Virtual Reality and Embodied Learning: Unraveling the Relationship via Dynamic Learner Behavior

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Abstract: Embodied Cognition theory asserts that the physical body, its environment, and the interplay between them hold a pivotal role in the process of embodied learning. In comparison to traditional and computer-based learning methods, Virtual Reality (VR) enhances embodied learning, primarily owing to its capacity to offer a sense of situatedness and engage learners through physical interactions. Furthermore, the incorporation of haptic sensations in VR-based learning introduces tactile sensory memory, complementing the existing auditory and visual sensory dimensions. Despite the evident advantages of VR in facilitating embodied learning, the current body of literature has yet to delve into the dynamic behaviors exhibited by learners within Virtual Reality Learning Environments (VRLEs) during embodied interactions, and their inherent relationship with the embodiment phenomenon. In this paper, we take a significant step by integrating the Interaction Behavioral Data (IBD) collection mechanism, a development from our previous work, into a VRLE. This integration is achieved by adopting a structured framework for embodied learning activities within a VR context. Through an empirical study involving 14 participants, we meticulously logged their interaction traces using the IBD logger. Subsequently, we effectively extracted the diverse embodied learning activities carried out by these participants within the VRLE, from the interaction trace data collected in the IBD logger. Our endeavor aims to establish meaningful connections between these embodied interaction activities and the overarching concept of embodiment. These correlations, once identified, will serve as invaluable insights for VR content developers, offering clear guidelines for the design and creation of VRLEs that optimally facilitate enhanced learning experiences. Ultimately, this knowledge transfer will not only empower instructors and learners to harness VR as a potent educational tool within their regular teaching and learning practices but also foster the seamless integration of VR into mainstream education.

Keywords: Embodied Cognition, Embodied Learning, Virtual Reality, embodied interactions, haptic feedback

1. Introduction

In line with the principles of embodied cognition theory, cognition emerges from the dynamic interplay between the body and its surroundings, closely tied to sensorimotor engagement (Rambusch & Ziemke, 2005). Both the fusion of the body with the mind and the surrounding environment contribute to cognitive processes (Wilson, 2002). The practical application of the theory of embodied cognition seen in embodied learning underscores the incorporation of the body within educational practices (Georgiou & Ioannou, 2019). In the context of embodied learning, learners acquire knowledge not solely through conceptual comprehension, but also through bodily postures, gestures, and facial expressions (Foglia & Wilson, 2013). Embodied learning encompasses sensorimotor activities, where sensory inputs such as touch, vision, and hearing highly influence the learning process. The literature presents substantial evidence of brain activation in sensorimotor regions during cognitive tasks, underscoring the intertwined nature of cognition and bodily actions (Lindgren & Johnson-Glenberg, 2013).

The emergence and progression of Information and Communication Technology (ICT) have precipitated a swift evolution of technology-facilitated embodied learning within the realm of educational practice over the past decade (Georgiou & Ioannou, 2019). Among these technological advancements, Virtual Reality (VR) stands out as a particularly sophisticated tool that fosters embodied learning (Georgiou & Ioannou, 2019; Li et al., 2020; Chatain et al., 2023). This article focuses on the utilization of VR and delves into its inherent attributes within the context of embodied learning.

Within the domain of VR, users are immersed in a simulated three-dimensional environment from a first-person perspective, engaging with virtual objects in a manner akin to real-world interaction. This immersion is a key factor underpinning embodied learning in VR, encapsulated by the trio of qualities known as the 3Is - Immersion, Interaction, and Imagination (Zhang, 2017; Yang et al., 2019).

- Immersion pertains to the VR system's capacity to envelop users within the virtual world to such an extent that their awareness of the external physical environment diminishes.

- Interaction denotes the VR system's ability to provide immediate responses and feedback based on the user's actions within the simulated setting.

- Imagination refers to the VR system's capability to induce the perception that the virtual environment is genuine, even if it does not exist in the tangible real world.

Leveraging the immersive quality of VR, learners find themselves able to completely engage with and encounter the virtual environment through a first-person perspective, momentarily suspending the acknowledgment of their real physical surroundings. This phenomenon allows learners to grasp a sense of situatedness, an aspect seldom replicated consistently within conventional classroom setups (Li et al., 2020). Situatedness stands as a key factor in the realm of learning, a notion widely recognized (Fors et al., 2013). At the heart of situated learning lies the principle that a substantial portion of learning is intricately tied to the context in which it unfolds (Anderson et al., 1996). The tasks undertaken by learners within specific contexts, aimed at achieving particular objectives, serve as vessels for the transmission of situated cognition. Herein, the interactive facet of VR offers the opportunity for learners to execute tasks within fabricated scenarios within the virtual realm, utilizing bodily movements. As a result, VR effectively cultivates conditions conducive to situated learning, affording experiences that combine perception and action, thereby enriching the landscape of embodied learning (Li et al., 2020).

