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Neuroeducation meets virtual reality: theoretical analysis and implications for didactic design

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Abstract

Immersive Virtual Reality (I-VR) is becoming increasingly prevalent in today's society and is a technology that is being used more and more in educational contexts and whose potential for learning has been widely discussed. Taking into account the latest research in neuroscience, we want to explore the potential of using immersive virtual environments to facilitate deep learning in educational contexts that invoke the value of experience, imitation and repetition. Neurodidactics seems to offer the most interesting insights into how participation in a virtual reality session can positively affect learning processes: this suggests that it is worth focusing on the learning processes that can be generated by this emerging technology. The paper concludes with some practical suggestions for design, addressing both the didactic experience and the learning objects.

Keywords: *Education; Immersive Reality; Neurodidactics; Neuroscience; Virtual Reality*

Introduction

There is considerable agreement that virtual reality can also be one of the emerging technologies in education (Freina & Ott, 2015; Kamińska, 2019; Radianti et al., 2016).

As Anderson (2010) points out, complexity theory can highlight the social structures we create at the organizational level to manage learning. To prevent these management functions from generating behaviors that do not promote deep learning, it is necessary to act with the goal of creating systems in which deep learning emerges rapidly and profoundly. Complexity theory also encourages us to think of learning contexts (classrooms, etc.) as entities in their own right.

The market for virtual reality displays is very complex; if we do not follow Anderson's suggestion, we may not be able to "surf at the edge of chaos" (Anderson, 2010, p. 29). To generate meaningful learning, it is necessary to focus on the learning processes that can be generated with this emerging technology, rather than considering the entire social infrastructure that seeks to control the market. Neurodidactics seems to offer the most interesting insights into how participation in a virtual reality session can positively affect learning processes.

The main objective of this conceptual paper is to show how learning scenarios inspired by the neurodidactic perspective can be easily implemented in virtual reality environments. For this purpose, we will present the three learning scenarios that, according to neurodidactic research, are primarily involved in learning processes and, for each of them, we will highlight possible connections with learning experiences implemented in virtual reality. For each scenario some data from international research and application examples will be presented.

1. The three educational scenarios of neurodidactics

Teaching and learning are complex, interactive, and interconnected processes (Laurillard, 2012) that are influenced by various cognitive factors, including perception, memory, attention, language, and emotion (Hannafin et al., 2003). In particular, research in cognitive neuroscience has emphasized the critical need to be aware of these aspects in order to support the learning process and increase the effectiveness of teaching (Privitera, 2021).

Advances in neuroscience have provided a wealth of knowledge about the structure, development, and functioning of the human brain (Dehaene, 2020), enabling all stakeholders in the educational field to understand the essential knowledge about the brain, memory, and learning processes. Moreover, as a result of the progress made in neuroscience and brain research in recent decades, a new interdisciplinary field of research has emerged: Neurodidactics (Preiss, 1998; Rosati, 2005). Although there have been some criticisms (Navarro Rincón et al., 2022), neurodidactics can be beneficial in providing practical suggestions for the educational process. In particular, several studies confirm that the learning process is mainly supported by three different scenarios through which our brain operates: modeling, repetition and experience (Rivoltella, 2012).

The first scenario highlights that students can learn how to behave by observing professionals working on a specific task or teachers using effective teaching methods. This is evident in modern school internships and is based on the identification of mirror neurons and an understanding of their function (Rizzolatti & Sinigaglia, 2006).

In the educational context, observing professionals or experienced teachers serves as a powerful tool for students to acquire knowledge, skills, and appropriate behaviors. By observing experts in action, students can gain insights into effective strategies or techniques that are relevant to the specific task or subject. This observational learning process helps students develop a cognitive representation of the desired behavior that can then be imitated and integrated into their existing cognitive structures (Ausubel, 1963).

