Applying Research in the Cognitive Sciences to the Design and Delivery of Instruction in Virtual Reality Learning Environments

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Abstract. Current approaches to the design and delivery of instruction in virtual reality learning environments (VRLEs) draw heavily from traditional instructional strategies and design practices. This is problematic given that these strategies and practices were developed for learning contexts lacking the dynamic nature and capabilities of technology-rich, immersive learning environments. This directly affects the instructional efficacy of VRLEs by creating a dichotomy between the learning interface, which emphasizes knowledge as object, and the learning environment, which can emphasize knowledge as action. Drawing from theory and research in the cognitive sciences on embodied and enactive cognition, we present an instructional strategy that addresses this dichotomy by incorporating techniques and design practices that are better aligned with the learning dynamics provided by VRLEs.

Keywords: Virtual reality learning environments · Simulation-based training · Instructional design · Embodied cognition · Enactive cognition

1 Introduction

Virtual reality learning environments (VRLEs) provide dynamic experiences that can positively influence instructional outcomes. However, current approaches to the design and delivery of instruction within these environments are largely based on traditional methods that tend to emphasize technological capabilities at the expense of the actual learning experience [1]. Emerging technologies are providing for higher degrees of physical and psychological immersion within VRLEs, resulting in greater levels of fidelity and providing opportunities for more profound and meaningful learner experiences, and hence, better instructional outcomes.

A review of the current literature reveals mixed results of the instructional efficacy of VRLEs. While some studies have demonstrated the instructional benefits of these environments, particularly with respect to learner control [2], and the ability of learners to leverage existing knowledge to create new concepts [3, 4], other studies have indicated that the use of these environments provide either marginal or negative effects on learning outcomes. The factors influencing these undesirable effects stem from an over-reliance on learning technologies, a lack of focus on the manner in which those technologies affect the critical factors that facilitate learning, and/or the absence of

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comprehensive instructional strategies and supporting design practices to guide the learning experience. These marginal or negative effects on learning outcomes are most prominent when these environments are used to teach conceptual knowledge [5–7].

The aim of this paper is to examine how research in the cognitive sciences can be applied to address current issues surrounding the instructional efficacy of VRLEs. While the strategies we provide are relevant to all types of learning in these environments, we are particularly focused on how VRLEs can positively mediate the development of conceptual knowledge. There are unique challenges to developing strategies for teaching this type of knowledge in VRLEs, and these challenges have typically been addressed by increasing the technological capabilities of these environments, with minimal positive results [1, 5]. Our approach to addressing these challenges relies not on technology, but on the use of the human body as an instrument to optimize learning and comprehension. Central to our approach is a distinction between the opposing concepts of knowledge-as-object and knowledge-as-action. The former treats knowledge as a separate reality that is external to, and must be obtained by, the learner, while the latter treats knowledge as the integrated result of a learner engaging with her environment through bodily action. Our approach emphasizes the treatment of knowledge as action by applying cognitive science research on embodied and enactive cognition (hereafter EEC) to conceptualize an instructional strategy that capitalizes on the dynamics and interactive nature of VRLEs.

More specifically, we make a distinction between two forms of EEC instructional design for VRLEs. The first can be construed of as a superior way to teach psychomotor knowledge and skills. It is superior because the VRLE helps the learner use her body for a task that requires the body. For example, an instructional objective could be to learn complex psychomotor skills such as performing a surgical procedure. In traditional learning contexts, a student would read about this and see diagrams with arrows indicating areas for cutting. In computer-based learning, a student could view an animation to see how the surgery is performed (e.g., observe it in real time). With a joystick, a student could manipulate certain parameters in a simulation to change a simulated scalpel. But, within a VRLE, a student can actually use her body by holding a wand that simulates a scalpel and can enact the kind of cutting that is necessary and “feel” the skin under the wand (with force-feedback, etc.). So this is, essentially, a high-fidelity simulation mimicking a complex task environment that draws from EEC, often implicitly, to make it better. We recognize the value of VRLEs for this type of learning, but we suggest pushing our thinking further. So we propose a more unique way to teach conceptual knowledge. It is unique specifically because it makes use of the body as a way to understand complex concepts that are actually abstract and difficult to comprehend/imagine (e.g., gravity). For example, an instructional objective could be to learn concepts from physics related to force, trajectory, velocity, and gravity. In traditional learning contexts, a student would read about this and see diagrams. In computer-based learning, a student could view an animation. With a joystick, a student could manipulate certain parameters (e.g., trajectory) and see a change. But within a VRLE, a student can use her body to apply force (e.g., a kick), and study trajectory (e.g., aim the kick), and see how velocity is altered when it nears a large or small celestial body [8, 9]. Recent work has specifically examined manipulations of forms of embodiment and enaction and their relationship to learning [10–13]. We build upon this work to formulate an instructional strategy that we call Structured Enactive Engagement in Learning (SEEL). The SEEL strategy codifies and formalizes a set of testable instructional design approaches to guide learning experiences in VRLEs.

