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Meaningful Learning Through Virtual Reality Learning Environments: A Case Study in Materials Engineering

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Featured Application: The key characteristics that a virtual reality learning environment (VRLE) must have to support an appropriate level of meaningful learning in higher education are detailed in this paper.

Abstract: The increasing dissemination of virtual reality learning environments (VRLEs) compels the elucidation of how these didactic tools can improve their effectiveness at the formative level. The motivation generated in students by a VRLE is revealed as a key factor in achieving meaningful learning, but such a motivation by itself alone does not guarantee the long-term retention of knowledge. To identify the necessary characteristics of a VRLE to achieve an appropriate level of meaningful learning, this paper compares a set of VRLEs created in previous years with a group of recently developed VRLEs, after being used by engineering students. A description of the design process of the both VRLEs groups is included in this paper. Most significantly, analysis of the response of a total of 103 students in a specific survey reveals how a step-by-step protocol system helped improve students' knowledge and retention after one year of using a VRLE. Thus, this study not only demonstrates the importance of using modern development engines when creating or updating a VRLE to achieve student motivation, but also justifies in many cases the use of a step-by-step protocol as a method to improve the long-term retention of knowledge.

Keywords: virtual laboratory; virtual reality learning environment; meaningful learning; design; materials science and engineering.

1. Introduction

There is a growing trend to use virtual reality learning environments (VRLEs) in education to enhance the student learning process and course learning outcomes [1]. This fact is also reflected in the instruction of materials science and engineering (MSE) in higher education [2,3]. To date, different tests of materials have been simulated in a VRLE (e.g., tensile testing [4,5], compression testing [6], impact testing [7,8], hardness testing [7,8], microscopic analysis [7,8], and non-destructive testing [9,10]). In addition, other key aspects related to MSE have been investigated in a VRLE (e.g., crystal lattices [11,12], phase diagrams [13,14], nanomaterials [15,16], and materials manufacturing processes [17]). Several educational benefits of implementing virtual reality (VR) in MSE have been reported in the literature [4,18,19]. The most important of these benefits are related to the fact that

VRLEs: (i) solve the shortcomings linked to overcrowded practical classes; (ii) provide a means to complement student learning experience, given the limited materials testing machine handling time per student in a traditional classroom or laboratory; (iii) offer high-quality visualizations which are not readily feasible in the traditional classroom; (iv) allow instructors to develop ad hoc didactic applications in the virtual environment for reinforcing acquired knowledge; (v) increase students´ engagement and motivation in almost any field of study by bringing them closer to a friendly and familiar environment; (vi) improve the quality of education in varied disciplines; (vii) help reduce the cost associated with modern laboratory classes; and (viii) decrease the potential risk of physical harm of students during the handling of real materials testing machines. Furthermore, a better teaching–learning process has been recognized in several research studies [20–22], leading to better understanding and higher motivation, among other benefits. Despite these advantages, the use of VRLEs in MSE also presents some potential risks, for instance: (i) the user usually feels safe, without realizing the dangers of handling certain types of real machinery [23]; (ii) the student often shows a lack of seriousness, responsibility and care when conducting an experiment in the VRLE [23], which means that the training effectiveness can be reduced; and (iii) the relation between the design of the VRLE and various pedagogical aspects (motivation, ease of use, educational usefulness) may vary over time, forcing the teacher or trainer to keep the software up to date [1,24].

It is particularly worth noting that the design of a VRLE plays a key role in the development of the teaching–learning process [11,24,25]. In fact, according to previous findings, "a direct relationship exists between the virtual tool design and the motivation generated in the user to keep on using it" [11]. Among the challenges of using VRLEs in the classroom include the fact that they: (i) can affect the personal student communication and interpersonal connections in a traditional class if a pedagogical implementation is not carefully designed; (ii) can exhibit lack of flexibility compared to a typical classroom experience where a student can ask questions and receive answers and clarifications (this issue can be addressed by designing more complete pedagogical materials with protocols from instructors); and (iii) can be costly as with other advanced technologies, however rapidly changing markets offer more affordable tools, thus VR will increasingly be used in learning, training, and fostering collaborative projects.

The latest advances in the field of VR are related to the users' immersion in the virtual environment [26–29], which is known as immersive virtual reality (IVR). However, such technology has not yet reached higher education and only a few isolated examples exist to date. There are varied applications based on IVR that can create and explore fullerenes molecules [30], investigate the case study of pneumatics [31], and observe fully programmed robotic manipulators [32], to name but a few. IVR makes use of head-mounted display (HMD) technology, with newer projects that include the CAVE (cave automatic virtual environment) system [33,34]. Forgarty et al. [35] have reported a recent application to improve student understanding of complex spatial arrangements using VR. Furthermore, there is an increasing growth in applications based on augmented reality (AR). For instance, Dinis et al. [36] have recently described how to improve the learning in civil engineering by focusing on building construction. Besides, there are contemporary studies comparing the effectiveness in learning when using VR, IVR, and traditional methods. Indeed, more recent studies [37] have confirmed that when students use VR in a learning setting, they are more engaged and are more motivated compared to when they use conventional tools such as slide presentations via PowerPoint. In contrast, some investigators [38] have found little or no difference in the learning effectiveness when comparing non-immersive VR and IVR, whereas the learning is reported effective in both cases.