Repetition plays a crucial role in the process of memorization and has a significant impact on learning. This concept, supported by the research of Kandel (2010), highlights how consistent repetition of a theory, idea, or movement can lead to stronger synaptic connections associated with that specific task. Our brain has a remarkable ability to change its structure and function in response to experience, a phenomenon known as neural plasticity (Mateos-Aparicio & Rodríguez-Moreno, 2019). Through repetition, the brain undergoes synaptic strengthening, in which the connections between neurons become more efficient and durable. When students repeatedly engage with a particular piece of information or practice a particular skill, these synaptic connections are strengthened, making it easier for the brain to retrieve and process that information in the future. The concept of repetition and its impact on memorization is consistent with the lifelong learning perspective, which emphasizes the continuous acquisition of knowledge and development of skills over a lifetime (Dewey, 2004; Rinaldi, 2016). From a neuroscientific perspective, repetitive practice not only strengthens synaptic connections, but also promotes the establishment of durable neural networks that allow for the long-term retention of information and skills (Kandel et al., 1995). This understanding supports the idea that learning is an ongoing process that can be enhanced through deliberate and repetitive engagement with the material.

Finally, experience plays an important role in the learning process. According to Kolb (1984), experiential learning can be defined as a process in which knowledge is created through the transformation of experiences that help learners develop new skills or attitudes. Kolb's idea builds on the work of various authors, including Dewey (2004) and Piaget (2000), who emphasized 'learning by doing' or 'learning from experience'. This perspective recognizes that learners actively engage with their environment and construct meaning and acquire contextual knowledge through practical experiences. This approach helps learners not only acquire new skills or attitudes, but also develop a deeper understanding of concepts. It also allows learners to develop a deeper and contextualized understanding of concepts (Rivoltella, 2013), improve problem-solving skills, make emotional connections (Damasio, 1999, 2003), and apply knowledge in both formal and informal settings.

It is possible to consider that, on the one hand, scientific studies offer numerous neurodidactic references that propose practical recommendations. On the other hand, it is also crucial to consider the research on emerging technologies (Veletsianos, 2010) and didactic devices (Garavaglia & Petti, 2021), which also make a significant contribution (Mao & Garavaglia, 2022). This is a case study on the application of head-mounted display (HMD) technology and immersive virtual reality (I-VR), which are becoming increasingly popular in our contemporary society (Hale & Stanney, 2014). The implementation of technology-assisted education as a pedagogical method is not a recent phenomenon, and studies on its effectiveness have been conducted for almost half a century (McLellan, 1996). As early as the 1970s, Ellinger and Frankland (1976) found that the use of early computers to teach economic principles produced learning outcomes comparable to traditional didactic methods such as the "chalk and talk" approach. Today, despite researchers' focus on the learning outcomes, intervention characteristics, design, and evaluation measures associated with the use of I-VR in education (Hamilton et al., 2021), there is a dearth of studies. However, the adoption of I-VR as a pedagogical method is challenging yet promising, as it appears to be useful and effective. For example, Jensen and Konradsen (2018) confirmed that learners who used an immersive HMD were more engaged, spent more time on learning tasks, and acquired better cognitive, psychomotor, and affective skills. Jang (2008) confirmed the hypothesis that an immersive learning experience can promote confidence and make the task relevant to the user, thereby increasing engagement and motivation to learn.

In addition, the advent of high-fidelity graphics and immersive content has revolutionized the way students engage with complex topics and environments (Anderson, 2010). These advances allow learners to explore and manage complexity in ways that traditional teaching methods cannot. This perspective could be relevant to improving the application of systems thinking in education (e.g., Dayarathna et al., 2021). It allows learners to engage with complex learning objects in an interactive manner, facilitating a deeper understanding of the interdependencies and dynamics of systems. By engaging with immersive content, learners can observe firsthand how changes in one part of the system affect many other components. Depending on the characteristics of the software, users can experiment with different variables, test hypotheses, and observe the resulting effects. This promotes a deeper understanding of the complexity of a learning object.

Graphics, including detailed, immersive visual representations, simulations, and 3D models, provide students with a visually stimulating and realistic learning experience. They present information in a visually appealing and engaging format that captures students' attention and improves their understanding of complex concepts. For example, in subjects such as anatomy or geography, high-fidelity graphics in immersive reality can allow students to explore complex structures and environments. This enables them to better visualize and understand spatial relationships and to engage with these subjects in a more interactive and dynamic way. This perspective, which focuses on the learning content ("what"), can be effectively enriched by reflecting on the teaching and learning process mentioned above ("how"). Modeling, repetition and experience could be considered as three different approaches that are helpful in exploring complex systems and environments. These approaches engage students in different learning scenarios, incorporating different perspectives and practices.