While Virtual Reality (VR) contributes to the advancement of embodied learning through its immersive and interactive attributes, previous research has yet to explore the correlation between learners' action-oriented behaviors within Virtual Reality Learning Environments (VRLE) and the embodiment facilitated by VR technology. This is because, there were no effective mechanism to log data related to the behavior of the learners while doing activities in VRLE. To bridge this gap, we devised a mechanism known as Interaction Behavioral Data (IBD) logging, designed to capture learners' real-time interactions, along with timestamps (Prakash & Rajendran, 2022). This IBD logging mechanism was seamlessly incorporated into MaroonVR (Pirker et al., 2019), a Virtual Reality Learning Environment utilized for the acquisition of physics concepts (Prakash et al., 2023). In this paper, we aim to find the relationship between the dynamic behavior and the related embodied interaction activities extracted from the IBD logging mechanism and the embodiment.

The paper is organized as follows: In Section 2, we delve into diverse categories of VR systems and their capacity to facilitate embodied learning. Additionally, this section challenges prevailing notions about interaction to foster an environment conducive to embodied learning. The IBD logging mechanism is detailed in Section 3, which also offers an in-depth explanation of the VRLE embedding the IBD logging mechanism. Section 4 provides a comprehensive portrayal of the framework underpinning embodied interaction activities. This section also enumerates the multimedia principles that have been integrated into the VR experience.

Moving to Section 5, we present the methodology of a study conducted with a cohort of 14 participants. In Section 6, we present the results of the study highlighting the extracted embodied interaction activities logged via IBD. Section 7 encapsulates the article by summarizing the current research, delineating its limitations, and casting a glimpse into the potential avenues for future exploration.

2. Literature Review and Background

In this section, we first describe the different types of VR and the level of embodiment supported by them and then various interactions favored in VR for embodied learning.

2.1 VR Device for Embodied Learning

The level of embodiment facilitated by VR is contingent upon the extent of immersion and interaction characteristics (Li et al., 2020). Consequently, VR can be categorized as follows: 1. Non-immersive VR, and 2. Immersive VR (iVR) (Freina & Ott, 2015).

Non-immersive VR involves viewing the virtual world on a desktop screen, promoting an allocentric viewpoint rather than an egocentric one. Hence, Immersion requires contextualization to compensate (Li et al., 2020). Furthermore, instead of physical bodily movements, interactions rely on keyboard and mouse controls (Li et al., 2020; Hamilton et al., 2021), making non-immersive VR less effective for embodied learning.

Within immersive Virtual Reality (iVR), users undergo spatial immersion through the aid of VR gears such as headsets and controllers. Accordingly, iVR can be further categorized into three distinct types: 1. Low-end VR (Freina & Ott, 2015; Radianti et al., 2020), 2. High-end VR (Freina & Ott, 2015; Radianti et al., 2020), and 3. Enhanced VR (Radianti et al., 2020).

Low-end VR is mobile VR, using devices like Google Cardboard and Samsung Gear VR. Interaction involves keyboards, handheld Bluetooth controllers, and gaze controls (Radianti et al., 2020). It offers three degrees of freedom (3DOF) allowing head rotation in roll, pitch, and yaw (Freina & Ott, 2015). Whereas, in high-end VR, users engage with the virtual environment using HMDs and integrated Hand Held Controllers (HHCs). High-end VR systems enable users to perform actions such as walking, touching, grabbing, and dropping objects, conducted through HHCs. These high-end VR headsets offer six degrees of freedom (6DOF), incorporating additional translational movements like forward-backward (surge), left-right (sway), and up-down (heave) within the simulated virtual environments (Freina & Ott, 2015). Devices like HTC Vive and Oculus Quest exemplify high-end VR technology.

Enhanced VR combines HMD, HHC, data gloves, and bodysuits with haptic sensors, offering immersive touch experiences (Radianti et al., 2020). Research indicates that learning can be significantly enriched when the sense of touch is engaged in addition to visual stimuli, highlighting its relevance (Magana et al., 2017). For optimal embodied learning, haptic-enhanced VR is preferred over high-end and low-end options. However, VR systems equipped with such haptic devices can be notably expensive (Magana et al., 2017). To address this, we opted for a high-end VR setup that integrates HHCs with haptic capabilities, thereby providing tactile feedback during the VR experience.