Meaningful learning refers to the idea that a learned knowledge (or fact) is fully understood by an individual who can then use it to make connections with other previously known knowledge. Based on the authors' experiences in using technology enhanced learning (TEL), not all VRLEs support the same level of meaningful learning experience and a VRLE may even be attractive to users but not effective at the formative level. Thus, teachers currently face the problem of not knowing what key factors are to be considered when creating or designing their VRLEs in order to achieve a high level of meaningful learning. Furthermore, to the authors' knowledge, there is no publication to date covering the influence of VRLEs' design on meaningful learning. Thus, taking into account the research trajectory of the authors, who have recently designed and implemented several virtual laboratories based on VR and IVR technology in the field of MSE [2,4,6,9–11,14–16,24,39–41], the main objective of this paper is to compare different VRLE designs to elucidate the most suitable features for achieving meaningful learning. Consequently, key factors that a TEL-based VR must have to promote a good level of meaningful learning experience in the classroom are described in this contribution. The implications of the present study are not limited to the field of MSE but are applicable to any other discipline that could readily benefit from using VR or IVR (e.g., biology, chemistry, bioengineering, and medicine).

2. Virtual Reality Learning Environments

In the past few years, several VRLEs have been utilized in the classroom and for training in the field of MSE. These systems have been described in detail in previous articles [4,6,9,11,40] and, given the fast pace of technology development, they could be considered "obsolete"—although they were created only about five years ago—and, consequently, relatively "undesirable" to students (Figure 1). Despite this, it is the authors' experience that these VRLEs have always been well received by students and, therefore, they can be compared with newer VRLEs that the authors more recently designed with modernized VR technology—some of them described in recent papers [11,41]—(Figure 2).

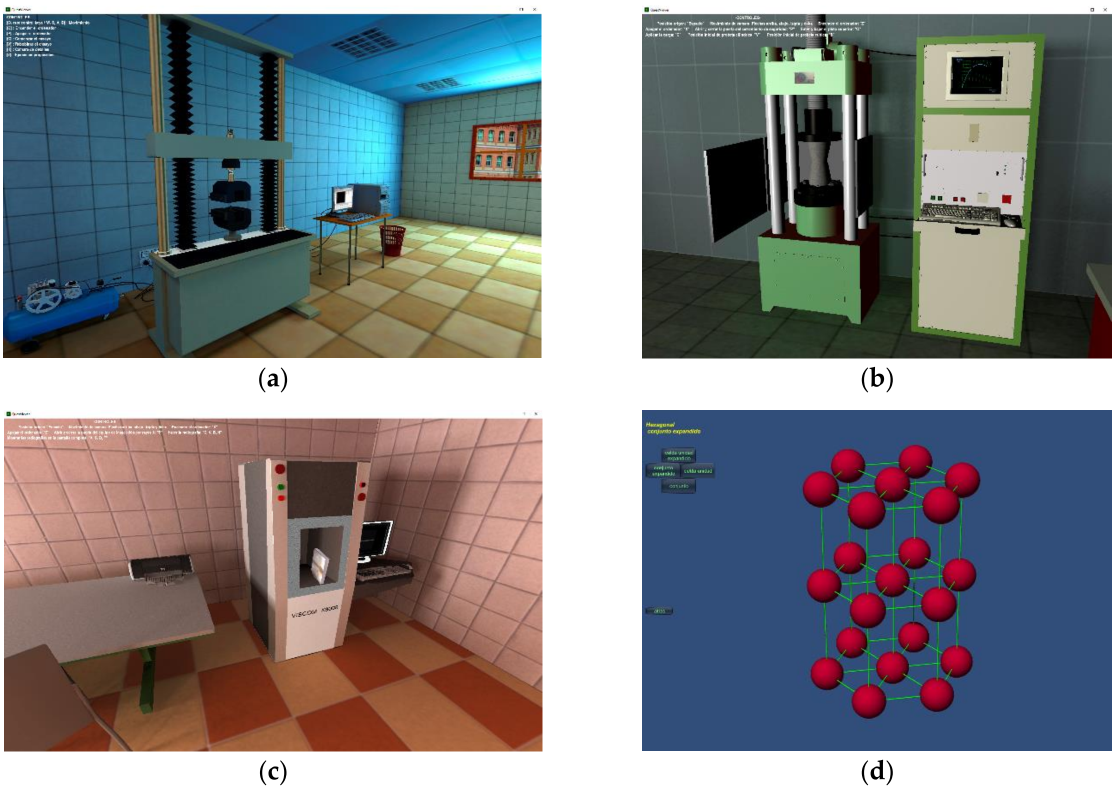
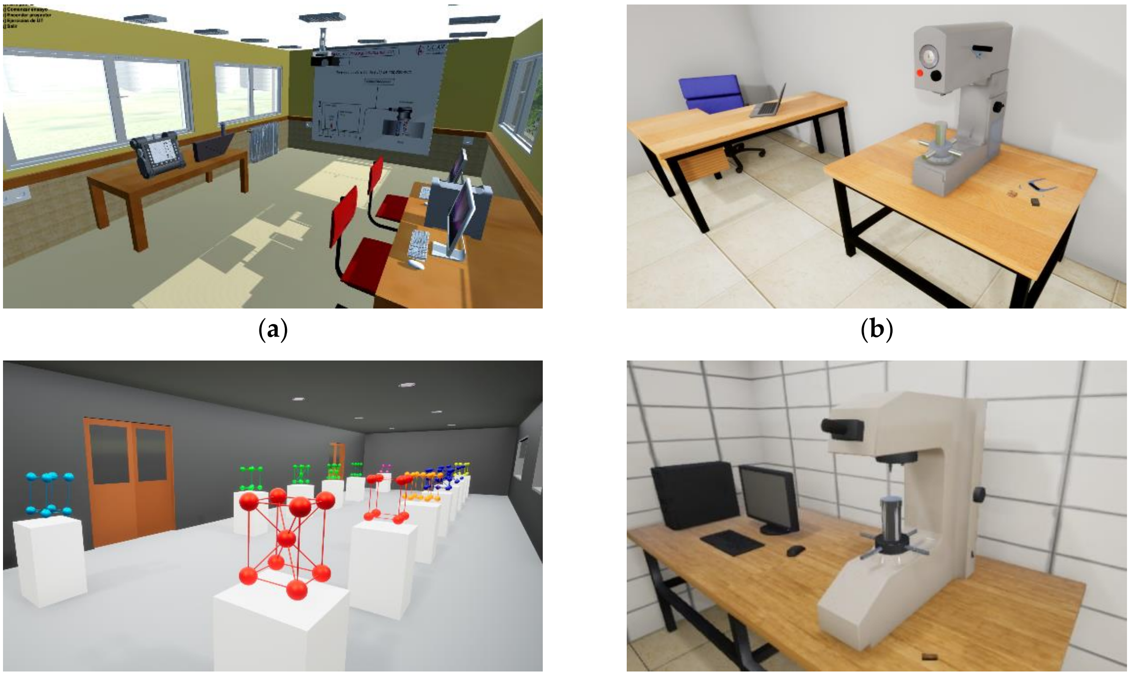


