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Incorporation of virtual learning environments for online STEM activities

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Incorporation of Virtual Learning Environments (VLE) for Online STEM Activities

Abstract

In this study, we investigated and documented the systematic design and implementation of a simulated lab learning experience for an online STEM course. The purpose of this paper is to detail our considerations and document our methodologies in developing and integrating such hands-on virtual learning activity in a fully asynchronous online learning environment. Thereby, our goal is to share our experiences, so that others can replicate, adapt, or expand on our approaches. Guided by various learning theories, merged into a framework of progressive competency development, a VLE was constructed that allows students to systematically develop methodological understanding and procedural application skills for the collection and analysis of data in a lab environment. Thereby, a simulation element was embedded into the larger didactic framework of the asynchronous online course, and provisions were implemented that allowed for ongoing formative feedback. The, in this way, collected quantitative and qualitative data seemed to support the suitability of our methodological approaches (especially after enhancements were made based on the feedback), while also underlining the importance of a comprehensive approach to design and implementation as well as the need for continuing support.

Introduction

The application of technology-enhanced learning approaches in higher education has seen a dramatic increase over the past two decades, with online-distributed courses and degree programs rapidly gaining in popularity at colleges and universities [1]-[3]. The learning opportunities afforded by low-cost, on-demand access from anywhere at any time seem to benefit especially non-traditional learners, and seem to acknowledge, as much as shape, the requirements for 21st-century professional and study skills [4]-[8]. Nevertheless, the application of e-learning approaches is not without controversy, as some [9] have observed a current lack of standards, experiences, and empirical data and others [10] even cautioned against the widespread implementation of, so far, unproven approaches.

On the one hand, online learning seems to require more learner self-engagement[1] and self-regulation [3],[5],[8],[11]-[14], and there seems to exist a greater danger for dissociation of participants in distributed learning environments [6],[7]. On the other hand, especially for science, technology, engineering, and math (STEM) education, traditional curriculum requirements that are based on physical manipulation and hands-on examination, such as lab practice and experimentation, so far, have been difficult to replicate in the online learning environment (OLE) [15]-[17]. Additionally, a new generation of 'digitally native' students may demand more interactivity and involvement [18]-[22] than what online education has provided thus far.

To foster greater student engagement while also accounting for individual learner differences and addressing some of the challenges of the distributed learning environment, a variety of approaches have been suggested, ranging from collaborative environments [9],[23],[24] over problem-, project-, situation-, or inquiry-based learning [25]-[27] to gamifications [6],[28]-[32]

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[1] The term *self-engagement* was introduced by [42] to signify the unification of cognitive elements of self-motivation, self-direction, self-reflection, self-regulation, and self-correction.

and interactive virtual environments (VEs) [17],[33],[34]. Thereby multiple approaches may be combined to enhance the user experience and increase the learning success. For example, a situation-based gaming environment may allow learners to explore content on their own, thus, increasing their sense of autonomy and progress control, factors identified as important to learner self-regulation and responsibility [11],[13],[24],[29],[35].

Through VEs users can be immersed in specific environments in order to elicit tasks under what is perceived as realistic circumstances. Thus, *fidelity* as "a measure of the degree to which a simulation system represents the real-world system" [36] may be assessed by comparing physical measures of the VEs against their real-world counterparts. Nevertheless, when developing simulations for the learning context, far more important than any physical match to the real world is whether a VE may be perceived as realistic by the user and whether it can reliably affect a desired behavioral or learning outcome [37],[38]. Therefore, the validation of a simulation as part of an online STEM course activity seems to require more than just an assessment of its realism. It requires a conscious alignment of its design and implementation with the desired learning processes, an ongoing evaluation of user-perceived usability and usefulness, as well as objective assessments for the achieved learning progress and outcome [36],[39]-[41]. Furthermore, mechanisms need to be created by which continuous improvements to design and implementation can be made in order to affect desired pedagogical objectives.

Purpose Statement

The purpose of this study was to investigate and document the systematic development and implementation of a simulated lab learning experience in an online STEM course. The long-term goal is, thereby, to advance task-technology-fit (TTF)[2] of simulations in online learning from mere logistic tools (i.e., technology used to merely replicate the traditional classroom activity) to didactic ones (i.e., fully leveraging the available technology to enhance online learning beyond the traditional activity) [40],[43],[44]. To this extent it is also the purpose of this study to eventually establish a method of designing high-quality online engineering labs that support the newly established online engineering programs. Thereby, the goal is to achieve a quality of education comparable to what is found in many traditional brick-and-mortar engineering degree programs in the form of physical labs, which is also a common requirement for outside accreditation. For example, the Accreditation Board for Engineering and Technology (ABET) requires as one quality criterion that engineering programs link "engineering concepts to engineering application" [45].Traditionally, this condition for quality is achieved by the application of principles in the lab. However, for the OLE, such application is much more difficult to accomplish.

As one of the leading distant-learning providers in the US, offering award-winning online degree programs to our students [46], we are constantly working on overcoming such challenges. In that respect, the development of new courses and activities for our degree programs always also offers a chance to address these shortcomings in online STEM education. Therefore, the purpose of this paper is to detail our considerations and document our methodologies in developing and integrating a hands-on virtual learning activity. The goal is to share what we did, how we did it, and why we did what we did in the way we did, so that others can replicate our methodologies,

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[2] The term was first used by [47] to explain information system suitability for specific task requirements and their corresponding impact on user performance, but it can also be applied to educational settings, for example, to describe the suitability and impact of learning management system (LMS) design [48],[49].

extract pertinent aspects of our framework, or expand on our thoughts. In that sense, we considered it paramount to provide an extensive review of the scholarly work that informed our decisions, to allow others to trace the origins of the herein presented ideas.

Delimitations

To directly address potential criticism of the rigor of the presented work (especially with regard to data analysis and results), we think it is important to understand that our primary goal was not to conduct experimental research in a controlled setting but to, first and foremost, develop and implement a pedagogical tool for our students. In that sense, the here presented study is intended as a starting point, documenting our ongoing action research (i.e., reflecting on practice to inform practice). As such, no claim is being made that the conditions were held constant for purposes of comparison with a control group or to enable a time-series type of data collection. To the contrary, we continuously fine-tuned our tools and methodologies as we made observations and received feedback and user inputs, which is also an essential part of the methodology presented here.