In summary, our perspective suggests that neurodidactics and I-VR studies should be designed in a collaborative manner to maximize the effectiveness of the teaching and learning process. This is particularly important given the growing body of scientific research (e.g., Dhimolea et al., 2022; Hamilton et al., 2021; Lai & Cheong, 2022) and the need to foster students' systems thinking (Arnold & Wade, 2015).

2. Modelling, repetition and experience in VR environments

The first learning scenario involves the concept of modeling. An I-VR environment provides a unique opportunity to present students with a virtual model that demonstrates how to behave in specific learning situations or contexts. This virtual model serves as a powerful instructional tool, allowing students to learn not only theoretical knowledge, but also procedural operations. Höffler and colleagues (2013) argue that dynamic images are more effective than static ones in enhancing the learning process, especially when the knowledge involves a process and the dynamism adds value. Furthermore, when the learning object involves movement, a virtual model that demonstrates animation is more effective than static images. This is because it helps form a mental model of the movement to be learned. By providing a clear example to follow, students can practice more effectively.

One of the key benefits of using VR in education is the ability to create immersive and interactive simulations. Through these simulations, students can observe and interact with virtual models that exemplify desired behaviors or actions within a specific learning scenario. For example, in fields such as medicine (Rose et al., 2021) or engineering (Pirola, 2019), VR can simulate real-world environments. This allows students to observe and learn the step-by-step procedures involved in performing a task or operating specific equipment.

By providing a visual and interactive representation, VR allows learners to move beyond theoretical understanding and directly engage with the practical aspects of a learning situation. They can observe correct procedures, follow the actions of the virtual model, and gain a deeper understanding of the sequential steps required for successful execution. This immersive learning improves students' ability to transfer their knowledge to real-world applications. In addition, using virtual models in VR environments provides a safe and controlled learning environment. Students can make mistakes, experiment, and learn from their actions without the risk of real-world consequences.

A second consideration is the concept of virtual feedback. In an immersive environment, the virtual model observes and monitors the student, providing personalized and immediate feedback. Focusing on the field of education, for example, it is interesting to mention a study conducted by Chen and colleagues (2022). This study involved 10 pre-service teachers who were placed in an I-VR situation to improve their classroom management skills, particularly in dealing with challenging student behavior. The results showed that real-time audio feedback had a positive impact and provided participants with a sense of encouragement and validation of their actions. In addition, the results supported the hypothesis that these feelings would reinforce the teacher's response in an actual classroom setting.

Here are two examples of applications from two different fields. The first comes from Arch Virtual (https://archvirtual.com/), a VR/AR development company that specializes in using these technologies to address real-world problems, particularly in the medical context. Their primary goal is to provide students with clinical experiences in a safe environment, allowing them to learn procedural operations through the examples provided by a virtual model (Figure 1). The second image is provided by AnotherReality (https://www.anothereality.io/), the company behind Virtuademy (https://www.anothereality.io/portfolio_page/virtuademy-demo/?lang=it), a business education platform (Figure 2).

Fig. 1 An example from Arch Virtual.

Fig. 2 An example from AnotherReality.

The second learning scenario we want to discuss concerns repetition. While acting or performing a task is an essential aspect of learning, it is not always sufficient to solidify a practice or action. Repetition plays a crucial role in the process of skill acquisition and mastery. Students need opportunities to repeat and reinforce what they are practicing in order to develop skill, dexterity, and confidence. In this regard, I-VR provides a safe and controlled environment that allows repetition without real-world consequences. The safety of the virtual environment is a key benefit. Learners can make mistakes without real-world consequences because they are fully aware that they are immersed in a simulated virtual environment. This freedom to make mistakes and learn from them without fear of negative consequences fosters a supportive learning environment in any learning scenario (e.g., Grantcharov et al., 2003; McGarr, 2021). By providing a safe environment for repetition and trial and error, I-VR allows learners to explore and experiment with different approaches and techniques. They can analyze the results of their actions, identify areas for improvement, and refine their strategies accordingly. This iterative process of repetition and adaptation improves learning outcomes and helps students build confidence in their abilities.