Figure 1. Representative virtual reality learning environments (VRLEs) designed with virtual reality (VR) software several years ago: (**a**) tensile testing; (**b**) compression testing; (**c**) X-ray evaluation; and (**d**) crystal lattices simulation.



(a) (b) (c) (d)

Figure 2. More recent VRLEs designed with newer VR software: (**a**) ultrasonic testing; (**b**) Rockwell hardness testing; (**c**) crystal lattices analysis; and (**d**) Vickers hardness testing.

Regarding the VRLEs depicted in Figure 1, the VR software used was Quest3D in several of its versions, which is the combination of a video game engine with a development platform where interactivity is programmed. Models and environments were initially created with older versions of Autodesk 3D Studio Max software, which offered limited possibilities. The Quest3D software was generally used for architecture, product design, video games, training software, and simulators (nowadays, this software is often used for video games). Among the key limitations of Quest3D are that it: (i) does not generate realistic results since it does not account for the physical–chemical characteristics of the interaction of light with a material surface; (ii) does not simulate particle or dynamic systems such as liquids, collisions, and fractures; (iii) does not allow creating immersive virtual reality environments; and (iv) demands a greater specialization in programming.

By contrast, the software used to design the 3D scenes of VRLEs, shown in Figure 2, were Autodesk 3D Studio Max (current versions) and Epic Unreal Engine 4 (UE4) for programming. UE4 is a new creation tool, much more powerful than Quest3D, which was designed for a less expert user and has enhanced photorealistic graphic results. In efforts to improve the performance of VRLEs, 3D environment modeling tasks were performed separately from programming tasks for interactivity via two general types of specialized programs for distinct purposes:

- Modeling software and 3D animation: dedicated programs were used to create three-dimensional virtual environments. These are the same software as those used in the production of current films, video games, and projects and previews of engineering and architecture. Although other software alternatives were available (Cinema 4D, Autodesk Maya, Blender, etc.), Autodesk 3D Max (v. 2018) was selected in the design of VRLEs shown in Figure 2.
- Game engines: originally created for video game programming, these engines are responsible for generating interactive images of a video game or an IVR application. These tools provide a rendering engine to generate: (i) 2D and 3D graphics; (ii) an environment that detects physical collisions between objects; and (iii) visualization of the responses to those collisions, interaction with the environment, realistic materials physically based rendering (PBR), lighting with bounces, raytracing, sounds and music, animation, artificial intelligence, communication with the network,

multi-users, memory management, etc. Another important feature is the possibility of developing different platforms and technologies for: (i) Android and iOS mobile devices; (ii) desktop computers including Windows, Macintosh, HTML5, and Linux; and (iii) consoles such as PlayStation, Nintendo Switch, and Xbox One. Although several options were available (e.g., Unity and CryEngine), UE4 was selected for the design of enhanced VRLEs shown in Figure 2.