Similarly, our goal was not to develop a research simulator capable of measuring a particular set of psychometric parameters to answer a specific hypothesis related to human learning. Our goal was to develop and implement a pedagogical strategy (based on a blend of multiple pertinent learning theories) for the achievement of desired learning outcomes in student knowledge and skill development that is aided by virtualization approaches. As such the simulation element is embedded into a larger didactic approach to learning activity design in online coursework, which is at the core of this study. Accordingly, the main purpose for the employment of a questionnaire was also not so much as a designated research instrument but to enable the desired ongoing quality control and improvement through feedback. Therefore, our methodology relied on a continuous improvement cycle in the development of the VLE.

VLE Design and Implementation Process

In this context of task-specific design and implementation of an online simulated lab learning experience, a systematic approach was needed. The process of modern instructional design and development ADDIE (Analyze, Design, Development, Implementation, and Evaluation) was selected to meet this challenge [50],[51]. The benefits of using the ADDIE model for designing and implementing the virtual simulated lab learning experience were several. Through the Analyze step we were able to decide who the primary user would be and take the learning characteristics of that particular end user into account. For example, important aspects, such as how the identified audience likes to use technology and what their expectations of the technology are, were determined. Also, the learning goals and desired learning progress were matched to applicable learning theory, which set the stage for the completion of the Design step in ADDIE. Once the raw design was accomplished and all necessary components of the VLE were determined, the software development for the simulation started, utilizing the Unity programming environment[3].

This Development step also further highlighted some of the inherent limitations with the simulation (as will be further discussed in the theoretical framework), setting the stage for the

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[3] Initially, to run the simulation, the desktop Unity player app was utilized and had to be separately downloaded by students. Due to compatibility concerns identified via the ongoing evaluation process, the VE was later changed to directly include the platform-specific (Mac or PC) Unity app in the simulation, which reduced some of the technical challenges students experienced. For a next update, it is contemplated to completely switch to the web-based version of the platform.

next crucial step: Implementation. It became rather obvious that, in order to achieve the goal to fully leverage the VE as a learning tool, the simulation by itself would not be enough but would require a task-oriented alignment with the rest of the course and the OLE. Therefore, the challenge during implementation of the newly developed virtual lab was to integrate it as part of a larger learning activity that complements the other elements within the module and course while uniquely enhancing the desired learning outcomes (DLOs). Lastly, the importance of the Evaluation step in ADDIE, which came in the form of both *summative* and *formative*[4] assessments and qualitative as well as quantitative data, cannot be overstated. These assessments were paramount for the ongoing improvement of the virtual lab and its incorporation into the OLE and characteristically exemplify our choice to apply ADDIE as a continuous, cyclic process for learning enhancement.

Analysis of VLE Requirements and User Characteristics

As previously indicated, the Analysis step of the ADDIE process involved a thorough study of the student end users to match their skills and expectations to that of the design and development of the VLE. This first step seemed especially crucial since, unlike in the past, in which OLE were mainly designed for continuing adult learners, current developments in higher education seem to indicate a growing number of online students entering especially STEM degree online programs directly after high school [2],[4],[8],[52]. Thus, besides the conventional adult learners that previously made up the majority of students in online courses [1],[3], an increasingly larger number of students expected to be using the online VLE will be born after the year 2000 and are regarded as Generation Z (Gen Z) learners. Therefore, a consideration of learner traits for these ‘digitally native’ students seemed beneficial.

One commonly stated characteristic of Gen Z students is that they tend to seek and absorb a great deal of information, and it is well documented that they have grown up learning by spending several hours a day searching the internet for information [52]. Limiting available information in the virtual simulated lab could lead the Gen Z student to a boring and non-challenging experience. Another critical aspect of Gen Z students is that they seem to perceive information mainly visually [52]. Therefore the visual learning experience of the simulation should be accurate and of the highest quality. Generation Z students also consider themselves to be great multitaskers [52], seemingly being as productive and preferring to study and complete their homework under conditions that would be otherwise considered distracting (e.g., while listening to music, running a TV, or receiving social media communications). This self-perceived ability to multitask and their desire to do so, along with the fact that they also tend to like independence and autonomy for their learning, seem to make them perfect candidates to excel using an online VLE [52].

The notion that Gen Z students are more technologically advanced users seems to make sense as computer technology has shaped the way they have learned. They are also the first generation that has grown up with smart phones and never experienced a world without the internet. They have used computers to do their homework and enjoy using ‘how-to’ videos and other technologies to learn with [52]. With such a keen sense of technology as a learning tool, it seems imperative that a VLE be designed with high quality technology learning in mind. Anything short will likely be less effective and possibly frustrating for the Gen Z learner. Another important aspect of the Gen Z learners in relation to technology is their constant use of social

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[4] formative in the sense that it aims to modify the learning approaches and environments based on the outcomes of the assessments

media and how it can support their learning [52]. Therefore, to enhance learning for these students, it seems, the design and implementation of a VLE also needs to take social exchange into consideration, for example, by providing ways for student-to-student and student-to-instructor communication.

Review of the Literature on Gamification and Virtualization

While ‘digitally native’ learners seem to be able to skillfully use computers for their studies and professional activities, they also seem to have been exposed to a greater amount of technology in the leisure aspects of their lives. In particular, computer games and online and mobile gaming applications seem to be ubiquitous to the Gen Z experience. Therefore, such aspects of gaming could also find their place in the quality design of VE, and Gen Z students that have played any number of high-quality computer games may expect a similar level of fidelity for a simulated lab. Furthermore, some forms of gamification could potentially be integrated into the design of the VLE and the associated learning tasks to address motivational aspects of Gen Z learners.

Current research related to gamification, although limited, does transcend that there are several important ways that gamification could be incorporated into a virtual lab. In a well-designed VLE, gamification approaches may provide the opportunity to combine multiple aspects of learner-centric education simultaneously. These could, for example, include embedding continuous, unobtrusive forms of assessment that provide for both progress control within the simulation and formative feedback about competency development [19],[24],[27]. Such gamified VLEs may also encourage exploratory, self-discovering engagement with all the content, by disguising any apparent relative importance of individual learning resources from the user. At the same time, integrating gamification approaches may provide an increased level of autonomy and decision-making to the user [53]. These factors were identified as important to learners’ self-engagement and their sense of responsibility [11],[13],[24],[29],[35]. One aspect of gamification approaches that seems centrally important for the interaction between learner and content is the application of virtualization methods to create immersive settings [6],[33],[38],[54],[55], which allow for user presence in and exploration of the VE [16],[37],[56].