2 Embodied and Enactive Cognition (EEC)

Recent developments in the cognitive and neural sciences view the mind, not as a symbolic logic processor passively operating upon inputs and generating outputs but, rather, as a mind embodied through which cognition is tightly coupled with the body's sensory and motor systems [14–16]. This perspective is in stark contrast to information processing theories of cognition (also known as "cognitivist" theorizing [17]). The theoretical starting point of this embodied view of cognition is that brains are control systems for biological bodies and that these bodies are immersed in, and interact with, rich real-world surroundings [18–20]. Notions of embodied cognition, coupled with the perspective of interacting with, and being reciprocally influenced by, the environment (i.e., enactive cognition), is a theoretical perspective that seeks to overcome limitations of information processing theory, which, essentially, disengaged the brain from both the body and the environment in which they are situated [20, 21]. In this way, cognition is integrated with, and influenced by, the body's adaptivity to its environment and a form of sensorimotor integration with the world. Extensive review of theory and research in the tradition of embodied and enactive cognition is beyond the scope of this paper and can be found elsewhere [15, 20, 22, 23].

We suggest that embodied and enactive cognition (EEC) provides an important stepping off point from which to conceptualize instructional approaches better able to leverage the dynamic, enactive nature of VRLEs. EEC reconceptualizes interaction in the VRLE in such a way that the use of brain and body forms a fundamental basis for learning. Deeper learning can emerge through a continuous process of interaction between the learner, the learning content, and the environment in which they are immersed [24, 25]. As such, EEC provides an important scaffold for considering interaction within VRLEs, as it focuses on the complex relationship between cognition, mind, and body-centric experience within a contextual learning space [26–28].

A growing number of experimental studies support EEC theorizing by documenting the interaction between the body and the environment in service of learning and performance [29, 30]. In this section, we provide an example of human performance that illustrates how theorizing based upon cognitivist views versus EEC would yield different instructional approaches. Specifically, the "outfielder problem" has been used to distinguish between cognitivist theorizing and the deeper aspects of EEC [31, 32].

The outfielder problem concerns itself with how a baseball outfielder knows where to position himself to catch a fly ball. In this scenario, the outfielder can use either predictive or prospective control methods to catch the ball. On the one hand, predictive methods are based on a cognitivistic approach and suggest that the outfielder attempts to determine where the ball is headed based on the development of a mental model using such factors as ball speed, angle, and trajectory. Once the prediction is made, the outfielder moves to the predicted position and attempts to catch the ball. If the prediction is flawed, the ball will not be caught. On the other hand, prospective control methods draw from EEC theory to suggest that the outfielder uses perception-action coupling and runs to align himself with the general trajectory of the ball. This negates its directional offset, and the outfielder moves either forward or backward to match the acceleration of the ball in order to be positioned in the right place at the right time to make the catch.

Importantly, the prospective control method makes no use of mental representations to predict the best position to intercept the ball. Instead, the solution to catching the ball evolves through an interaction of the outfielder with his movements and his dynamic perceptions of the changing environment as the solution is implemented [33]. In essence, the outfielder and his environment become structurally coupled, and, through their interaction, they co-emerge to achieve a successful outcome [24]. To test these predictions, Fink, Foo, and Warren [31] used their Virtual Environment Navigation Laboratory, which allowed for whole-body displacement in an experimental setting. Specifically, by varying trajectories of the ball in the virtual environment, they were able to test whether participants relied upon predictive or prospective control. Their results suggest that participants tracked the ball based upon apparent acceleration, thus supporting EEC-based prospective control theory.