The use of UE4 software allows creating much more realistic VRLEs, with greater possibilities of interaction, and IVR environments. UE4 is a virtual reality engine that allows programming in two different ways: (i) coding in C++ language; and (ii) using the Blueprints Visual Scripting (BVS) system. The programming mode used in the newer VRLEs (Figure 2) is BVS, which is a graphical programming system based on object-oriented programming (OOP) that does not require coding. Programming using the BVS system saves considerable time compared to programming by coding. Although certain functionalities can only be programmed by writing C++ codes, all the interactivity of the VRLEs developed more recently (Figure 2) has been achieved exclusively via the BVS system.

Regarding BVS, two key components are emphasized next: (i) blueprints, which are the basic programming units from which the objects characterizing the OOP are created; (ii) graphic programming board, corresponding to each blueprint. Each blueprint is programmed using its own graphic programming board: on this board are placed pre-configured nodes that define specific functionalities (e.g., read the spatial coordinates of an item contained in the 3D scene). Each node is connected to other nodes by means of wires, thus establishing a relationship between them.

There are numerous blueprints available in UE4 oriented to a broad range of functionalities. However, VRLEs in Figure 2 have mainly required the use of the following types of blueprints:

- Level: contains the main code, from which key elements (user inputs, movement of objects and cameras, and the show-and-hide of interfaces, buttons and help elements) are created.
- Character: establishes the avatar that the user controls.
- Game Mode: defines a centralized repository of variables required by other blueprints.
- Player Controller: specifies aspects of user control.
- Widgets: position the interfaces that allow displaying of buttons and messages.
- Actors: allow the use of objects in a given scene with advanced functionalities.

Usually the needs that arise during programming are met through nodes with trivial functionalities. However, there are circumstances that require specific combinations of nodes that are not always easy to infer or find either in specialized literature or in the wide range of developer forums available on the Internet.

Due to the increasing power and accessibility of computers, and the relentless evolution of the development of 3D modeling tools, the current VRLEs present a series of important improvements. To effectively compare VRLEs shown in Figure 1 (5 years ago) and Figure 2 (more recent), the main technical features are summarized in Table 1. Several advantages are evident in the newer VRLEs: (i) higher graphic realism; (ii) better adaptation to the interactivity level established in the design criteria of the application; (iii) simulation of physical phenomena in experiments, such as collisions; and (iv) easiness of development and updating on multiple platforms, including those based on IVR. The importance of such characteristics in a VRLE has been thoroughly discussed in previous studies [1,2]. Since these traits influence the level of students' motivation [24], the VRLEs designed with updated software (Figure 2) are found to be more engaging than older versions (Figure 1), despite having only about five years difference between them.

Table 1. Comparison of main characteristics of VRLEs developed by the authors at different stages.

Feature	VRLEs (5 years ago) Figure 1	VRLEs (updated) Figure 2
• Light bounces according to optic equations	No	Yes
• Realistic physically based rendering materials	No	Yes
• Virtual environment subject to laws of physics	No	Yes
• Easy adaptation to platforms other than the computers	No	Yes
• Possibility of adaption to immersive virtual reality (IVR)	No	Yes
• High knowledge in programming required for development or updates	Yes	No

3. Design Considerations of a VRLE

Prior studies [1] have reported that the development of a VRLE should be carried out following a design process (Figure 3) that involves steps to: (i) decide the level of realism required to achieve the objectives of the VRLE; (ii) choose the level of interactivity for the VRLE; (iii) select the software and hardware that best suits the development needs arisen from the previous steps; (iv) simulate the virtual environment and program the interactivity; and (v) test the application with pilot users and make the required modifications upon analysis of the results from such tests.

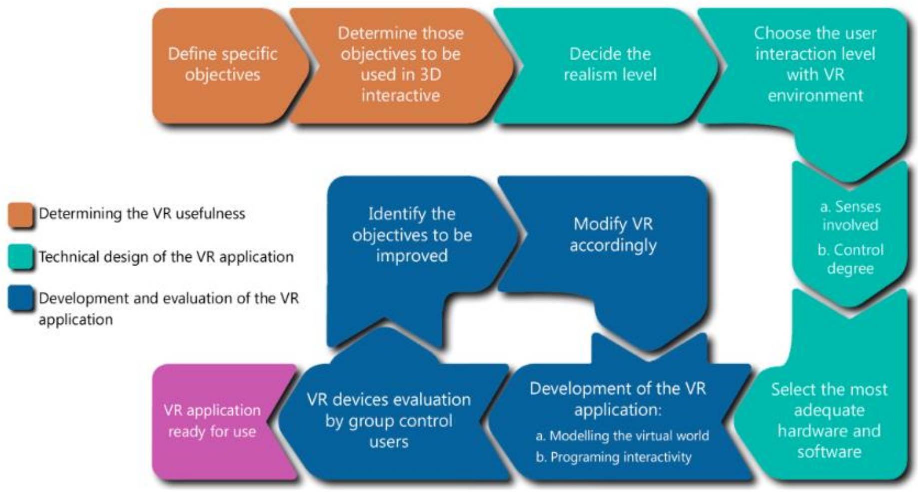


Figure 3. Design process of a VRLE previously described and published elsewhere.