While interactive simulations seem to provide the necessary level of *immersiveness* [16],[34] to enhance student engagement, they may also allow for hands-on practice, skill development, and the acquisition of situation-based competencies [17],[56]-[58] and, thus, support the learning process as well as the learning content [53]. This research direction into virtualizations can be characterized as “incorporating reality as the content” [58], for which the three key directions, *situated/context aware learning* (e.g., problem-based scenarios in [56]), *mixed-reality-based learning* (e.g., reality augmentation and the DynaMus in [54]), and *interactive response learning* (e.g., simulation in complex machine operation training in [59]) mirror the objectives identified by [16] for the application of virtual laboratories in STEM education.

There is ample evidence describing the benefit of applying VEs in the classroom. For example, a modular interactive teaching package, called Virtual Learning System (VLS), is discussed in [60]. VLS provides a comprehensive and conducive yet dynamic and interactive environment that can be incorporated into various courses in Mechanical and Manufacturing Engineering. A key benefit, and good trait for VE’s in general, is that VLS can be used by people with little prior computer experience. Educational uses of a virtual learning environment (VLE) concerned with learning, training, and entertainment were explored in [61], which revealed that VLEs are a means of enhancing, motivating, and stimulating learners’ understanding of certain events, especially those for which the traditional notion of instructional learning has proven inappropriate or difficult. Collaborative learning in a multiuser 3D-simulation environment was investigated in [62], which showed that interactions with elements in the 3D virtual worlds can enforce collaboration. These examples are just the tip of the iceberg with studies supporting the value of VE in the classroom, but it leaves room for additional work in the asynchronous learning environment.

Additionally, [17] used a methodology similar to the one documented here to evaluate and refine the pilot implementation of a remote laboratory (RL) that allows students to conduct science experiments in real-time from a distance, and according to [16], virtual manipulatives (VM) also have demonstrated the potential to provide such means for successful distant application of hands-on activities in STEM education. However, as research into VLE use in electrical engineering education in [57] has found, simulations and virtualizations may not necessarily increase learning effectiveness unless they also provide increased interactivity, and this need for interactivity seems to vary depending on the different types of knowledge involved. Therefore, further investigation into learning from VEs is recommended [16],[53],[57].

Theoretical Framework

An important aspect of our analysis process was also to identify pertinent learning theories that can guide the design, development, and implementation of the VE. Based on a constructivist understanding of learning as an active process that involves the learner in the creation of knowledge from his or her own experiences through meaning-making, a variety of shortcomings of the conventional OLE and its design were identified. For one, the traditional content- and outcome-oriented approach to online course design and activity development that is, for example, stipulated by the Backward Design Process [63]-[65] seems to be based on the assumption that a subject-specific fixed body of content knowledge exists, which needs to be transmitted and subsequently tested. Therefore, this approach seems to consistently result in an over-reliance on summative assessments as well as the compartmentalization of knowledge in rigidly-structured topical units that are mostly divorced from their application in authentic contexts [44],[66]-[68]. Similarly, conventional OLEs seem to presume that every student will enter a learning unit or activity at the same stage and with the same level of pre-existing knowledge and later exit it with a pre-definable amount of new knowledge added; thus, a simple summative post-test strategy is usually deemed sufficient to establish the achievement of the DLOs.

However, such traditional OLE design seems to insufficiently address individual learner differences in their predispositions towards learning, their learning preferences, and their learning speeds, as well as inadequately account for variability in students’ pre-existing skills and competencies. It also often fails to properly situate the learning content within the context of its application [44],[66]-[68], thus, while achieving short-term knowledge acquisition for academic testing purposes, it misses to develop long-term retention and transferability of any gained knowledge. Additionally, the development of procedural and meta-cognitive knowledge, often impliedly required and tacitly applied in the competent accomplishment of professional tasks such as problem-solving, critical thinking, decision-making, etcetera [66],[67],[69], seems not sufficiently supported by conventional online learning activities especially in the STEM context. Therefore, for the development of the VLE, a more process- and progress-oriented learning model and a more formative approach to continuous learner competency development was sought.

The Cognitive Apprenticeship Model (CAM)

A well-developed framework that incorporates all of the mentioned aspects is provided by the Cognitive Apprenticeship Model (CAM) of learning [69], which was, for example, previously applied in [70] and re-conceptualized as an instructional development tool in [44] to create a more learning-centered online environment. At its core, the CAM identifies four dimensions that need to be considered when developing authentic learning spaces in which students can acquire and develop competencies in a guided manner (i.e., through apprenticeship): content, which stresses the importance of different types of knowledge (e.g., factual, procedural, conceptual, meta-cognitive); method, which highlights the different mechanisms (such as modeling, coaching, scaffolding, articulation, and reflection) by which the competency development can be supported; sequencing, which identifies the changing learning needs (e.g., from simple to more complex and diversified) during skill development; and sociology, which emphasizes the contextual nature of learning such as in situated activities [44],[67],[70].

The CAM provided the overall framework for the desired emphasis on learner progress and guided development in the VE, because it seems to accurately describe the requirements and processes that have been crucial to effective lab training in traditional, brick-and-mortar engineering education settings. For example, in the simulation part of the VE, it supports the applied training flow that lead students from equipment familiarization over scripted part-task accomplishment with feedback to independent measurement-taking (i.e., applying the principles of increasing complexity and decreasing guidance [44],[67],[70]). It also allowed to integrate the virtual lab simulation itself within the larger context of learning activities for the development of STEM-related lab skills (e.g., providing for articulation and reflection opportunities in the lab report that followed the simulation [44],[67],[70]). Nevertheless, to provide an even more detailed and structured approach to the development and sequencing of the learning tasks, a second important framework was integrated into the development of the VLE: Experiential Learning Theory (ELT), which maintains that learning from experiences happens through an interactive process, “whereby knowledge is created through the transformation of experience” [71],[72].

Experiential Learning Theory (ELT)

At the core of ELT is the Experiential Learning Cycle (ELC), which consists of a repeating sequence of the four phases, Concrete Experience (CE), Reflective Observation (RO), Abstract Conceptualization (AC), and Active Experimentation (AE), of which two are always at the opposing ends of the two dimensions Experience Grasping (EG), which contrasts CE with AC, and Experience Transformation (ET), for which AE counters RO [25],[73]-[75]. According to [71], a learner’s mind is never as “blank as a paper on which we scratch our outline,” implying that every new experience is met with an existing set of preconceived assumptions and that it is the conflict between new insights and existing theory that drives learning. Thus, consistent with the constructivist view of learning, knowledge is constantly (re)created and (re)tested in the context of new experiences and “not an independent entity to be acquired or transmitted” [71] [72]. Accordingly, learning environments and activities constructed with ELT in mind should provide opportunities for students to actively engage in the complete ELC while taking into account any differences that may exist between individual students' abilities to address the four different learning requirements [73],[75].