The implications of these results to the design and delivery of instruction in VRLEs are profound, yet thoroughly underexplored. Specifically, studies like this show how embodiment and enaction are used to develop solutions to problems through one's interaction with the environment; solutions co-emerging as the body moves through the environment. This is critical given that such solutions were previously assumed to be solved purely internally by the brain, essentially, acting independent of the body. With respect to instructional strategies used in VRLEs, this concept of co-emergence precludes the use of the prescriptive, linear processes upon which traditional instructional approaches are based. Our argument is that the capabilities of VRLEs need to be better leveraged through the application of holistic instructional strategies that optimize the interaction between brain, body, and environment. Thus, EEC can be used to develop learning techniques that carefully balance the structural constraints of the learning experience with the ability of the learner to freely interact within the learning space. It is this type of embodied, enactive engagement that recent work has shown to have the most direct impact on the development of a more robust and effective learning experience [34]. It is from this perspective that we have developed the SEEL instructional strategy.

3 Structured Enactive Engagement in Learning (SEEL)

The SEEL strategy represents an important step in modifying the design and delivery of instruction in VRLEs and the incorporation of the underlying theories that better support instructional practices within these environments. It is not intended to completely replace current instructional design principles. Instead, it is meant to inform and guide the next generation of instructional design and development for VRLEs by providing the conceptual framework from which new research and practice may emerge. It provides a holistic perspective for the development of learning experiences that integrate the findings of cognitive science research with established, complementary design practices to optimize the means by which instruction is designed and delivered in dynamic, enactive environments.

The SEEL strategy provides an iterative approach to enactive learning engagement based upon theory and empirical research. It consists of five distinct phases that provide a comprehensive approach to enactive instructional design, development, and application. We next describe these in turn.

3.1 Analyze/Determine Instructional Context

The initial phase of the SEEL strategy involves the analysis and determination of the instructional context of the learning experience. Since learning and performance are not prescribed within the EEC paradigm, the intent of this phase is not to develop precise instructional interactions. Rather, it is to identify the overall instructional context and the underlying strategies within which a set of learning outcomes can be facilitated [35].

Foundational to this phase of the SEEL strategy is the concept that separation between the learner and what is to be learned should not exist. In other words, in line with situated theories of learning, cognition is shaped by the learner's interactive experience, both mental and physical, within specific contexts [24–26]. The focus is on enactive engagement and the embodied nature of the learning experience and how these can establish the overall structure of the instructional approach. This phase involves a thorough analysis and identification of the learning objectives that can be enacted and embodied. This includes using learners as active models to demonstrate an underlying concept or theory, as opposed to presenting that same concept or theory statically (e.g., as text or as an unchanging diagram). This phase repurposes traditional task, learner, and instructional analyses by extending their application toward more enactive, embodied instructional techniques.

The goal, then, is to identify what learning objectives can be implemented in the VRLE such that the learner is able to interact with that content. For example, if the learner needs to understand physical principles or formulas, we explore how those can be made concrete in the VRLE, such that the learner is not passively taking in that information and is, rather, actively engaged with content to understand the underlying principles. Consider that computer-based learning provides approaches such as interactive algebra. These allow learners to sketch graphs and see how formulas changed or modify formula inputs to see how graphs changed [12]. We suggest that VRLEs can leverage such approaches and make them more engaging through full body interaction to foster deeper learning.

3.2 Analyze/Identify Instructional Resources

The analysis and identification of instructional resources focuses on the tools, technologies, and settings used to create the learning experience. The specific efforts pursued during this phase focus on the acquisition or development of the artifacts used to facilitate learning. These artifacts may include objects, models, interfaces, systems, or the environment itself relevant to the instructional context. Key efforts during this phase include the identification of context-relevant artifacts to support the learning outcomes identified in the previous phase. Artifacts should be used to embody learning objectives, instead of merely being used as tools or props to demonstrate concepts or procedures. In this sense, artifacts are not just things that support the learning experience, they are intimately wedded to the learning experience.

