technology*, 107–111.

Button, G. (1997). Cognition in the Wild, Edwin Hutchins. *Dordrecht*, *6*(4), 391–395.

Buttussi, F., & Chittaro, L. (2018). Effects of Different Types of Virtual Reality Display on Presence and Learning in a Safety Training Scenario. *IEEE Transactions on Visualization and Computer Graphics*, *24*(2), 1063–1076.

Cheng, A., Yang, L., & Andersen, E. (2017). Teaching Language and Culture with a Virtual Reality Game. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 541–549.

Chen, J. A., Tutwiler, M. S., Metcalf, S. J., Kamarainen, A., Grotzer, T., & Dede, C. (2016). A multi-user virtual environment to support students' self-efficacy and interest in science: A latent growth model analysis. *Learning and Instruction*, *41*, 11–22.

Chen, M., Ebert, D., Hagen, H., Laramee, R. S., van Liere, R., Ma, K.-L., Ribarsky, W., Scheuermann, G., & Silver, D. (2009). Data, information, and knowledge in visualization. *IEEE Computer Graphics and Applications*, *29*(1), 12–19.

Chu, X., Xie, X., Ye, S., Lu, H., Xiao, H., Yuan, Z., Chen, Z., Zhang, H., & Wu, Y. (2022). TIVEE: Visual Exploration and Explanation of Badminton Tactics in Immersive Visualizations. *IEEE Transactions on Visualization and Computer Graphics*, *28*(1), 118–128.

Cottone, A. M., & Yoon, S. (2020). Improving the Design of Undergraduate Biology Courses toward the Goal of Retention: The Case of Real-World Inquiry and Active Learning through Metagenomics. *Journal of Microbiology & Biology Education: JMBE*, *21*(1). https://doi.org/10.1128/jmbe.v21i1.1965

Dasu, K., Ma, K.-L., Ma, J., & Frazier, J. (2021). Sea of Genes: A Reflection on Visualising Metagenomic Data for Museums. *IEEE Transactions on Visualization and Computer Graphics*, *27*(2), 935–945.

Deci, E. L., & Ryan, R. M. (2008). Self-determination theory: A macrotheory of human motivation, development, and health. *Canadian Psychology/Psychologie Canadienne*, *49*(3), 182–185.

Dede, C. (2009). Immersive interfaces for engagement and learning. *Science*, *323*(5910), 66–69.

Dehesa, J., Vidler, A., Lutteroth, C., & Padget, J. (2020). Touché: Data-Driven Interactive Sword Fighting in Virtual Reality. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 1–14.

De Michell, G., & Gupta, R. K. (1997). Hardware/software co-design. *Proceedings of the IEEE, 85*(3), 349–365.

Dunnagan, C. L., Dannenberg, D. A., Cuales, M. P., Earnest, A. D., Gurnsey, R. M., & Gallardo-Williams, M. T. (2020). Production and Evaluation of a Realistic Immersive Virtual Reality Organic Chemistry Laboratory Experience: Infrared Spectroscopy. *Journal of Chemical Education*, *97*(1), 258–262.

Dyer, E., Swartzlander, B. J., & Gugliucci, M. R. (2018). Using virtual reality in medical education to teach empathy. *Journal of the Medical Library Association: JMLA*, *106*(4), 498–500.

Eccles, J. S., & Wigfield, A. (2002). Motivational beliefs, values, and goals. *Annual Review of Psychology*, *53*, 109–132.

El Beheiry, M., Doutreligne, S., Caporal, C., Ostertag, C., Dahan, M., & Masson, J.-B. (2019). Virtual Reality: Beyond Visualization. *Journal of Molecular Biology*, *431*(7), 1315–1321.

Exposito, M., Zeamer, V., & Maes, P. (2017). Unobtrusive Note Taking: Enriching Digital Interpersonal Interactions Using Gestures. *Companion of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing*, 167–170.

Farič, N., Potts, H. W. W., Hon, A., Smith, L., Newby, K., Steptoe, A., & Fisher, A. (2019).

What Players of Virtual Reality Exercise Games Want: Thematic Analysis of Web-Based Reviews. *Journal of Medical Internet Research*, *21*(9), e13833.

Fisher, A. V., Godwin, K. E., & Seltman, H. (2014). Visual environment, attention allocation, and learning in young children: when too much of a good thing may be bad. *Psychological Science*, *25*(7), 1362–1370.