Nonetheless, based on the authors' own experience, the design process shown in Figure 3 does not guarantee the achievement of meaningful learning. Thus, we recommend in this article to include a robust step-by-step protocol in the design process of those VRLEs that simulate realistic laboratory experiments. In fact, the concept of a step-by-step protocol for a VRLE implies that it meets the following criteria: (i) displays a sufficient level of interactivity to carry out the virtual experiment in a motivating and effective way at the formative level (i.e., if the level of interactivity is low, the user does not interact with the VRLE and does not retain knowledge; however, if the interactivity is too high, the user can lose the thread of the experiment and become unmotivated); (ii) always indicates to the user what is the next step to take and how to complete it; and (iii) does not allow the user to carry out unnecessary actions or lead the user to fail the experiment. The step-by-step protocol of a virtual experiment hence helps the user to focus on understanding each stage of the experiment, avoiding the need to spend a lot of time learning how to use the VRLE [41]. Figure 4 shows the result of adapting the step-by-step protocol to the prior flow chart of Figure 3.

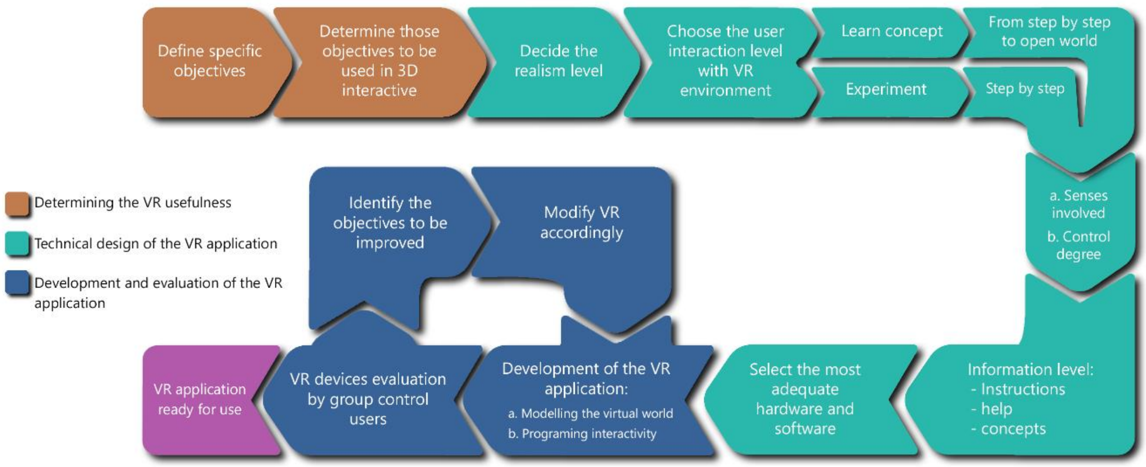


Figure 4. A newer design process, including a step-by-step protocol, as described in this publication.

The main difference between both flow charts (Figures 3 and 4) is the level of attained interactivity which will vary depending on the aim of the VRLE, namely to: (i) help the user to learn how an experiment shall be carried out, or (ii) help the user to understand a concept. When a student conducts an experiment in a real laboratory, before starting the actual test, he/she receives a procedure from the teacher that contains a detailed sequence of steps that the student must follow from beginning to end, for successful completion of the test. Similarly, a student who performs a virtual experiment in VRLEs that simulate real experiments (by means of a step-by-step protocol) should receive the same detailed steps that the student would follow in a real laboratory. By contrast, when the objective of the VRLE is to help the student to understand a basic concept, different levels of interactivity can be chosen for distinct scenarios: (i) a step-by-step approach, which would allow little freedom of action; (ii) an open world, which would allow the student to freely explore with a high degree of freedom. Another difference between Figures 3 and 4 is the amount of information that is displayed to the user while using a VRLE. This information is mainly of three types: (i) instructions; (ii) help information; and (iii) conceptual information. The former refers to information that tells the user how to use the application (e.g., what options are available, what steps shall be followed, how to use the controls). The second refers to information that is shown when the user makes a mistake or when he/she asks for help when facing problems to continue using the application. The third case refers to information that clarifies concepts related to the experiment itself or concepts studied through the VRLE.

Based on the development process outlined in Figures 3 and 4, we focus on the fact that before starting the development of a VRLE, two requirements must be met [1]: (i) the tool to be developed must improve the teaching–learning process; and (ii) the effort required to develop the tool must be justified, which will depend essentially on the advances in computation at that moment. Regarding this last point, it can be inferred that before starting the development of a VRLE it is very important to know the following data of the technology to be used: (i) availability in the market where the VRLE is to be developed; (ii) dissemination in universities and target students; and (iii) current price. For example, the development of a VRLE that requires a high-range HMD system would not be justified in a developing country because: (i) the necessary hardware cannot be acquired since it is often scarce or not available; (ii) the technology is not widespread in universities or among students in those countries; and (iii) the acquisition likelihood by universities or students in these countries is almost impossible due to its high cost. On the contrary, the development of such VRLE would be justified if it was designed to be used in a personal computer with medium or low computing capacity since these types of computers: (i) can be purchased in most cities; (ii) are currently widely spread in universities and among students; and (iii) are accessible and economical, and therefore their price would not stop their acquisition if necessary.