A number of studies have demonstrated the distinct advantages of employing techniques that emphasize embodied, enactive engagement with instructional artifacts. As examples, studies focused on situated and simulation-based learning [36], model progression schemas and inquiry learning [37], and enaction within the context of mathematics education [10, 13], have each documented the interaction between learner and artifact in support of knowledge acquisition. Learning is embodied in experience, and, through embodied engagement, in practice. Through the use of material artifacts, new experiences are made and additional skills are acquired. This, in turn, transforms future experiences and the responses afforded by such situations [38]. As such, the tools, technologies, and settings used to facilitate learning should focus on the instructional experiences of the learner. Recent work has specifically examined manipulations of forms of embodiment and their relation to learning. Johnson-Glenberg, et al. [11] varied instructional artifacts in embodied, enactive learning contexts to enable learners to map abstract concepts to their bodily movements. This study included an experiment in which the concept of chemical titration was taught by allowing learners to manipulate virtual molecules on a floor projection with a hand-held tracking wand. The objective here was to create a fully titrated virtual solution, as indicated by visual and aural cues within the learning environment. Two groups of participants were subjected to a sequence of regular and embodied instructional strategies with the order of the sequence counterbalanced among the groups. Learning outcomes were measured using a pretest, midtest, and posttest. Learning gains were significantly higher using embodied instruction. Lindgren, et al. [9] developed a room-sized mixed reality simulation that enabled learners to explore the concepts of gravitational forces in space by using their bodies to guide the path of an asteroid as it interacted with the gravitational effects of celestial objects. In an experiment in which participants compared their whole-body experience in the simulated environment with a desktop version of the same simulation, the whole-body experience rated significantly higher in facilitating learning and learner enjoyment. Both of these examples illustrate how instructional artifacts, from hand-held wands to learners' own bodies, can be used to ground abstract concepts in embodied actions and facilitate better learning outcomes.

3.3 Establish/Revise Learning Environment

This phase is concerned with the initial development and subsequent revision of the learning environment, which encompasses the physical setting in which learning will occur as well as the instructional, physical, and virtual interfaces with which the learner will engage.

Co-emergence is a key component in this phase since it focuses on the recursive changes that occur between the learner and the learning environment based on their interactions [39]. Indeed, one of the foundational premises of enactive learning is that cognition and environment are inter-connected and that the interaction dynamics of learners, technologies, interfaces, and the instruction itself, facilitates mutual learning [40]. Following on naturally from our prior phases, here the emphasis is on 'how' interaction with the artifacts can be instantiated. Phase 1 identified what learning objectives could be targets for enaction and Phase 2 helped determine what could be made concrete by leveraging EEC theory. This phase is meant to explicate how co-emergence can occur; that is, how the learner's interaction with artifacts and the environment can make the learning content more apparent. The goal, then, is to ensure VRLEs create and reinforce *instructional interactions*.

Our concept of instructional interactions and the co-emergence they provide is exemplified by the Mathematics Image Trainer for Proportion (MIT-P) [34]. This device consists of a vertically oriented computer monitor and motion tracking devices to track the positions of a learner's hands. Learners are seated at a desk in front of the monitor and are able to change the screen color by manipulating the relative positions of their hands. Learners interact with the device to embody the concepts of proportionality and ratios, with a specific focus on multiplicative scaling (i.e., a proportional progression, such as 1:2 = 2:4). The device measures the relative positions of the learner's hands, calculates the ratio of these measures, and compares it to a preset value. The color of the screen is green if the ratio matches the present value. If it doesn't match, the screen is red. The learner attempts to maintain the green screen color while increasing the distance between her hands. The objective of this experience is to explore the complex concept of proportional progression through interaction with a changing environment. The dynamics of the learner's actions and the changing environment that results from those actions are the co-emergent properties that facilitate learning.

3.4 Implement/Guide Learning

This phase involves the actual *performance* of instruction. Building on the concept of co-emergence, the performance of instruction focuses on an ongoing exploration of enactive experiences. Here the concept of knowledge as action is instantiated. Within this activity, the roles of the learner and instructor become less distinct than in traditional instructional approaches. The role of the instructor is now to help facilitate the learning experience by guiding the learner's attention through questions, practice, highlights, or other such strategies [35].

Central to the facilitation of learning in this phase is the concept of sense-making. In this context, sense-making characterizes knowledge as a domain of possibilities created by the meaning a learner ascribes to the experience gained through embodied interaction with the environment [38, 39]. VRLEs, thus, enable a large repertoire of action possibilities the learner must navigate and, through this navigation, come to understand how the learner's movements are related to learning objectives. Through the rich virtual experience (e.g., complex interactions, improved perceptual capacities), the learner engages with the learning content, acting and reacting with the changing environment through the principle of co-emergence. This engagement affords predictions about the learning content that can be tested through additional movement within the VRLE and with the material artifacts [39, 41]. In this way, VRLEs provide an ideal opportunity for sense-making as they allow learners to apply the knowledge and skills they are acquiring through full-bodied interactions with material artifacts used to embody the learning experience. Within the context of the structured engagement, this may facilitate sense-making as a function of the degree to which learners are able to diagnose flaws in their current understanding and receive feedback that allows them to improve their understanding [42–44].