Fu, H.-L., Fang, P.-H., Chi, C.-Y., Kuo, C.-T., Liu, M.-H., Hsu, H. M., Hsieh, C.-H., Liang, S.-F., Hsieh, S., & Yang, C.-T. (2020). Application of Brain-Computer Interface and Virtual Reality in Advancing Cultural Experience. *2020 IEEE International Conference on Visual Communications and Image Processing (VCIP)*, 351–354.

Fuller, U., Johnson, C. G., Ahoniemi, T., Cukierman, D., Hernán-Losada, I., Jackova, J., Lahtinen, E., Lewis, T. L., Thompson, D. M., Riedesel, C., & Thompson, E. (2007). Developing a computer science-specific learning taxonomy. *SIGCSE Bull.*, *39*(4), 152–170.

Fu, X., Zhu, Y., Xiao, Z., Xu, Y., & Ma, X. (2020). RestoreVR: Generating Embodied Knowledge and Situated Experience of Dunhuang Mural Conservation via Interactive Virtual Reality. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 1–13.

Gao, H., Bozkir, E., Hasenbein, L., Hahn, J.-U., Göllner, R., & Kasneci, E. (2021). Digital Transformations of Classrooms in Virtual Reality. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 1–10.

Garcia, S., Kauer, R., Laesker, D., Nguyen, J., & Andujar, M. (2019). A Virtual Reality Experience for Learning Languages. *Extended Abstracts of the 2019 CHI Conference on*

Human Factors in Computing Systems, 1–4.

Gero, K. I., Chilton, L., Melancon, C., & Cleron, M. (2022). Eliciting Gestures for Novel Note-taking Interactions. *Designing Interactive Systems Conference*, 966–975.

Gershon, N., & Page, W. (2001). What storytelling can do for information visualization. *Communications of the ACM*, *44*(8), 31–37.

Géryk, J. (2015). Using visual analytics tool for improving data comprehension. *International Educational Data Mining Society*. http://files.eric.ed.gov/fulltext/ED560521.pdf

Gilakjani. (2012). Visual, auditory, kinaesthetic learning styles and their impacts on English language teaching. *Journal of Studies in Education*. https://www.academia.edu/download/50341580/Visual-Auditory-Kinaesthetic-.pdf

Harold, J., Lorenzoni, I., Shipley, T. F., & Coventry, K. R. (2016). Cognitive and psychological science insights to improve climate change data visualization. *Nature Climate Change*, *6*(12), 1080–1089.

Healey, C. G., & Enns, J. T. (2012). Attention and visual memory in visualization and computer graphics. *IEEE Transactions on Visualization and Computer Graphics*, *18*(7), 1170–1188.

Hodgson, P., Lee, V. W. Y., Chan, J. C. S., Fong, A., Tang, C. S. Y., Chan, L., & Wong, C. (2019). Immersive Virtual Reality (IVR) in Higher Education: Development and Implementation. In M. C. tom Dieck & T. Jung (Eds.), *Augmented Reality and Virtual Reality: The Power of AR and VR for Business* (pp. 161–173). Springer International Publishing.

Hutchins, E. (1991). The social organization of distributed cognition. In L. B. Resnick (Ed.), *Perspectives on socially shared cognition , (pp* (Vol. 429, pp. 283–307). American Psychological Association, xiii.

Huynh, E., Nyhout, A., Ganea, P., & Chevalier, F. (2020). Designing Narrative-Focused Role-Playing Games for Visualization Literacy in Young Children. *IEEE Transactions on Visualization and Computer Graphics*, *PP*. https://doi.org/10.1109/TVCG.2020.3030464

Ibrahim, R. H., & Hussein, D.-A. (2016). Assessment of visual, auditory, and kinesthetic learning style among undergraduate nursing students. *Int J Adv Nurs Stud*, *5*(1), 1–4.

Ji, Y., Zhong, S., Zhang, B., & Sean, C. (2021). Constructing Embodied Interaction of Intangible Cultural Heritage Course through Immersive Virtual Reality. *The Ninth International Symposium of Chinese CHI*, 133–138.

Johnston, E., Olivas, G., Steele, P., Smith, C., & Bailey, L. (2018). Exploring Pedagogical Foundations of Existing Virtual Reality Educational Applications: A Content Analysis Study. *Journal of Educational Technology Systems*, *46*(4), 414–439.

Kirsh, D. (2006). Distributed cognition: A methodological note. *Pragmatics & Cognition*, 14(2), 249–262.