While combining the ideas of ELT with the CAM for the development of this VLE, a conception of STEM learning emerged in which the learner processes through a continuing ELC at ever-higher levels of mastery. Figure 1 depicts the repeated application of Kolb's ELC [74], in which every cycle constitutes increasing progress towards the mastery of a task, competency, or skill. Consistent with the ideas of the CAM, this progress is also tracked as different levels within an apprenticeship-type program (right side), highlighting the changing requirements for the support the VLE should provide at each level of application. Thus, Figure 1 represents the core model that was used for the sequencing of student learning tasks during the design, development, and implementation of the VLE.

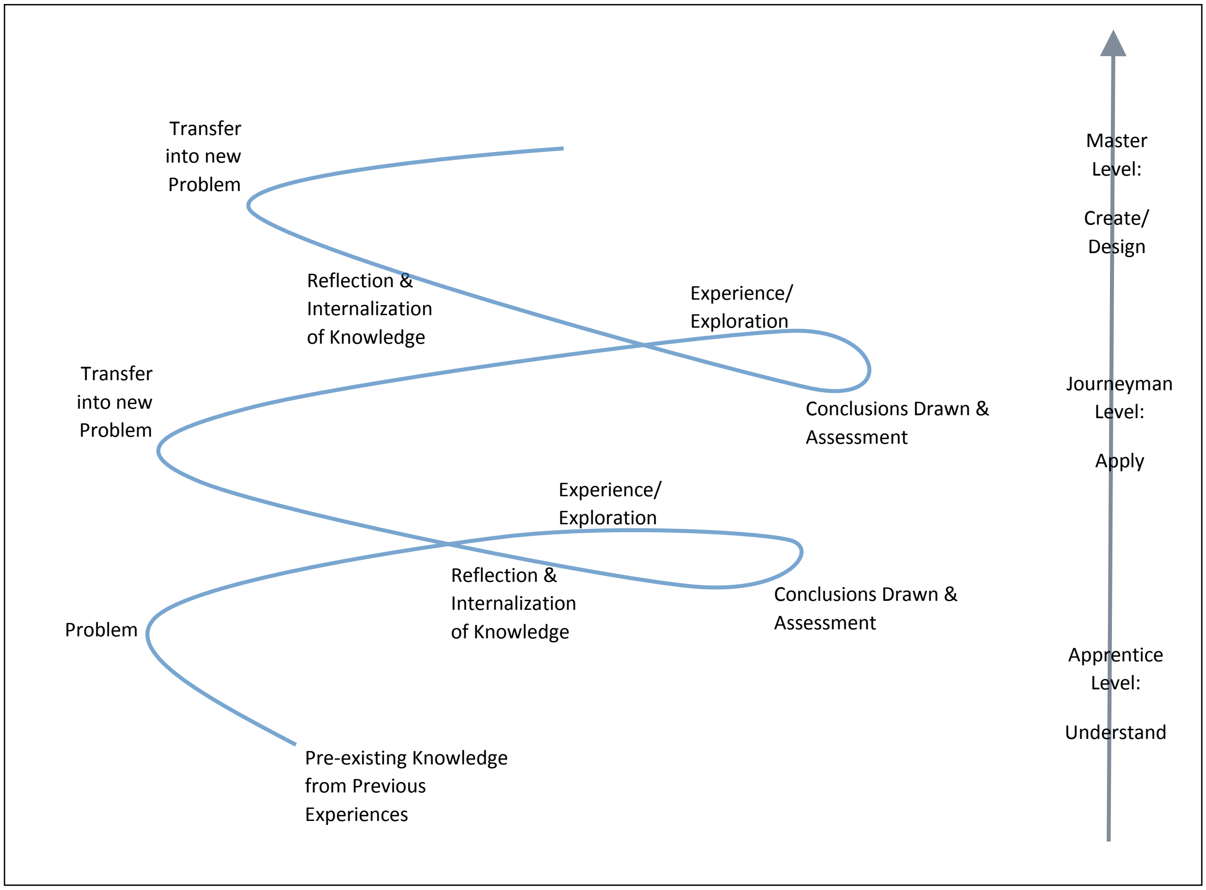


Figure 1. Application of the Experiential Learning Cycle (ELC) as repeating at increasing level of mastery in an apprenticeship-type context. Spiral of Experiential Learning adapted from [74].

Bloom's Taxonomy

Another important consideration for the design and development of online course content is the definition of DLOs. If for nothing else than accreditation and accountability in higher education, course curricula and activities should be aligned with learning goals. Traditionally, such as in the before-mentioned Backward Design Process [63]-[65], this alignment is accomplished by describing measurable student performance abilities that are expected as the result of an educational intervention, using action verbs that signal the level of cognitive achievement.

Bloom’s taxonomy [24],[76] and Bloom’s revised taxonomy [77] provide an established framework for this process. Thereby, particularly Bloom’s revised taxonomy [77] allows to define DLOs along two dimensions: the level of cognitive engagement along the vertical and the type of knowledge or information that this engagement requires or is directed at along the horizontal axis of the matrix.

Accordingly, Bloom’s revised taxonomy [77] was also utilized here; however, consistent with our emphasis on learning progress and development, rather than just identifying a desired learning outcome (i.e., an endpoint that signifies achievement of a specific learning goal) within the taxonomy, we sought to establish how students would ‘move’ through the taxonomy matrix during their apprenticeship. Therefore, the level of mastery can also be seen by the level of cognitive involvement signified through the action verbs as it is, for example, indicated in Figure 1 (right side mastery levels). At the same time, and consistent with the CAM’s content dimension (as initially mentioned) [44],[67],[70], this approach allowed us also to account for the different types of knowledge that are subject of the VLE learning activities, by aligning them along the horizontal axis of Bloom’s revised taxonomy [77].

Cognitive Load Theory

Furthermore, acknowledging the role of these different types of knowledge and information in the desired learning processes permitted us to incorporate a variety of cognitive considerations into the design and implementation of the VLE. For example, concerning the training in and learning from simulations, it is noteworthy that not all forms of learning seem to be affected equally by VEs. While the procedural type of learning seems to benefit most from virtualizations, especially if enhanced through *interactivity enriching features* (IEF), conceptual understanding appears to be less affected, showing no significant differences in learning outcomes when compared to less engaging methods [57]. Furthermore, content-oriented learning may, under certain conditions, even be reduced by VEs due to the cognitive load involved in processing the presented information [78],[79], as outlined in Cognitive Load Theory (CLT), a theoretical framework that is concerned with the resource allocation in humans’ working memory [35],[59],[78]-[86].