3.5 Analyze/Assess/Revise Learning Outcomes

This phase highlights the adaptable, iterative nature of the SEEL strategy by providing a means for analyzing, assessing, and revising learning outcomes based on changing situational or learner requirements. Analysis and assessment activities may involve qualitatively or quantitatively derived evaluations of the instructional efficacy of the implemented strategy. Results from these analyses can be used to modify any aspect of the instructional approach to address learning issues or meet changing needs. Activities performed during this phase can be accomplished through formative and summative evaluation efforts. Formative evaluations would be used to improve instructional approaches in the VRLE through design feedback and other types of validation efforts and this would typically occur during the development process. After the instructional approaches have been implemented, summative evaluation techniques would be used to determine the quality of the instruction and its role within the overall learning paradigm. The main objective of this phase is to focus on the learning experience itself and the efficacy of instructional approaches.

4 Conclusion

Current approaches to the design and delivery of instruction in VRLEs draw heavily from traditional instructional design practices. This is problematic given that many of these practices were developed for learning and training contexts lacking the fidelity provided by modern simulation and training environments. This directly affects the instructional efficacy of VRLEs by creating a dichotomy between the learning interface, which emphasizes knowledge as object, and the learning environment, which provides an opportunity for knowledge as action. In this paper, we have addressed this dichotomy using the concept of embodied and enactive cognition to conceptualize an instructional strategy more in line with the dynamic, immersive nature of VRLEs. In this context, embodied and enactive cognition help to reconceptualize the interaction between the learner and the learning environment and strongly influences instructional approaches and applied practices that facilitate increased instructional efficacy within these environments. It is from this perspective that the SEEL strategy was developed. Table 1 provides a summary of the key elements of this strategy.

As noted, we conceive of the SEEL approach as a method of leveraging theory in cognitive science as well as developing concepts in the learning sciences. Granted,

Table 1. Key Elements of the SEEL Strategy

Phase	Focus/Goal	References
Analyze/Determine Instructional Context	• Establish the instructional context of the learning experience. • Identify the learning objectives that can be enacted and embodied.	[24–26, 35]
Analyze/Identify Instructional Resources	• Determine the tools, technologies, and settings used to create the learning experience. • Identify instructional artifacts that ground target concepts in embodied action.	[9, 11, 34]
Establish/Revise the Learning Environment	• Design the learning experience through the integration of the environment, context, and instructional artifacts. • Establish and instantiate how the learner's interaction with artifacts and the environment can make the learning content more apparent.	[34, 39, 40]
Implement/Guide Learning	• Facilitate ongoing exploration of enactive experiences. • Promote sense-making through the use and expansion of action possibilities within the learning space.	[38, 39, 41–44]
Analyze/Assess/Revise Learning Outcomes	• Establish qualitatively or quantitatively derived evaluations to assess the instructional efficacy of implemented approaches. • Modify the instructional approach as required to address learning issues or meet changing needs.	[34, 35]

VRLEs naturally lend themselves to teaching psychomotor knowledge and skills because they afford the opportunity to teach a task where the learner uses her body in a task that requires the body. But what we propose is that VRLEs can do much more. That is, they can provide a unique context where the learner uses her body in a task not requiring the body. The key element is the amount of immersion into an experience the VRLE provides and the degree to which the body is used to alter the learning content and target the learning objectives. The focus is on teaching conceptual knowledge; that is, teaching an abstraction that is difficult to experience through something like text or diagrams alone. An enactive VRLE makes it more concrete by putting the body into the experience and allowing the body to feel the abstraction and alter the abstraction, thus adding a new modality to the learning experience.

In sum, supported by the congruence between embodied cognition and the enactive, immersive nature of VRLEs, the SEEL strategy represents a shift in the development and use of instructional approaches and the underlying theories that support those approaches. It provides a holistic perspective for the application of learning strategies that integrate the findings of cognitive science research with established, complementary practices to optimize the learning experience in VRLEs. Overall, the SEEL strategy establishes a foundation for the development of an instructional approach more suited for virtual environments, while also providing a basis from which a new generation of instructional research and practice may emerge.

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