Further analysis of the flow charts of Figures 3 and 4 reveals that all aspects related to the technical design of an application (e.g., determination of the level of realism, determination of the mode of interaction, selection of hardware and software) are closely related to what has been previously exposed. In this sense, we noticed a straightforward correlation: the higher the budget of the hardware, the higher the level of realism and interactivity the VRLE can offer, but the dissemination among end users will be lower. By contrast, the smaller the budget of the hardware, the greater the dissemination of the VRLE but the lower its realism and interactivity, thus becoming an "undesirable" tool for the student.

4. Meaningful Learning Analysis

4.1. Problem Statement

The typical training involving an MSE machine is usually carried out with large groups of students, which hinders a good teaching–learning process [6]. A possible solution to this problem is the implementation of VRLEs. In the first case (a large group of students around an MSE machine) is logical to expect a less meaningful learning experience, but in the second case (an individual instruction though a VRLE) the expectation should be the opposite, i.e., students would undergo a highly meaningful learning experience. However, during the last five years using several VRLEs similar to those displayed in Figure 1, the authors have verified that students hardly remember how a real MSE machine works in the following year upon training. Even during subsequent visits to real laboratories, it was found that some students did not remember having handled virtually (through a VRLE) some of the machines that were in those laboratories the previous year. For this reason, through the analysis of the data obtained in this study it is intended to explain what factors are the most significant to explain this fact.

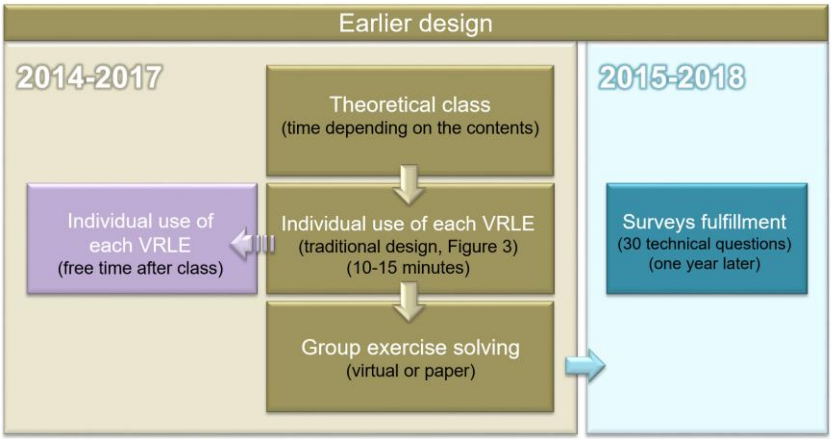
4.2. Methodology

The methodology used in the recent VRLEs described in this work (e.g., Figure 2) is divided as follows: (i) assume a theoretical class —the process will vary in time depending on the real machine desired to simulate; (ii) estimate the time for individual use of the VRLE, which may take approximately 10–15 minutes (besides, students can reuse the VRLE in their free time); (iii) determine the resolution of the virtual exercises for small groups (2–3 students) including the VRLE [4,9,10] or traditional classroom exercises (using paper); and (iv) collect individual fulfillment of an specific survey one year later, which contains technical aspects of the different VRLEs used the previous year (e.g., the students who handled the VRLE in 2014 completed the technical survey in 2015, which allowed to know the level of knowledge of MSE machines that they still remembered a year later). For the reader to get an idea of the type of questions that have been raised in the survey, some examples are shown in Table 2. Three questions of a total of 30 have been selected; through these questions the students are asked about concepts of MSE simulated through a virtual environment (e.g., tensile testing [4], compression testing [6,40], industrial radiology [9], ultrasonic testing [10], crystal lattices [11], ternary phase diagrams [14,39], and hardness testing [41]). Although Table 2 does not include all the questions, it should be noted that the survey questions were the same during all the years considered in the present study, hence ensuring that the results from different years are comparable.