Khan, M., Trujano, F., & Maes, P. (2018). Mathland: Constructionist Mathematical Learning in the Real World Using Immersive Mixed Reality. *Immersive Learning Research Network*, 133–147.

Klein, Klein, Moon, & Hoffman. (2006). Making Sense of Sensemaking 2: A Macrocognitive

Model. In *IEEE Intelligent Systems* (Vol. 21, Issue 5, pp. 88–92). https://doi.org/10.1109/mis.2006.100

Knierim, P., Schwind, V., Feit, A. M., Nieuwenhuizen, F., & Henze, N. (2018). Physical Keyboards in Virtual Reality: Analysis of Typing Performance and Effects of Avatar Hands. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 1–9.

Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2020). Effects of audio support on multimedia learning processes and outcomes in students with dyslexia. *Computers & Education, 150,* 103858.

Koulouris, J., Jeffery, Z., Best, J., O’Neill, E., & Lutteroth, C. (2020, April 21). Me vs. Super(wo)man: Effects of customization and identification in a VR exergame. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI ’20: CHI Conference on Human Factors in Computing Systems, Honolulu HI USA. https://doi.org/10.1145/3313831.3376661

Kuckartz, U., & Rädiker, S. (2019). *Analyzing Qualitative Data with MAXQDA: Text, Audio, and Video*. Springer, Cham.

Kwon, O.-H., Muelder, C., Lee, K., & Ma, K.-L. (2016). A Study of Layout, Rendering, and Interaction Methods for Immersive Graph Visualization. *IEEE Transactions on Visualization and Computer Graphics*, *22*(7), 1802–1815.

Limniou, M., Roberts, D., & Papadopoulos, N. (2008). Full immersive virtual environment CAVETM in chemistry education. *Computers & Education*, *51*(2), 584–593.

Liu, Z., Nersessian, N., & Stasko, J. (2008). Distributed cognition as a theoretical framework for information visualization. *IEEE Transactions on Visualization and Computer Graphics*, *14*(6), 1173–1180.

Löcken, A., Golling, C., & Riener, A. (2019). How Should Automated Vehicles Interact with Pedestrians? A Comparative Analysis of Interaction Concepts in Virtual Reality. *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 262–274.

Magner, U. I. E., Schwonke, R., Aleven, V., Popescu, O., & Renkl, A. (2014). Triggering situational interest by decorative illustrations both fosters and hinders learning in computer-based learning environments. *Learning and Instruction*, *29*, 141–152.

Ma, K.-L., Liao, I., Frazier, J., Hauser, H., & Kostis, H.-N. (2012). Scientific Storytelling Using Visualization. In *IEEE Computer Graphics and Applications* (Vol. 32, Issue 1, pp. 12–19). https://doi.org/10.1109/mcg.2012.24

Mania, K., Wooldridge, D., Coxon, M., & Robinson, A. (2006). The effect of visual and interaction fidelity on spatial cognition in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, *12*(3), 396–404.

Markowitz, D. M., Laha, R., Perone, B. P., Pea, R. D., & Bailenson, J. N. (2018). Immersive Virtual Reality Field Trips Facilitate Learning About Climate Change. *Frontiers in Psychology*, *9*, 2364.

Mayer, R. E. (2021). Cognitive Theory of Multimedia Learning. In *The Cambridge Handbook of Multimedia Learning* (pp. 57–72). https://doi.org/10.1017/9781108894333.008

Mazur, J. M., & Lio, C. H. (2004). Learner articulation in an immersive visualization environment. *CHI '04 Extended Abstracts on Human Factors in Computing Systems*, 1355–1358.

Mei, H. H., & Sheng, L. S. (2011). Applying situated learning in a virtual reality system to enhance learning motivation. *International Journal of Information and Education Technology, 1*(4), 298–302.

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education, 70*, 29–40.

Merkel, S., & ASM Task Force on Curriculum Guidelines for Undergraduate Microbiology. (2012). The development of curricular guidelines for Introductory Microbiology that focus on understanding. *Journal of Microbiology & Biology Education: JMBE, 13*(1), 32–38.

Merriam, S. B., & Tisdell, E. J. (2015). *Qualitative Research: A Guide to Design and Implementation*. John Wiley & Sons.

Meyer, O. A., Omdahl, M. K., & Makransky, G. (2019). Investigating the effect of pre-training when learning through immersive virtual reality and video: A media and methods experiment. *Computers & Education*, *140*, 103603.

