Integrating VR/AR with Haptics into STEM Education

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Abstract. About 80% of the world's students are not in school as a result of many countries shutting educational institutions in response to the COVID-19 pandemic in 2020. To address this challenge, schools and universities are stepping up their efforts to leverage educational resources and offer remote learning opportunities. Many educational applications, platforms, and tools are available to facilitate student learning during periods of school closure. While these approaches provide critical support to society, they are mostly focused on the transfer of theoretical content. There is a lack of support for hands-on laboratory work and practical experience. This is especially relevant for science, technology, engineering, and mathematics (STEM) departments, which must constantly improve their labs and pedagogical resources to offer meaningful study plans. In this paper, we present a novel perspective for a sustainable integration of virtual and augmented reality (VR/AR) with haptic wearables into STEM education to achieve multi-sensory learning. We highlight a unique viewpoint on existing pedagogical concepts and discuss the implications. We seek to stimulate global efforts towards the achievement of fully-immersive, open, and distance laboratory learning.

Keywords: VR · AR · haptics · STEM · education

1 Introduction

Educational institutions respond to the restrictions introduced to face the COVID-19 pandemic. They are intensifying their efforts to utilise educational technologies of all sorts to provide remote learning opportunities for students, while schools are closed. To help parents, teachers, schools and school administrators facilitate student learning and provide social care and interaction during periods

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of school closure, the United Nations Educational, Scientific and Cultural Organisation (UNESCO) elaborated a list of educational applications, platforms and resources [50]. These solutions include resources to provide psycho-social support, digital learning management systems, systems built for use on basic mobile phones, systems with strong offline functionality, massive Open Online Course (MOOC) Platforms, self-directed learning content, mobile reading applications, collaboration platforms that support live-video communication, tools for teachers to create of digital learning content, and external repositories of distance learning solutions [49]. Although these solutions offer an essential support to society in these unprecedented times, they are mostly oriented in enabling theoretical content transfer. One of the biggest drawbacks of the majority of these existing solutions is that limited support is provided to hands-on laboratory work and practical experiences.

Hands-on experiences are essential to significantly advance learning at all levels of science education and across all disciplines. This is particularly important for science, technology, engineering, and mathematics (STEM) departments, which must continuously develop their laboratories and pedagogical tools to provide their students with effective study plans. The creation of contents accessible on-line and the possibility of providing immersive experience for lab activities is useful in the short term to face the COVID-19 related issues, but it could also open the door to the introduction of novel e-Learning resources in the long run.

A common teaching strategy of STEM modules involves the ideas of *Learning by Doing* (LBD) [48], the approaches of *Problem Based Learning* (PBL) [54] and the concepts of *Active Learning* (AL) [41]. In fact, one of the most effective ways of teaching students how to perform a useful engineering task consists of actively involving them and letting them do it in the lab. The LBD method is not a new instructional theory, it is exactly what it sounds like. Aristotle stated: "One must learn by doing the thing, for though you think you know it, you have no certainty until you try". Similarly, Confucius declared: "I hear and I forget. I see and I remember. I do and I understand". More recently, John Dewey became one of the strongest proponents of the LBD approach. Dewey argued: "Education is not preparation for life, it is life itself". This educational methodology is perfectly in line with the concept of multi-sensory learning [42], which assumes that individuals learn better if they are taught using more than one sense (modality). The senses usually employed in multi-sensory learning are visual, auditory, kinesthetic, and tactile – VAKT (i.e., seeing, hearing, doing, and touching), as shown in Fig. 1. The recent advances in virtual reality (AR), augmented reality (AR) and haptic technology may potentially enable the possibility of extending the multi-sensory learning approach to e-Learning and for re-designing study modules and engineering remote laboratories. Through this strategy, the community of educators and students may be enabled to explore the new frontiers of education.