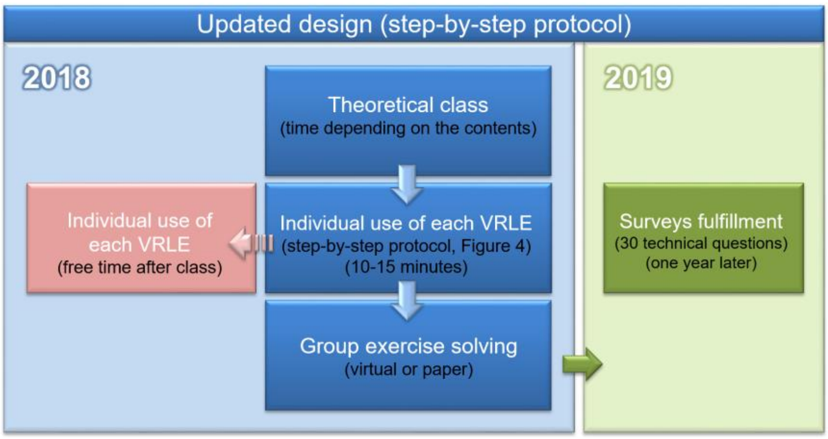
For the sake of clarity, a scheme of the methodology followed in this study is presented in Figure 5. The implementation and evaluation of the VRLEs were carried out during the academic courses between 2015 and 2019. Students of MSE subjects of the degree in mechanical engineering taught at the Catholic University of Ávila (Spain) participated in this study. Each year approximately 20 students participated. During the first four years (2015–2018) the study was based on the VRLEs created with the design process shown in Figure 1, which were used by students the previous years (i.e., 2014–2017) to fulfil the student survey requirement. However, more recently, in 2019, the study was based on the new design process (step-by-step protocol), as illustrated in Figures 2 and 4. In this case, the students used the updated VRLEs from 2018, which were designed as shown in Figure 4.

Table 2. Examples of questions and answers included in our student surveys.

Question	Answers
• Which Rockwell scale would you use for a high strength steel?	(a) HRC (b) HRB (c) HR15N
• In a tensile test, what does UTS mean?	(a) Yield strength (b) Young modulus (c) Maximum strain (d) No answer is correct
• In Vickers hardness testing, what is the shape of the indenter?	(a) Hardened steel ball (b) Diamond in the form of a cone (c) Diamond in the form of a square-based pyramid



(**a**)



(**b**)

Figure 5. Schematic of the methodology followed in the present study: (**a**) during 2015–2018; and (**b**) in 2019.

To improve the retention of content, authors have decided to modify the design of the VRLEs by including a step-by-step protocol. Thus, the design process (and, specifically, the step-by-step protocol) is the main significant difference between the methodology used with the VRLEs of Figures 1 and 2.

4.3. Results

The improved VRLEs were implemented in a course within the Mechanical Engineering major, which covers MSE. One year after, these same students were enrolled in other classes focused on other topics related to industrial and manufacturing processes where several MSE machines are applied again (e.g., contents dealing with quality control). Since authors verified that many of the students did not remember how these machines work, they began doing surveys to assess quantitative data to measure the level of such knowledge. Some examples of the types of technical questions raised in the survey are shown in Table 2.

A summary of such data related to the concepts recalled by a total of 103 students (approximately 20 students each year) is shown in Figure 6. These results show the average value of the technical questions correctly answered by the students (students' marks), which reveals the level of knowledge they remembered about MSE machines and contents (which they studied one year prior to the survey through VRLEs). In addition, statistical variables of the survey results (the number of right answers), such as mean and standard deviation, were collected (Table 3).

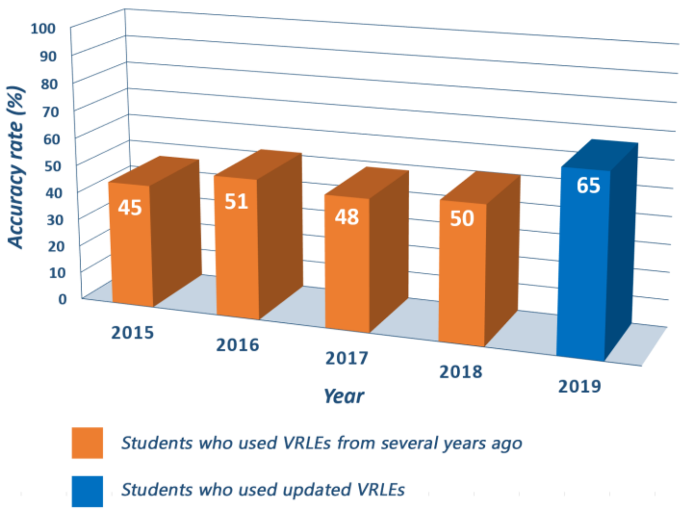


Figure 6. Accuracy rate (students' marks) of survey questions provided by students, who participated a year earlier in class sessions covering fundamental concepts in material science and engineering (MSE) through VRLEs.

Table 3. Statistical results of students' marks after using VRLE one year prior.

Students' Marks	2015	2016	2017	2018	2019
Mean (%)	45.33	51.33	48.41	49.84	64.76
Standard deviation (%)	6.93	7.60	7.50	7.11	11.23

5. Discussion

Clearly, it is practically impossible for all students to retain knowledge for a year without forgetting anything (i.e., to achieve 100% accuracy rate in Figure 6). In spite of this unrealistic expectation, both Figure 6 and Table 3 show that the percentage of retained knowledge varies from one year to another: between 2015–2018 there are hardly any differences, but there is an increase in 2019. The results from 2015–2018 are based on the use of earlier VRLEs designed several years ago (Figures 1 and 3), whereas the results obtained from 2019 are related to the use of updated VRLEs designed more recently (Figures 2 and 4). During the period 2015–2018 the accuracy rate varies between 45% and 51% (Figure 6), while in 2019 the mean value rises to almost 65%, thereby increasing approximately 30% over previous years. On the other hand, the standard deviation is quite similar in the period 2015–2018, indicating a non–significant variation from year to year (extending the number of right answers from 11 to 20 out of 30). However, the higher standard deviation in 2019 suggests a greater dispersion of results, emphasizing that the new design process (step-by-step protocol) is quite effective for some students but, at the same time, it is not too effective for others. Nevertheless, taking into account that the range of data in 2019 is between 13 and 24, it is possible to ensure that the new design favors a higher level of meaningful learning.