Montagni, I., Guichard, E., & Kurth, T. (2016). Association of screen time with self-perceived attention problems and hyperactivity levels in French students: a cross-sectional study. *BMJ Open*, *6*(2), e009089.

Munzner, T. (2014). *Visualization Analysis and Design*. CRC Press.

Narayan, M., Waugh, L., Zhang, X., Bafna, P., & Bowman, D. (2005). Quantifying the benefits of immersion for collaboration in virtual environments. *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, 78–81.

Nguyen, C., & Liu, F. (2016). Gaze-based Notetaking for Learning from Lecture Videos. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 2093–2097.

Norman. (n.d.). The design of everything things. *Currency Doubleday, USA.*

North, M. M., Sessum, J., & Zakalev, A. (2004). Immersive visualization tool for pedagogical practices of computer science concepts: a pilot study. *J. Comput. Sci. Coll.*, *19*(3), 207–215.

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. *Journal of Educational Psychology*, *110*(6), 785–797.

Peres, S. C., Pham, T., & Phillips, R. (2013). Validation of the System Usability Scale (SUS): SUS in the Wild. *Proceedings of the Human Factors and Ergonomics Society ... Annual Meeting Human Factors and Ergonomics Society. Meeting*, *57*(1), 192–196.

Petersen, G. B., Klingenberg, S., Mayer, R. E., & Makransky, G. (2020). The virtual field trip: Investigating how to optimize immersive virtual learning in climate change education. *British Journal of Educational Technology: Journal of the Council for Educational Technology*, *51*, 247.

Pirker, J., Holly, M., Lesjak, I., Kopf, J., & Gütl, C. (2019). MaroonVR—An Interactive and

Immersive Virtual Reality Physics Laboratory. In P. Díaz, A. Ioannou, K. K. Bhagat, & J. M. Spector (Eds.), *Learning in a Digital World: Perspective on Interactive Technologies for Formal and Informal Education* (pp. 213–238). Springer Singapore.

Qian, Y., Hambrusch, S., Yadav, A., Gretter, S., & Li, Y. (2020). Teachers' perceptions of student misconceptions in introductory programming. *ACM Journal on Educational Resources in Computing*, *58*(2), 364–397.

Reed, S. K. (2006). Cognitive Architectures for Multimedia Learning. *Educational Psychologist*, *41*(2), 87–98.

Reimer, Y. J., Brimhall, E., Cao, C., & O'Reilly, K. (2009). Empirical user studies inform the design of an e-notetaking and information assimilation system for students in higher education. *Computers & Education*, *52*(4), 893–913.

Riche, Riche, Hinckley, & Panabaker. (2017). As We May Ink?: Learning from Everyday Analog Pen Use to Improve Digital Ink Experiences. *Comparative Haematology International*. https://www.microsoft.com/en-us/research/wp-content/uploads/2017/04/riche-chi2017.pdf

Roberts, J. C., Frankenberg-Garcia, A., Lew, R., Rees, G., & Sharma, N. (2018). Visualisation Approaches for Corpus Linguistics: towards Visual Integration of Data-Driven Learning. *3rd Workshop on Visualization for the Digital Humanities – Vis4DH 2018*, 1–5.

Roberts, J. W. (2012). *Beyond learning by doing: Theoretical currents in experiential education*. *Routldege*. https://doi.org/10.4324/9780203848081/beyond-learning-jay-roberts

Ruchikachorn, P., & Mueller, K. (2015). Learning Visualizations by Analogy: Promoting Visual Literacy through Visualization Morphing. *IEEE Transactions on Visualization and Computer Graphics*, *21*(9), 1028–1044.

Self, B. P., Miller, R. L., Kean, A., Moore, T. J., Ogletree, T., & Schreiber, F. (2008). Important student misconceptions in mechanics and thermal science: Identification using Model-Eliciting Activities. *2008 38th Annual Frontiers in Education Conference*, S2G – 1–S2G – 6.

Seo, J. H., Smith, B. M., Cook, M. E., Malone, E. R., Pine, M., Leal, S., Bai, Z., & Suh, J. (2017). Anatomy Builder VR: Embodied VR Anatomy Learning Program to Promote Constructionist Learning. *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, 2070–2075.

Shin, D. (2018). Empathy and embodied experience in virtual environment: To what extent can virtual reality stimulate empathy and embodied experience? *Computers in Human Behavior*, *78*, 64–73.

Shirey, L. L., & Reynolds, R. E. (1988). Effect of interest on attention and learning. *Journal of Educational Psychology*, *80*(2), 159–166.