Additionally, the differing learning objectives of acquisition, retention, and transfer may respond differently to the applied training methods, with conditions favorable for the durability of knowledge not necessarily being beneficial to its generalizability [59],[82],[84],[86]. Furthermore, according to [84] the type of information involved may be more important than the nature of the performed task, with *declarative information* (i.e. factual knowledge) generally demonstrating greater generalizability but less durability and *procedural information* (i.e. application skill) allowing for better retention but also exhibiting higher specificity with less transfer. Accordingly, we decided that the simulation element of the VLE should primarily focus on the acquisition of procedural skills in the lab and secondarily introduce some conceptual understanding of the lab equipment and methodologies; however, factual background knowledge (e.g., the formulas and calculations involved) as well as metacognitive reflections about the process were intentionally left for the accompanying reading and documentation activities (e.g., the students’ lab reports) within the non-virtual environment of the online learning space.

VLE Design and Implementation

The development of the VE to explore this approach is focused on teaching students to gather and evaluate data related to radiation patterns associated with wave-emitting systems. A virtual laboratory simulating the measurement of radiation patterns emitted by a circular speaker within an anechoic chamber was selected as a representation of that behavior. In this case, the objective of the experiment is for students to measure far-field sound pressure in relation to speaker orientation. The far-field sound pressure is a function of frequency, distance from the baffle, and angle [87].

Figure 2 illustrates a schematic of the experimental concept. In this figure the speaker is shown in a constant orientation while the observer (shown by the ear) moves around it at a distance *r* to measure the sound pressure. In the virtual lab the inverse was implemented by holding the measurement position constant and rotating the speaker (see also Figure 4). Figure 3 shows a graphical representation of measurement results for a low-, a medium-, and a high-frequency radiation pattern, showcasing the desired results of student experimentation. It can be observed that careful attention must be paid to the gathering of the data so as to accurately capture the patterns. Thereby, in contrast to many virtualizations that seem to be mainly aimed at content comprehension (i.e., show'n'tell simulations to demonstrate a physical relationship), the main learning goal here was to understand and develop methodological skills in experimentation and documentation through hands-on practice in the virtual lab.

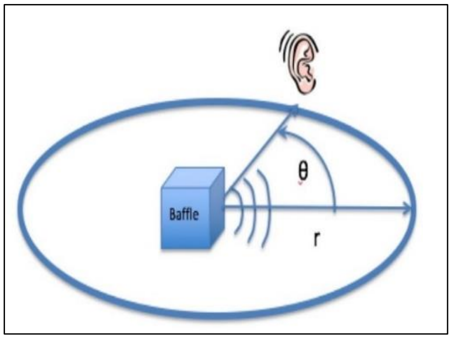


Figure 2. Schematic of baffle lab experiment.

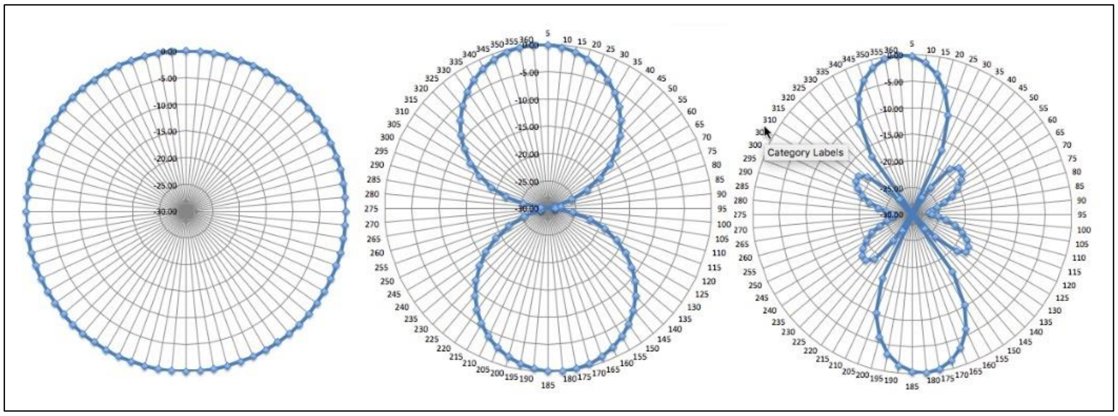
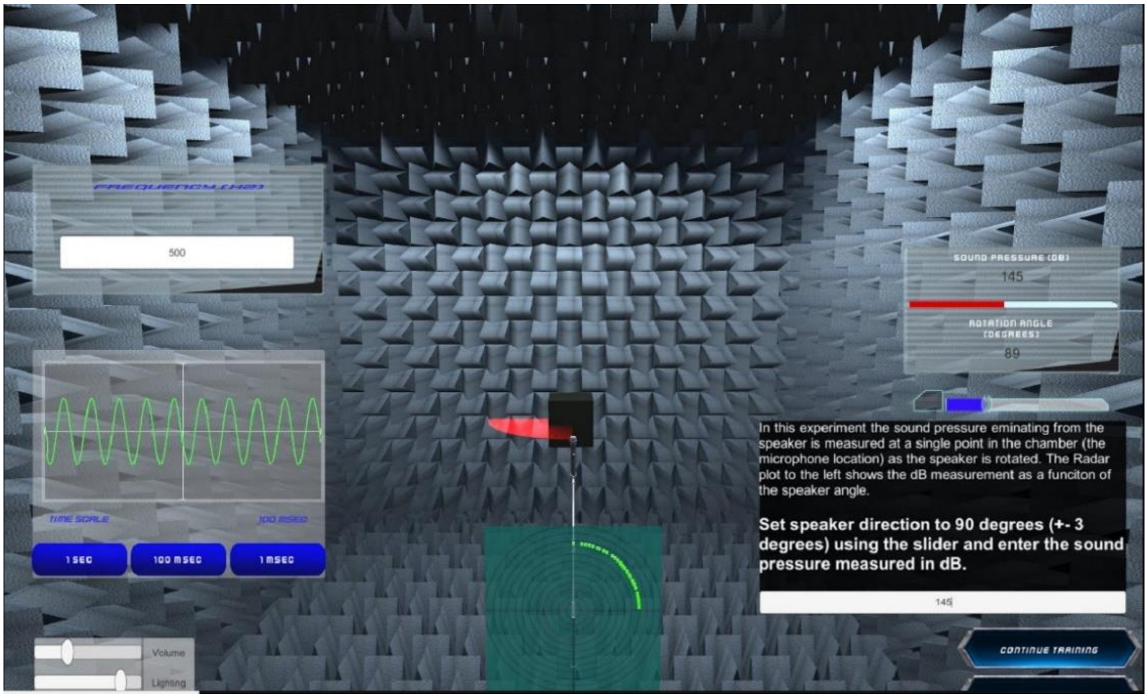