In this work, we describe a unique perspective for incorporating virtual and augmented reality (VR/AR) with haptic wearables into engineering education to accomplish multi-sensory learning. The goal of this paper is to give a fresh

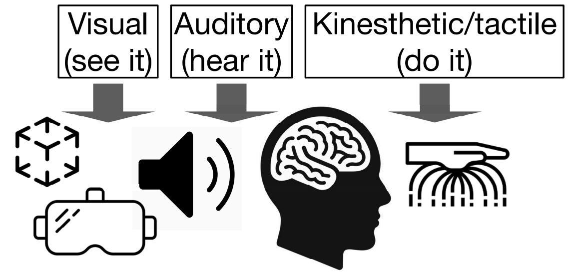

Fig. 1. The multi-sensory learning approach, which involves visual, auditory, kinesthetic, and tactile – VAKT feedback.

and distinct perspective on current educational principles and to examine the ramifications of this approach. We want to encourage worldwide efforts to make fully immersive, open, and remote laboratory learning a reality.

This paper is organised as it follows. A review of the theoretical background from a learning perspective is given in Section 2. The strategy adopted in our perspective study is provided in Section 3. An overview of related VR, AR and haptic technology are presented in Sections 4, 5 and 6, respectively. Finally, concluding remarks are presented in Section 7.

2 Learning Theories

In this section, we draw the background of the considered learning theories. In the STEM fields, some concepts may be too difficult to understand when taught with the traditional method, based on lectures and tutorial exercises, promoting *passive learning*. To increase the attraction and retention of students, many universities have adopted *active learning* (AL) pedagogy for over 20 years [23]. AL can be generally defined as "any instructional method that engages students in the learning process. AL requires students to do meaningful learning activities and think about what they are doing" [5]. In this student-centered approach, the learning responsibility is shared between the learner, the group, and the instructor. The instructor holds the responsibility for organising the conditions on which effective learning depends [8].

There are several strategies and techniques to implement AL into STEM courses. Some of the more common, although complex, are project-based learning, problem-based learning, cooperative-based learning, and competence-based learning. *Project-based learning* and *problem-based learning* are often perceived as complementary and used together, since they have similar objectives and methodologies [8]. Students are required to develop a solution to a problem presented by the instructor, individually or in groups, during multiple learning activities [21]. *Cooperative-based learning* is centered on the human capability to learn socially; students are divided into groups and work together to achieve a goal, such as conducting a research project or multiple-step exercises [23]. This pedagogy promotes peer teaching and collaborative skills. *Competency-based learning* uses systems of instruction, assessment, grading, and academic reporting to ensure that students learn the knowledge and skills deemed to be essential to succeed in the profession.

When in person teaching is not possible or laboratories are not physically accessible, immersive learning may be included in AL pedagogy. This considers options ranging from interactive physical environments to avatars in virtual worlds [37]. Interactive physical environments enable multiple learner collaborative experiences; engaging in virtual worlds as an avatar provides a cost-effective, safe, and expansive learning experience [16]. In immersive environments, students can securely participate in controlled experiments that would be high risky in the real world. Moreover, some phenomena, that would otherwise be unobservable can be visualised and presented in a clear way that allows for deep understanding of core concepts. To achieve high fidelity immersive environments, instructors can integrate VR and AR technology into their classes [13]. The use of such technology during immersive learning experiences can optimise students' knowledge acquisition and motivate them to be active participants in their own learning [16]. Furthermore, multi-sensory technologies enable multi-sensory learning with VAKT feedback. This makes it possible to achieve higher levels of affinity between the student and the simulated learning environment. Tactile feedback, e.g., force and texture, can be rendered with the use of haptic technologies, while other multi-sensory technologies can enable olfactory and audio feedback. These technologies help develop more accurate mental models and representations of different concepts, thus enhancing learning [37].

A recent study conducted a review on the usage of immersive VR technology in higher education, learning theories for VR application design as well as the evaluation methods and the learning outcomes [34]. The study shows that VR applications engage scholars as the article found 18 domain applications in higher education. The article points out the lack of learning theories as a foundation to develop learning-oriented VR applications. However, this study neither examines the adoption of haptic technologies, nor how can they be relevant for STEM in higher education. A market study of available apps [33] brings complementary results but does not include haptic technologies, either.