Focusing on the application of the repetition concept, the figure below (Figure 3) shows an example. On Labster (Labster.com), you can find more than 250 virtual labs for universities and high schools, covering a wide range of science topics. In these immersive labs, students can repeat the processes they are practicing many times, from putting on the gown to performing the experimental procedure. Thanks to the implementation of these virtual labs, students can practice specific operations and acquire pre-learning that will increase their mastery and confidence during the procedure.

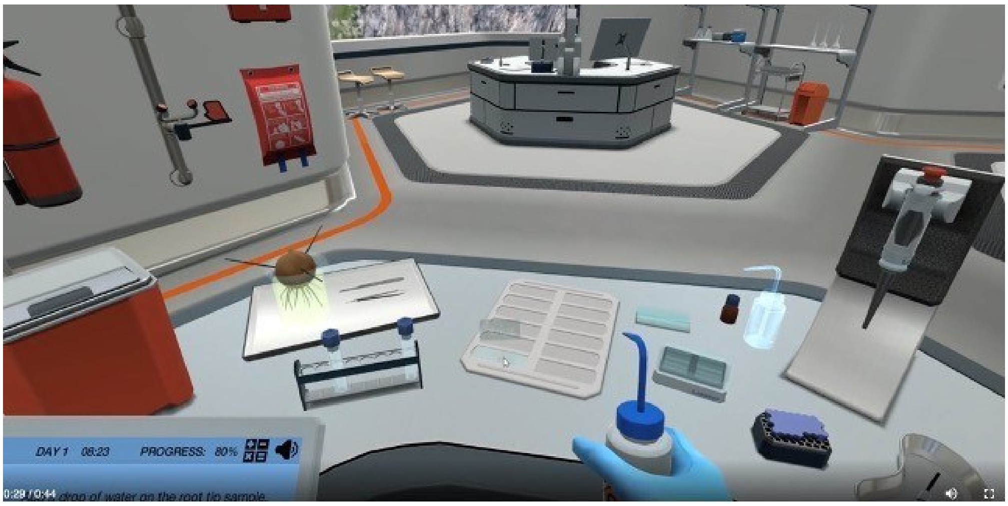

Fig. 3 An example from Labster.

The third learning scenario we want to discuss concerns the experience of I-VR. First of all, we have to mention the possibility that I-VR offers to teachers to explore learning environments and spaces and their characteristics.

Immersive technologies can be used to create teaching scenarios related to cultures that are far away in space (Cavaletti & Terrenghi, 2023) and time. In just a few minutes, teachers can transport an entire class to the pyramids or back to ancient Greece.

It is also possible to explore a specific learning object from the inside, such as a cell or a volcano. This perspective, based on the student-centered learning paradigm, is considered effective, especially for increasing motivation and engagement. In a recent review (Nurbekova, 2022), virtual learning objects were identified as one of the most appropriate solutions for ensuring reuse, accessibility, durability, and compatibility of educational resources. In addition, they promote learner autonomy (Salvador et al., 2017) and a higher level of interactivity. Furthermore, Makransky and colleagues (2022) support the hypothesis that immersive travel can increase students' engagement and interest in the didactic proposal. The results of their study confirmed that the group of students who had an immersive experience with an HMD had a better sense of presence, enjoyment, interest, and retention compared to their classmates who had a desktop experience.

A second consideration relevant to reflection on the experience is the ability of immersive technologies to enhance the sense of presence and immersion for those participating in the experience. Freina and Ott (2015) define immersion as the perception of being physically present in a non-physical world that provides the user with surrounding images, sounds, and often other stimuli. This characteristic of the immersive experience is primarily due to the latest VR HMDs, which allow users to achieve a high level of immersion. When users are immersed in a realistic environment, their perception of time and the real world often becomes disconnected, creating a sense of "being" in the task environment (Fromm et al., 2021). This is a crucial aspect that supports the effectiveness of a learning experience in I-VR.