Figure 3. Example of low, mid, and high frequency radiation patterns

The VE incorporates two main phases. Consistent with our theoretical model, the first phase signifies the Apprenticeship Level (see Figure 1), in which the students receive guided training in the lab equipment and its uses, as well as the methodologies required to take measurements. Tasks include, for example, frequency selection, speaker rotation, and data gathering, with the required performance in this phase corresponding to the lower levels (e.g., ‘understand’) of Bloom’s Revised Taxonomy [77]. The second phase is conceptualized as at the Journeyman level (see Figure 1) and corresponds to the mid-level of the taxonomy (e.g., ‘apply’). At this level, students are given random frequencies and are tasked to gather the data required to produce their radar plots (see examples in Figure 3) as well as discuss the observed directional dependency in their lab reports. In this way, students are further lead up the apprenticeship/taxonomy scale towards cognitive levels of ‘analyze’ and ‘evaluate’).

The lab simulation was, thereby, incorporated into the larger module structure of the course, utilizing the other elements of the OLE (e.g., discussion boards, written assignments, reflection wiki, and multimedia tutorials) to create a comprehensive learning experience: the VLE. As exemplified, to achieve reflection and conceptualization opportunities, the students were tasked to incorporate their lab observations and measurements into a lab report, complete with literature-research-based discussion of expectations before the experiment, as well as error analysis and evaluation after its conclusion. Similarly, follow-on discussions allowed for the realization of generalizable concepts, as well as some amount of social exchange between learners. Thereby, supplementary STEM-related competencies such as the comprehension of decibel (dB) scales in measurement or the creation of radar-plot diagrams in computational tools (e.g., Excel or MatLab) were acquired and practiced in an inquiry-based but guided manner, thus, highlighting again the comprehensiveness of our approach to VLE design and implementation: For effective learning from a VE, it is not enough to just create a realistic simulation tool but also to pro-actively consider how it will be integrated into meaningful learning activities.



FREQUENCY (HZ) 500

SOUND PRESSURE (DB) 145

ROTATION ANGLE (DEGREES) 89

In this experiment the sound pressure eminating from the speaker is measured at a single point in the chamber (the microphone location) as the speaker is rotated. The Radar plot to the left shows the dB measurement as a funciton of the speaker angle.

Set speaker direction to 90 degrees (+- 3 degrees) using the slider and enter the sound pressure measured in dB.

145

Figure 4. Example screenshots of the lab simulation.

Evaluation Methodology and Preliminary Results

A similarly comprehensive approach was taken for the evaluation of the effectiveness of the VLE. Thereby, our goal was not just to assess summarily the achievement of learning outcomes or measure students' comprehension as a result of the simulation but to implement formative evaluation methods by which the VLE design and the student competency development can be continuously improved. Therefore, a combination of formative as well as summative, subjective as well as objective, and qualitative as well as quantitative measures were used. Lab report assignment scores of $N = 70$ undergraduate students that attempted the course between January 2018 and December 2019 (a total of six course offerings), indicated that 70% of students ($n = 49$) successfully completed the task with a passing score (70% or above). Overall, the average student score in the assignment category (i.e., a combined summative score for all course assignments that involve the development of engineering-related comprehension and application competencies) was 72.4% (including scores of 0% for students that did not complete the assignments or dropped the course[5]).

While these descriptive statistics seem to indicate an overall effectiveness of the VLE in achieving the desired learning outcomes and may have led to the conclusion that its implementation was a success, we were more interested in how to further enhance its usefulness as an online learning tool and, in turn, positively affect student development. Therefore, more interesting than the question of how many students successfully completed the assignment and the course was an investigation into those students who did not, especially those that scored 0% on the lab report assessment because they had trouble with the simulated tasks. For example, it was observed that the number of non-completions of the lab assignment seemed to increase during 2018, with only 10% of students (1 of 10) scoring 0% in January, 40% (6 of 15) in August, and 45% (5 of 11) in October, prompting us to review the VE implementation. It was discovered that students may have experienced increasing technical difficulties with the usability of the simulation due to technological turn-over (e.g., recent browser and software platform updates), which was confirmed by qualitative student feedback. Thus, we updated the software to improve its user-friendliness and also provided more technical guidance, resulting in a significant drop in zero-score-rates in the following terms (18% [2 in 11] in January 2019 and 19% [3 in 16] in August 2019).

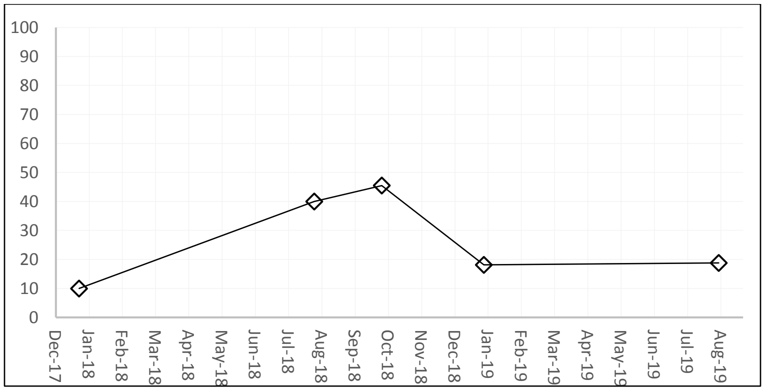


Figure 5. Non-completion over time.

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[5] For the evaluation of the effectiveness of a learning intervention, we considered it paramount to not just assess students that completed a course or assignment but also those that failed the course, did not complete all assignment, or did not attempt this particular task. Furthermore, it was our goal to determine why the successful completion for these students may have been hindered and what might need to be changed to better support their learning success.

Besides the assessment of learning outcomes and ongoing quality control for the usability of the VE, another major emphasis in our evaluation was on student perceptions about the usefulness of the simulation, particularly the applied apprenticeship approach in guiding students through the assignment tasks. For this purpose, a questionnaire was developed and implemented, and students were encouraged to voluntarily[6] share their experiences and provide feedback after completing the assignment tasks in the VE. The overall response rate for this survey instrument was 24% (17 of 70); though, if corrected for the known number of students that did not complete the VLE task (from assignment scores, see discussion above), the response rate increases to 33% (17 of 51).