Several factors could influence these results: (i) the teacher; (ii) the contents given during class in the different years; (iii) the methodological process used during classes; (iv) the survey questions; (v) the academic level of the students; (vi) the software used to create the VRLEs; and (vii) the design process used in the VRLEs. Given that the first four factors have been the same during all years (2015–2019)—the teacher was the same during such a period, the contents did not vary from year to year, the methodological process was identical in all the academic courses, as shown in Figure 5, and the survey questions were the same in all cases)—and that the students' scores were similar as well, the key variables that may have had significant influence on the improved results in 2019 are: (i) the software used to create the VRLEs (i.e., newer, more powerful, and more versatile in 2019 than in 2015–2018, consequently, the VRLEs are more appealing and engaging for students [24]); (ii) the new design process used in the VRLEs in 2019 (Figure 4) with an enhanced step-by-step protocol.

It should be noted that updating a VRLE with a better realism helps the student to be more motivated, thereby being more engaged and focused on the contents of the VRLE (which likely leads to a higher level of meaningful learning). However, based on the authors' own experience in designing different VRLEs for several years, the more relevant aspect influencing the meaningful learning experience is the step-by-step protocol. In previous studies [4,6,9–11,15], the authors have verified that, in general, the motivation is always high when using this type of TEL. However, this aspect (higher level of motivation by updating the software) cannot be the key factor that has favored the increase reflected in Figure 6 of approximately 30% in the knowledge retained one year after. Taking into account that no significant differences are found when comparing the overall grades of students during the academic courses considered in this study ranging from 2015–2019, the higher level of motivation generated in students when using an updated VRLE should not have significative influence on the meaningful learning. Consequently, the more relevant aspect affecting meaningful learning via a VRLE should be the new design process including a step-by-step protocol.

In addition, the fact that students use a step-by-step protocol in an MSE virtual laboratory is much more effective at the didactic level than doing the practical classes in a real MSE laboratory, where usually only the instructor handles the machines. Prior studies have also reported the effective use of a step-by-step protocol to design interactive lessons via audio-visual e-books for MSE learning [42]. The authors have experienced throughout the years a better understanding of the contents at the time of using the VRLE and the need to improve the design process, which will lead to a higher level of student retention of such contents over time and thus meaningful learning.

There are certainly circumstances where VRLEs do not need a step-by-step protocol (e.g., when the simulated experiment consists of a single step or the VRLE is intended for understanding a basic concept) and the meaningful learning should be empowered in a different way. Therefore, in this scenario it is important to consider the graphical requirements (i.e., desirable visuals) and the use of VRLEs (e.g., new interactivity methods via IVR and haptic responses). In fact, since UE4 allows the design of VRLEs to be used in immersive environments (ranging from economic systems such as Google Cardboard to professional HMD systems such as HTC Vive Pro), future research on the influence of immersion level on meaningful learning is compulsory to better understand both the origin of the differences observed thus far and the promising ways to improve them.

6. Conclusions

Virtual reality learning environments are powerful and useful tools in the educational field as they can solve some of the typical problems that occur during practical classes in real laboratories, e.g., some students fail to see all details when a test or experiment is carried out (even when the student group is large, some of them cannot see anything from the experiment), other students cannot listen the technical explanation when the test is carried out, etc.

The advantages that a VRLE could present from a didactic point of view directly depend on the design process. A proposed design to improve the level of meaningful learning in a VRLE was presented in this paper. The design process includes a step-by-step protocol as a key component, which was corroborated in a five-year research by means of using different VRLEs in the field of materials science and engineering. Based on the results thus far, it is worth noting that the design process in a VRLE has an influence on the students' meaningful learning, much more than other aspects such as the software used to create the VRLE or others. Therefore, to ensure a better level of meaningful learning through the use of a VRLE, the authors recommend designing the didactic resource with a step-by-step protocol whenever possible, as they will provide optimum experience.

Furthermore, the amount of data being collected, recorded and stored routinely nowadays through VRLEs is increasing at a fast rate due to inexpensive computing, widespread use of electronic records, digitalization of imaging, storage capability, and rapid development of other technologies (e.g., augmented reality, artificial intelligence, machine learning). Therefore, future efforts will also rapidly increase to foster new cyberinfrastructures (i.e., network of VRLEs where users collaborate on projects remotely) to accelerate materials discovery, learning, and training of individuals seeking new skills (e.g., data science) and opportunities. This would require fast and specialized frameworks, efficient didactical methods designed for many disciplines, varied levels of interactivity, etc., in order to efficiently adapt to different team sizes, degrees of complexity, etc.

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