3 Perspective Strategy

In this section, we highlight our strategy in surveying literature regarding technologies that may enable multi-sensory learning with VAKT feedback. We assert that the way how these technologies have been used in education, especially in STEM for higher education, is understudied. Most literature focuses on technicalities, design, models of interaction, but rarely examines technologies in the higher education context for STEM. Moreover, most of the existing rendering devices are still relatively costly and therefore still not available to the vast majority of students [45]. This represents a consistent gap in the systematic review of VR/AR and haptics for e-Learning. Among the existing technological solutions, the focus of this paper is on the possibility of adopting low-cost commercial off-the-shelf (COTS) components for STEM learning purposes to enable multi-sensory learning with VAKT feedback.

4 VR Technology

There are many definitions for Virtual reality (VR). VR is investigated from different perspectives, such as technology, interaction, immersion, semantics and philosophy [56]. All of these perspectives are important when talking about applications of VR in learning. For examples, Mütterlein [26] discusses the three pillars of VR, i.e., immersion, presence and interactivity, and investigates how they are interrelated. When considering application of VR solutions in learning, VR technology should support these three pillars as well as tackling sensory perception channels for multi-sensory learning [11].

Immersive VR devices seek to place a user in a virtual environment. The best-studied solutions are VR CAVE systems and head mounted displays (HMDs). Early HMD systems were seeking accurate and fast tracking of the head rotation. It was necessary to solve the Motion-to-Photon (End-to-End) latency problem [55], because high latency does not allow full immersion. People can sense the delay and the artificial nature of the environment. Nowadays this problem is largely solved, but some low-cost solutions, such as Google cardboard, still can not provide full immersion; even worse, response lags and jittery movements may lead to motion sickness [9]. The latter can also affect users of high-end HMDs if these do not cater for individual needs [25].

Another step into enhancing the immersiveness is allowing six degrees of movement freedom that requires tracking not only rotation, but also head movements. The two approaches in use include outside-in and inside-out tracking. Outside-in tracking uses external devices (e.g., base stations in the HTC Vive systems [27]) to ensure head motion within tracked area. The inside-out tracking adopts cameras inside HMDs to track movements.

The immersiveness is further enhanced by tracking body parts and even external devices (e.g., pens, guns, sports equipment). This is relevant for learning applications that require the learning by doing approach. Tracking is done by using additional devices. The systems that could use such tracking are the outside-in systems. The inside-out systems can track palms and fingers, using infrared cameras, but the use-cases are limited in comparison to outside-in tracking systems. The additional trackers that are used in outside-in systems come in various dimensions and forms. For example, the VR ink device [20] from Logitech use a similar form as a normal pen. This device or similar ones could be used for activities that require precision. Usage may span a wide range; a pen-like instrument could be used for such virtual activities as cutting tissue as part of an operation or learning to solder.

VR technologies enables educators to provide comprehensive assistance, because the tracked students' activities can be used to give feedback in real-time or for briefing/debriefing purposes. Some recently introduced VR systems (e.g., HTC VIVE Pro Eye [43], HoloLens [28], ...) also include eye tracking capabilities. Eye tracking makes it possible to automatically adjust the interpupillary distance (IPD) and track the gaze of the user. Gaze tracking is used in many areas and it might be important for learning applications as well [46].

5 AR Technology

AR superimposes virtual information over a user's view of the surrounding environment, in such a way that this information seems naturally part of the real environment [1]. The main advantage over VR is that "AR connects users to the people, locations and objects around them, rather than cutting them off from the surrounding environment" [2]. This effect has a big potential in education, as it is demonstrated in an increasing number of research papers [3, 6, 14].

While the performance of AR technology has increased steadily over time, the main components of the hardware have stayed the same: sensors, processors, and displays. The role of the sensors is to provide information for tracking and registration. This is mainly achieved through an optical camera, with or without the help of sensors such as Global Positioning System (GPS), accelerometers, and gyroscopes. Optical tracking is categorised in the literature as marker-based, in which a static image is recognised (such as a quick response (QR) code), or marker-less, in which natural features of the surrounding environment are recognised. Other forms of tracking exist, but are much less common, such as acoustic, electromagnetic or mechanic [10].