The questionnaire contained 15 main questions that employed a combination of Likert-scale, ranking-based, and open-answer questions concerning the two main phases of the simulation, the Apprenticeship level (i.e., guided training) and the Journeyman level (i.e., task execution). However, for the quality-control and improvement purposes of this project, a slightly modified approach to the instrument design was taken: Instead of a standard five-point Likert scale, the middle value was omitted, forcing respondents to take an either positive or negative stance in their perception about the aspect in question. Similarly, instead of employing an individual Likert scale for each sub-component of the simulation, students were asked to rank the different VE parts by their perceived usefulness and usability. Such forced-choice responses have the advantage to allow between-participant comparisons because scoring becomes normative [88]. Additionally, in our case, they also allowed between-item comparisons by preventing overall biases that may skew the results. For example, if a participant is overall very satisfied with the entire simulation, he or she may just evenly provide high Likert scores across all single stimulus response items. Similarly, an overall dissatisfied student may provide only low scores across the board of such Likert scales. Thus, it becomes impossible to extract which design feature contributed the most to a specific perception.

Additionally, besides identifying simulation elements that were perceived as contributing most to the learning outcomes, through ranking, it was also possible to confirm that increases in conceptual knowledge ($M_{\text{Ranking}} = 1.79$, SD = 0.74) and procedural ability ($M_{\text{Ranking}} = 1.92$, SD = 0.82) were, indeed, perceived as more prevalent training outcomes than the acquisition of factual knowledge ($M_{\text{Ranking}} = 2.79$, SD = 0.86) or any gains in metacognition ($M_{\text{Ranking}} = 3.36$, SD = 1.00), and that the cognitive involvement of ‘understanding content’ ($M_{\text{Ranking}} = 2.43$, SD = 1.59), ‘applying content’ ($M_{\text{Ranking}} = 3.00$, SD = 1.15), and ‘analyzing content’ ($M_{\text{Ranking}} = 2.71$, SD = 1.31) were ranked as more applicable to the simulation tasks than, for example, ‘remembering content’ ($M_{\text{Ranking}} = 5.23$, SD = 0.72), ‘evaluating content’ ($M_{\text{Ranking}} = 4.07$, SD = 1.69), or ‘creating content’ ($M_{\text{Ranking}} = 3.36$, SD = 1.69).

Since ranking was performed in order from most applicable (at Position 1) to least applicable (at the last position), a lower ranking score indicates greater perceived applicability. The means of individual item ranks are insofar relevant as their deviation from the middle of the ranking scale will indicate the consistency/certainty with which students deemed each item either applicable (if significantly below the ranking scale middle) or irrelevant (if significantly above the ranking scale middle). If just randomly ranked by a sufficiently large sample size of participants, it would

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[6] Since the course assignments and the associated use of the VLE are, obviously, obligatory tasks for students to accomplish in their studies (i.e., exempt from Institutional Research Board (IRB) oversight IAW 45 CFR §46.10 (d) (1)), general ethical considerations were addressed by making the questionnaire about the VLE voluntary, incorporating an informed consent start page, and anonymous data recording (IAW 45 CFR §46.10 (d) (2)).

be expected that each item's mean rank statistically approaches the middle value of the ranking scale. Conversely, observed deviations of mean rank scores from that middle of the ranking scale seem to indicate other than a random chance distribution of ranks while confidence intervals that do not extend over the middle may be considered indicators for the significance of that observed deviation.

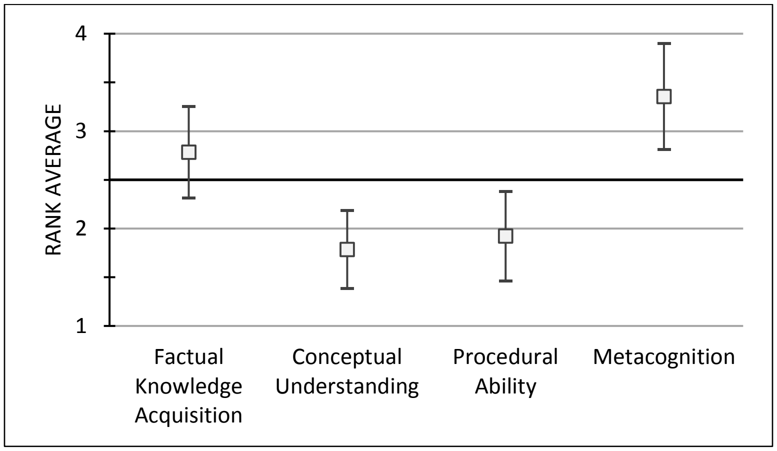

Figure 5. Perceived learning outcome ranking means with confidence intervals ($\alpha = 0.05$).

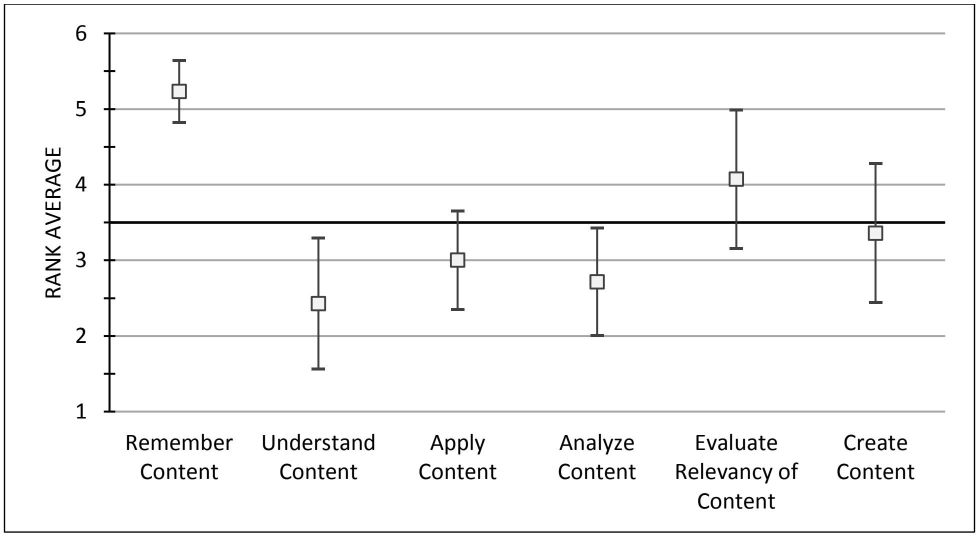

Figure 6. Perceived cognitive involvement ranking means with confidence intervals ($\alpha = 0.05$).