Snyder, C. W., Vandromme, M. J., Tyra, S. L., Porterfield, J. R., Jr, Clements, R. H., & Hawn, M. T. (2011). Effects of virtual reality simulator training method and observational learning on surgical performance. *World Journal of Surgery*, *35*(2), 245–252.

Southgate, E. (2019). Virtual Reality for Deeper Learning: An Exemplar from High School Science. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 1633–

1639.

Steen, M., Manschot, M., & De Koning, N. (2011). Benefits of co-design in service design projects. *International Journal of Design*, *5*(2). http://index.ijdesign.org/index.php/IJDesign/article/view/890

Takac, M. (2020). Application of Web-based Immersive Virtual Reality in Mathematics Education. *2020 21th International Carpathian Control Conference (ICCC)*, 1–6.

Truchly, P., Medvecký, M., Podhradský, P., & Vančo, M. (2018). Virtual Reality Applications in STEM Education. *2018 16th International Conference on Emerging eLearning Technologies and Applications (ICETA)*, 597–602.

van Dam, A., Forsberg, A. S., Laidlaw, D. H., LaViola, J. J., & Simpson, R. M. (2000). Immersive VR for scientific visualization: a progress report. *IEEE Computer Graphics and Applications*, *20*(6), 26–52.

van Wijk, J. J. (2006). Views on Visualization. *IEEE Transactions on Visualization and Computer Graphics*, *12*(4), 421–432.

Vogel, J. J., Greenwood-Ericksen, A., Cannon-Bowers, J., & Bowers, C. A. (2006). Using Virtual Reality with and without Gaming Attributes for Academic Achievement. *Journal of Research on Technology in Education*, *39*(1), 105–118.

Wendrich, R. E. (2011). Distributed Cognition, Mimic, Representation and Decision Making. *Proceedings of Virtual Reality International Conference (VRIC 2011)*. https://www.researchgate.net/profile/Robert-

Wendrich/publication/257002733_Distributed_Cognition_Mimic_Representation_and_Decision_Making_Hybrid_Interaction_Environments_in_Support_of_Collaborative_Design_Processes/links/0c9605242dae546dd2000000/Distributed-Cognition-Mimic-Representation-and-Decision-Making-Hybrid-Interaction-Environments-in-Support-of-Collaborative-Design-Processes.pdf

Wyart, V., & Tallon-Baudry, C. (2008). Neural dissociation between visual awareness and spatial attention. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *28*(10), 2667–2679.

York, J., Shibata, K., Tokutake, H., & Nakayama, H. (2021). Effect of SCMC on foreign language anxiety and learning experience: A comparison of voice, video, and VR-based oral interaction. *ReCALL*, *33*(1), 49–70.

Zhang, D., Zhao, J. L., Zhou, L., & Nunamaker, J. F. (2004). Can e-learning replace classroom learning? *Communications of the ACM*, *47*(5), 75–79.

Zhang, J., & Patel, V. L. (2006). Distributed cognition, representation, and affordance. *Pragmatics & Cognition*, 14(2), 333–341.

Zhang, L. (2022). *Investigating interactivity and storytelling in immersive virtual reality for science education*. https://vtechworks.lib.vt.edu/handle/10919/107808

Zhang, L., Bowman, D. A., & Jones, C. N. (2019). Exploring Effects of Interactivity on Learning with Interactive Storytelling in Immersive Virtual Reality. *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*, 1–8.

Zhao, J., LaFemina, P., Carr, J., Sajjadi, P., Wallgrün, J. O., & Klippel, A. (2020). Learning in the Field: Comparison of Desktop, Immersive Virtual Reality, and Actual Field Trips for Place-Based STEM Education. *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 893–902.

Zhu, L.-H., Chen, L., Yang, S., Liu, D., Zhang, J., Cheng, X., & Chen, W. (2013). Embryonic NOTES thoracic sympathectomy for palmar hyperhidrosis: results of a novel technique and comparison with the conventional VATS procedure. *Surgical Endoscopy*, *27*(11), 4124–4129.

Conclusion

In this dissertation research, I examined the affordances of educational immersive visualization from design, development, and evaluation.

With the first study, I present an immersive visualization of a marine ecosystem designed to facilitate learning Metagenomics datasets. I used a learner-interaction design framework grounded in interest theory and HCI design principles. Findings demonstrate the value of theory-based visualization design for knowledge comprehension. Furthermore, this design illuminated new ways of utilizing computing systems for educational purposes, combining perspectives from the interactive design process, visualization techniques, and pedagogical theories. This new approach used a learner-centered design to aid education.