Processors are a generic term which refer to those components that manage the data acquired by the sensors and deliver appropriate information to the displays. Displays are the most prominent part of the hardware and the most spectacular for the end user. They are usually visual ones, in the form of head mounted displays (HMD), handheld displays (HHD) or spatial AR (SAR) [51]. Other displays, less common, are tactile, audio or olfactory. Input devices are often considered as a separate category, ranging from keyboards to voice inputs .

Nowadays, due to their ubiquity and versatility, handheld devices, in the form of smartphones, have become the main vehicle for AR experiences in many fields, including education [17]. While hardware in smartphones has not changed fundamentally in recent years (yet continued to advance gradually), software evolution has been much more prominent (e.g., see the work presented in [36]).

Regarding software in AR, besides the low-level software that powers sensors, processors and displays to perform their tasks, higher-level software is used to enable creators for designing different AR experiences. Depending on the technical skills of the creator, and the business or educational needs, one can use AR software development kits (SDKs) such as Vuforia, Wikitude, ARKit or AR-Core, or all-in-one platforms, such as Cospaces Edu or EON Reality (which do not require programming skills).

A search in the scientific literature revealed no consistent existing research on exploiting AR in STEM education for fully-immersive remote laboratory learning. Most literature surveys cover the whole spectrum of target groups, from early childhood education to doctoral education. In general, AR is known to increase the understanding of the learning content, especially in spatial structure and function, compared to other forms of media, such as books or video; to aid with long-term memory retention, compared to non-AR experiences; to improve physical task performance, but also collaboration; to increase student motivation, through providing satisfaction and fun to the activities [35]. Use cases for education might be transferable from non-educational, professional AR usage such as from application that counter information overload [12].

A recent review of the literature on how AR is supporting STEM education [17] showed that the majority of the developed applications were exploration apps and simulation tools. At the same time, most were self-developed native applications, while the others used AR development tools. Also, the vast majority were marker-based and only a few were location-based. These existing applications almost exclusively stimulate the sight, leaving other senses unexplored. The study also surveyed what learning outcomes were measured and how, concluding that we are missing a deeper understanding of how AR learning experiences take place in STEM environments [17].

Another recent review on AR in STEM recognises intensive research in this area in the last years [44], although this work still mainly addresses early childhood education. The authors categorised the advantages of applying AR in STEM: contribution to learner, educational outcomes, student interaction and others. However, they also identified challenges. Most of these are owed to technical problems (i.e., weak detection of markers or GPS position). Other challenges include teachers' resistance to adopting the AR technology, in which the prolonged periods to develop high-quality content plays an important role [44].

6 Haptic Technology

Touch is one of the most reliable and robust senses, and is fundamental to the human memory and in discerning. To provide the user with tactile information, haptic technology can be employed. Haptic feedback, also known as haptics, is the use of the sense of touch in a human-computer interface. A variety of possible applications are made possible by the use of haptics, including the possibility of expanding the abilities of humans [40]: increasing physical strength, improving manual dexterity, augmenting the senses, and most fascinating, projecting human users into remote or abstract environments. Haptic technology is a key for achieving the tactile feedback experience of the VAKT model. Early examples of haptic technology applied for gaining "touch" experience of the users through the sensation of forces, vibration or motion can be found here [52, 53].

Most of the haptic devices available on the market like the sigma.x, omega.x and delta.x series (force dimension) or the Phantom Premium (3D Systems, Inc.)) [47] are usually very accurate, and able to provide a wide range of forces. However, such devices present a limited workspace with an high cost of production. The pursuit of bigger workspace and the possibility to achieve multi-contact interaction [38] lead researchers to the development and design of exoskeletons, a type of haptic interface grounded to the body [18]. Exoskeletons can be seen as wearable haptic systems, however they are rather cumbersome and usually heavy to carry, reducing their applicability and effectiveness.