Overall, except for one student (for whom the simulation did not seem to run properly, based on the open-ended feedback provided), all participants that took the survey also assessed their impression with the simulation flow (Question 13) as either 'mostly positive' or 'completely positive' ($M_{\text{4-point Likert}} = 3.27$, SD = 0.80), and they either 'mostly agreed' or 'completely agreed' that the VLE activity helped them to develop a methodical approach to experimentation and documentation (Question 14; $M_{\text{4-point Likert}} = 3.06$, SD = 0.68). Similarly, students had an overwhelmingly positive overall impression of the VE (Question 1; $M_{\text{4-point Likert}} = 2.94$, SD = 0.83). Qualitative, open-ended feedback further assisted in identifying specific problems that students may have encountered. For example, one student commented on browser difficulties:

> "I had to use safari, then firefox. Reseting all my securities, downloading more items. It took me longer to do those items than it did to do the experiment."

, while another highlighted functionality issues:

> “I believed that the training was rather well done, however there was one thing that I found by accident … just using your mouse make it almost impossible to obtain the specific degree needed. Maybe just adding some detail either within the instructions to the module or the training that one could raise or lower the degrees by pressing the arrow keys would probably be super helpful.”

In general, the feedback seemed to also confirm some of the assumptions about the audience: ‘Digitally native’ users seem to pay particular attention to technical aspects of the simulation such as compatibility with a Mac or mobile device, ease of installation and setup, level of interactivity, ease of control of visual elements via mouse click, utility of in-app data logging and downloading provisions, etcetera. It also highlighted the wide spectrum of possible user predispositions and experiences a VLE may have to account for and the need to attend to those individual issues through ongoing technical support.

Discussion

To fully understand the limitations to student learning activities and instructional interventions in distance learning, a few important aspects of the asynchronous OLE should probably be highlighted. For example, it is important to understand that the asynchronous OLE is a predominantly *student-pulled* learning approach, in which the students have almost complete control over when, where, and how they study [89], including whether and which of the provided resources they use [19],[90]. Research suggests that students in OLE selectively access only those resources and assignments that they perceive as important enough for their individual learning goals (i.e., their goal orientation) [19],[90], whether these goals are intrinsically mastery-oriented (e.g., maximizing knowledge acquisition) or extrinsically performance-motivated (e.g., passing with a sufficient score) [91],[92]. Approaches commonly suggested and utilized to account for these learner tendencies are to either disguise the apparent value of each activity or to make all activities in the OLE at least partially consequential (i.e., contributing to the overall score) [19],[27].

Thus, course designs for the OLE often dramatically differ from conventional classroom approaches in that student grades are much less dependent on a single or a few high-stakes assessments. Therefore, it is neither surprising nor uncommon if students, consistent with their goal orientation, may elect to skip certain activities within online courses that they consider as either too unimportant or too resource-intensive (e.g., requiring too much time, workload, coordination efforts, technical know-how, etc.) for the perceived benefits such activities may provide. Consistent with this understanding, these tendencies were also observable in our study: For example, as technical challenges increased, students seemed to start weighing whether the perceived benefit from the VLE still justified the increased investment in solving the technical problems.

It is important to understand that a properly designed online course is not merely a classroom course uploaded into the online environment, and it is against this backdrop that, for example, individual students’ assignment scores of zero in our collected data should be interpreted (i.e., for not submitting the assignment). Thus, far more important than to assess whether the average of student scores for the introduced learning activity fell within a certain achievement range (e.g., above a specific passing grade threshold) is to identify why certain students may have elected not to complete the assignment. Such formative investigation into students' reasons not to engage seems more beneficial to our approach to continuous VLE enhancement. While the qualitative, open-ended comments within the questionnaire could only limitedly answer such question (because students who did not participate in the activity usually also did not complete the user experience survey), additional inputs and questions posed in student discussions, emails, and other communication during the course, as well as the feedback within their end-of-course surveys provided some clues, pointing among other to the need for ongoing technical support as well as instructional guidance and mentorship.

Similarly, another aspect that was, in general, recognized as contributing to students' decisions not to complete assignments in the OLE is the demand placed on students' prearrangements. Because of the selective nature of students' interactions with the course activities [19],[90], designers and facilitators should be cognizant about any additional requirements that could be perceived as too burdensome by some students. Such burdens may be in the form of additionally required materials for a course or activity, the need for cumbersome technical setup (e.g., installing software – see, for example, the received student feedback highlighted above), or complex coordination and administration requirements (e.g., needing to register for an account or to log in at a particular day and time). After all, online learners predominantly chose this modality for the freedom, flexibility, and accessibility that it provides [8],[14], and any perceived restrictions to these attributes may disenfranchise students. That aspect alone may make the application of more VLEs in the OLE attractive, as they may reduce the prearrangement demands on students.

Limitations and Recommendations

Our main concern in this study was with the design and implementation of a VLE, founded in relevant learning theories and based on a structured approach. Accordingly, our main emphasis was on the development, testing, and documentation of a sound methodology that can be replicated in other STEM OLEs. While we can conclude that our VLE approach seemed successful in achieving the desired outcome of creating an engaging, relevant, and meaningful learning experience in the OLE, we will not claim causality (i.e., that our approach caused the observed student developments and perceptions) or superiority (i.e., that our approach was better in achieving these outcomes than conventional or other methods in online education). To lay such claims, more rigorous, hypothesis-based testing of the applied theory would be required and research designs with better controls (e.g., experimental or quasi-experimental) should be implemented[7], which was outside the scope of the current study. In that sense, our research should be characterized as exploratory rather than confirmatory, and mainly aimed to document what we did and why, so applicable aspects can be replicated in other settings. Consistent with this objective, we also restricted our quantitative analysis to purely descriptive statistics. Our study should be followed up with more rigorous empirical research to further confirm the validity of our findings.

Conclusion

In this study, we presented a structured approach to the design and implementation of a VLE that aims to foster the development of STEM-related student competencies in the OLE. Based on our

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[7] Since the development of the VLE was, from the beginning, intended as a student learning activity for a newly developed course, no pre-test or controls were available or could be easily implemented that would have allowed for a comparison with the more traditional approaches in OLE design. The main objective during VLE development was effective student learning, not theoretical research in a controlled environment.

findings, we concluded that virtually guiding students through experiential-learning-based activities along an apprenticeship-type development model under consideration of cognitive limitations provided a useful conceptual framework for the development of such a VLE. Through our work, we also recognized that, for the creation of meaningful learning experiences, a simulation alone does not suffice, and that there is a need to integrate these virtual elements into a larger pedagogical concept. Additionally, it became apparent that ongoing, formative evaluation, continuing technical support, and constant fine-tuning is required for the successful implementation of the VLE. An open-ended, cyclic application of the ADDIE process provided a practical outline for such an enduring quality-control and improvement strategy and seems to mirror rapid prototyping strategies in other software development and implementation endeavors.

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