The second study focuses on the impact of VR on students' learning motivations and retention outcomes in higher education classrooms. In collaboration with the class instructor, I designed and developed a VR application for teaching Sauerkraut Fermentation in Food Microbiology undergraduate laboratory class. This study found that HMD VR with appropriate instructional design guidelines aids students' long-term knowledge retention from increased immersion and motivation. Students' perceived immersion and motivation are associated with their retention score changes.

Overall, the two studies provide converging evidence on the promise of leveraging VR technologies to support individual learning. The findings are intended to be generalized to add to our growing understanding of learning through immersive visualization. I am optimistic that the development of immersive visualization can support our learning and cognition. Therefore, I discuss several future directions below.

First, my studies reveal that human performance is influenced by the interaction between the individual and the virtual environment (e.g., immersion, motivation, engagement, usability, and motion sickens) when learning through immersive visualization. Recent HCI research also confirmed the importance of considering motivational-affective in system design for educational purposes (Gottardo & Pimentel, 2017; Oleson et al., 2021). It is believed that these elements contribute to designing positive interaction between users and the VR environment and thus support one's active learning in an immersive space through the same mechanism as conventional active classroom experiences (Liou & Chang, 2018). As such, learners' positive affective perceptions derived from immersive visualizations may continuously affect their later relevant learning performance. For example, in this regard, such affective-cognitive association within VR can be expanded from leveraging one's declarative learning to supporting one's procedural learning. A few researchers started to notice this gap but are still in the initial stage of development (Garcia Fracaro et al., 2021; K. Babu et al., 2018). One of my ongoing studies aims to understand how increased long-term retention and positive perceptions from VR lectures can be applied to students' subsequent hands-on procedural learning during their laboratory sessions. Overall, an in-depth and comprehensive exploration of how VR facilitates affective processing deepens one's declarative and procedural knowledge acquisition and can potentially provide ubiquitous opportunities for students and teachers.

Moreover, this dissertation highlights several theoretical and practical implications relevant to learning cognition, HCI, and design research. Although humans have been perusing advanced technology for a better life over long periods, researching the association, balance, and interaction between technology and humanity requires a complex endeavor from different academic perspectives. Researchers need to holistically rethink how to better design and develop effective VR applications to meet a variety of learning needs. Therefore, more in-depth interdisciplinary collaborations between educational researchers and computer scientists will push educational VR research forward to identify design pipelines derived from theories, user-centered principles, and visualization design considerations. As reflected in the construction and my personal experiences of this dissertation, collaborative efforts to examine how learning occurs within and after VR applications using a long-term intervention can generate critical insights in our scientific community regarding theoretical framework construction, data mining, data processing, system development, study design, testing, and evaluation.

The intention of introducing VR into a broader educational context is not to replace traditional classroom instructions - but to leverage learning opportunities by providing additional and unique experiences to complement our everyday learning experiences. Furthermore, by studying the well-established research in learning sciences and HCI, researchers, educators, and developers will be able to take a theory-driven approach to the design, development, and evaluation of learning through immersive visualization.

References

Garcia Fracaro, S., Chan, P., Gallagher, T., Tehreem, Y., Toyoda, R., Bernaerts, K., Glassey, J., Pfeiffer, T., Slof, B., Wachsmuth, S., & Wilk, M. (2021). Towards design guidelines for virtual reality training for the chemical industry. *Education for Chemical Engineers*, *36*, 12–23.

Gottardo, E., & Pimentel, A. R. (2017). Affective Human-Computer Interaction in Educational Software: a Hybrid Model for Emotion Inference. *Proceedings of the XVI Brazilian Symposium on Human Factors in Computing Systems*, 1–4.

K. Babu, S., Krishna, S., R., U., & Bhavani, R. R. (2018). Virtual Reality Learning Environments for Vocational Education: A Comparison Study with Conventional Instructional Media on Knowledge Retention. *2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT)*, 385–389.

Liou, W.-K., & Chang, C.-Y. (2018). Virtual reality classroom applied to science education. *2018 23rd International Scientific-Professional Conference on Information Technology (IT)*, 1–4.

Oleson, A., Wortzman, B., & Ko, A. J. (2021). On the Role of Design in K-12 Computing Education. *ACM Trans. Comput. Educ.*, *21*(1), 1–34.