Considering the sense of presence and immersion that VR develops, we can say that I-VR can also support embodied cognition (Niedenthal et al., 2005). Students can move within an environment, interact with objects, and even embody a character (Banakou et al., 2018). I-VR technology has the potential to support and enhance embodied cognition by providing a multisensory and interactive experience. When immersed in a virtual environment, users can engage with the digital world through their bodily movements, gestures, and interactions. This embodiment allows for a more holistic and intuitive understanding of virtual space. By physically interacting with virtual objects, users can manipulate and explore the virtual environment as if they were interacting with objects in the real world. This sensorimotor engagement facilitates a sense of presence and agency, allowing users to embody virtual avatars (Banakou et al., 2018) and navigate digital space using their own body movements. This embodied interaction increases the sense of immersion and realism, creating a more intuitive and engaging experience.

Finally, we know that emotions play an important role in the learning process (e.g., Garner, 2010; Tyng et al., 2017). Many studies suggest that certain VR situations can elicit intense emotional responses similar to our everyday experiences (Lavoie et al., 2021). In a recent study, Riva and colleagues (2007) confirmed the efficacy of VR as an effective medium. When users interact with an "anxious" and a "relaxed" virtual environment, they experience feelings of anxiety and relaxation.

Although the features currently presented depend on the type of application used, it is undeniable that the proliferation of increasingly inexpensive and powerful devices will make these possibilities accessible to a larger group of students. The virtual and immersive market is developing very rapidly, and we believe that it could represent the future of education (Bailenson, 2018; Garavaglia, 2016).

3. Conclusion and practical suggestions for implementing immersive experiences

According to the above considerations, we can state that it is feasible to implement I-VR to facilitate the three learning scenarios we have discussed and to promote students' deep learning.

We have seen how neurodidactics suggests ways to use virtual reality to enable students to focus primarily on learning environments by activating immersive processes such as imitation, repetition, and experiential learning.

This is because I-VR easily provides a virtual model that can show students how to behave or perform precise movements, giving them personalized and immediate feedback. It also allows students to repeat movements multiple times in a safe environment that allows for mistakes, helping them to solidify their practice or practical skills. Finally, it allows them to move and interact in different environments with a high level of presence and immersion.

We believe it is crucial to improve these learning scenarios and support a virtual didactic proposal. However, we also believe that it is important to consider some practical design suggestions.

They concern, on the one hand, the characteristics of the didactic content and, on the other hand, the characteristics of the didactic experience itself. When considering the first, it is important to take into account that:

- the immersive experience should be short (Kourtesis, 2019). Digitization and virtualization suggest that formal educational contexts should focus on micro-contents, micro-activities and micro-times (Hug, 2007). First, a short learning experience is functional to keep students' attention active and focused on the task. In addition, teachers need to consider that HMDs are still very heavy and it is not comfortable to wear them for long periods of time;
- the immersive experience should be meaningful to the student (Mei & Sheng, 2011). It is crucial to propose a real-life situation that is closely related to the student's interests and knowledge;
- The immersive environment should have an interactive function that allows students to interact with objects and/or classmates and perform functional tasks (Hamilton et al., 2021). This is important to stimulate active behaviors and help learners become the primary actors in their learning process.

When thinking about the characteristics of the didactic experience, teachers should consider the importance of both a preparation and a debriefing phase:

- the class needs to be prepared for the experience; the teacher should anticipate goals, objectives, and possible scenarios. In this way, students will be cognitively prepared for the learning tasks, increasing their engagement and motivation, gaining a better understanding of the theoretical elements and focusing on the most important details (Ferrari & Terrenghi, 2021);
- a final debriefing phase is essential (Fanning & Gaba, 2007; Rivoltella, 2013). In this case, it is suggested to include a final moment where students are asked to reflect on their experience, develop a deeper understanding of the processes activated, correct any misconceptions, critically analyze the experience and engage in peer discussions.

These suggestions come primarily from the didactic-educational paradigm and can be applied in a functional way, especially when the learning path includes immersive moments or activities. In these didactic phases, the teacher should have recourse to a type of explicit planning (Laurillard, 2012) that, while remaining open to contextual adaptations to the situation (Rivoltella, 2021), requires detailed reflection on learning objectives, disciplinary content, didactic phases, settings and evaluation methods.

Attributions

The article is the result of the authors' comparisons and reflections, who shared the entire structure. According to the author declaration system CRediT: Ilaria Terrenghi: Conceptualization, Investigation, Writing original draft & review, Visualization (par. 1, 2, 3). Andrea Garavaglia: Writing original draft & review, Visualization, Supervision (par. Introduction, 3).

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