To deal with these limitations, a new generation of wearable haptic interfaces have been investigated [29]. Haptic thimbles [19,24,32], haptic rings [22,31], and haptic armbands [4], have been designed for several applications, ranging from tele-operation to VR or AR interaction. Wearable haptic interfaces are only capable of providing cutaneous cues that indent and stretch the skin [7], and not kinaesthetic cues, i.e., stimuli that act on skeleton, muscles, and joints [15]. Wearable haptic interfaces, providing only cutaneous stimuli, do not exhibit any unstable behaviour due, for instance, to the presence of communication delay in the closed haptic loop [30]. As a consequence, the haptic loop with wearable tactile interfaces results to be intrinsically stable. Wearable haptic devices are light, portable and can be used in combination to achieve multi-contact interaction [39]. Most of the proposed devices are built combining rapid prototyping techniques with off-the-shelves components including servomotors, vibromotors, programmable board, etc. This aspect can drammatically foster the diffusion of these devices in "at home" scenarios. We can immagine that students could easily print and build their own devices and access to haptic contents available in novel VAKT model of e-learning.

7 Concluding Remarks and Perspectives

To conclude our work, we name implications and limitations before presenting a research agenda. Studying virtual/augmented realty (VR/AR) technology and haptics, and then putting them into the light of STEM educations allows for implications to be analysed. The whole field of our study can be characterised as heterogeneous and highly dynamic when it comes to its maturity to be brought into STEM education, as multi-sensory learning.

We can conclude – in alignment with other works(e.g., [34]) – that approaches often are experimental and exploratory. Even if learning and teaching are explicit goals, the theoretic foundations in education tend to be shallow. Educators who want to use VR, AR and haptics typically need to start from scratch and *try out* what might work. Arguable, the state-of-the-art of AR and haptics in education is even less mature than that of VR, where educators find more and more practical advice [13].

At the same time, the technological progress is rapid. Hardware and arguable to an even higher degree software support for VR, AR and haptics is continuously becoming more powerful, and the application in other areas – such as entertainment – will likely pave the way for easier usage also in education. Existing tools are still relatively expensive and not commonly available to all students. Even for educational institutions, buying hardware for large courses seems unfeasible. However, it can be expected that this problem will become less important with a wider spread of VR, AR and haptics applications.

Our work has limitations that need to be mentioned. First, we worked rigorously with the literature. However, our paper is not a systematic literature review but rather a perspective paper. This choice was deliberate, as we want to stimulate research.

Second, there are few works yet that combine VR or AR (let alone VR *and* AR with haptics in an educational context, and that specifically in STEM subjects. As a consequence of this immaturity of the field, lessons need to be taken from any of the fields individually. As an extension to the first limitation, it is impossible to get a full overview of any combination of VR, AR, haptics, and education. Thus, we might have missed works that do not squarely fall into our topics but would still help to get a better understanding of innovative pedagogic models for learning in immersive environments.

Third, the development in the field is rapid, which makes it hard to project future progress. Additionally, advances from non-scientific research could offer new possibilities or render current approaches obsolete.

The limitations of our work do not diminish its value – in fact, they align with the implications we identified.

The need for maturing the multi-sensory learning concept in combination with the technological opportunities allows for an outlook. In particular, we propose which steps research should take to leverage the current possibilities, aiming at improving STEM education. We setup the following research and implementation agenda:

- to operationalise further the multisensory learning concept for STEM education by taking advantages of current development of the VR, AR and haptic technologies, by focusing on the more affordable technologies;
- to focus on hand-son laboratory work and pedagogical tools that provide practical experiences for the students;
- to provide assessment tools for educators by having competencies evaluation on using VR, AR and wearable haptics in the STEM education;
- to explore open source libraries of VR, AR and wearable haptics to be used for re-designed study modules and engineering laboratories;
- to develop teaching modules and to test our concept with engineering students in an experimental setting, to evaluate the applicability of the concept.

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