2.2 Interactions For Embodied Learning

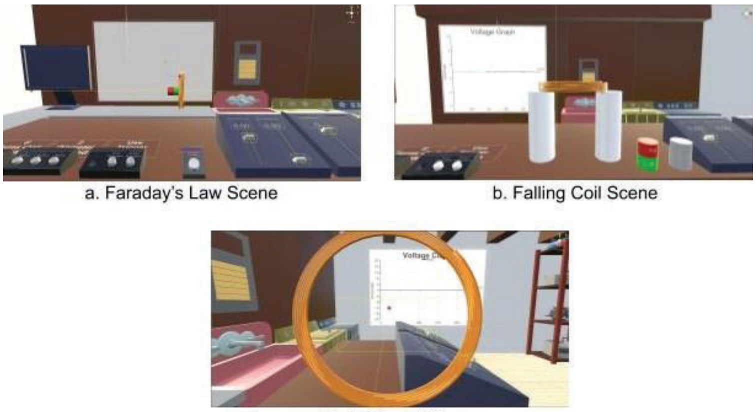
Embodied learning is supported by embodied interactions (Chatain et al., 2023). Within Virtual Reality (VR) learning environments designed to cultivate egocentric perception, interactions can manifest through visual, manual, or bodily means. However, certain VRLEs may not fully facilitate interactions. For instance, Sun et al. (2018) conducted a study using a virtual museum as a VR learning environment (VRLE). Learners navigated the environment with a first-person perspective and engaged physically with the virtual objects (Magana et al., 2017). Visual cues above objects directed attention to relevant information. Similarly, Sharma et al. (2018) created LearnDNA, a VRLE for understanding DNA concepts. LearnDNA allowed learners to explore a virtual DNA representation. However, both lacked interactions, leading to limited hands-on experience. Although immersive, these environments lacked interaction, resulting in limited embodiment.

Certain VRLEs with serious games as educational content blend heightened immersion and interaction. Sankaranarayanan et al. (2018) created an immersive simulation for healthcare training, involving extinguishing a fire in an operating room. Learners navigate around flammable objects, interacting through touch, grab, and drag actions. However, it's worth noting that there is no evidence of haptic feedback being utilized in this context. The absence of a haptic device detracts from the tactile sensations that would normally accompany interactions with various objects. Consequently, the absence of tactile feedback could potentially result in a diminished sense of embodiment within the immersive and interactive environment.

Tactile engagement through hands-on activities holds a pivotal role in shaping cognition. Magana et al., (2017) explored hands-on learning of electricity and magnetism using visuohaptic simulation. Learners interacted with virtual electric charges through a haptic device, merging touch sensation while learning. Results showed no significant differences among visuohaptic, visual-only, and conventional groups in post-test scores. Although visuohaptic learning introduced embodied learning elements, the interactions were mediated by an external haptic device rather than being inherently tied to the learners' own bodily movements. Additionally, the portrayal of the virtual environment on a computer screen adopted an allocentric perspective, contributing to a diminished sense of embodiment. Considering our literature analysis, we selected a VRLE that promotes embodied interaction through auditory, visual, and tactile sensory channels to enrich embodied learning in VR.

3. Virtual Reality Learning Environment (VRLE)

We developed a comprehensive Interaction Behavioral Data (IBD) collection mechanism to capture interactions in the Virtual Reality Learning Environment (VRLE) (Prakash & Rajendran, 2022; Prakash et al., 2023).



a. Faraday's Law Scene

b. Falling Coil Scene

c. Embodiment Scene

Figure 1. VRLE Scenes

The Interaction Behavioral Data (IBD) collection was integrated into MaroonVR (Pirker et al., 2019), a VRLE focused on physics learning. We applied the IBD logging mechanism to scenes involving Faraday's law and a falling coil experiment, enhancing comprehension of electromagnetic induction—a phenomenon characterized by the induction of electromotive force (emf) within a coil when subjected to the magnetic influence of a moving magnet. We added VR interfaces (virtual buttons and sliders) for varying coil turns, coil diameters, coil resistance, and magnetic strength and toggle the graph plot between the voltage curve and current curve to enhance the interactive experience in the VRLE. A new scene placed learners in the magnet's perspective, inducing emf and plotting real-time data on a virtual graph based on the whole physical body movement of the learners. The scenes present in the VRLE are shown in Figure 1.

4. Embodied Learning Activities Framework in VR

After reviewing the literature, we opted for the Oculus Quest 2 VR system developed by Meta. It offers heightened immersion with a 3D VRLE experienced through an HMD providing a first-person view and 6 DoF. Additionally, the integrated HHCs offer vibrotactile haptic feedback, alerting users in specific situations through vibrations.

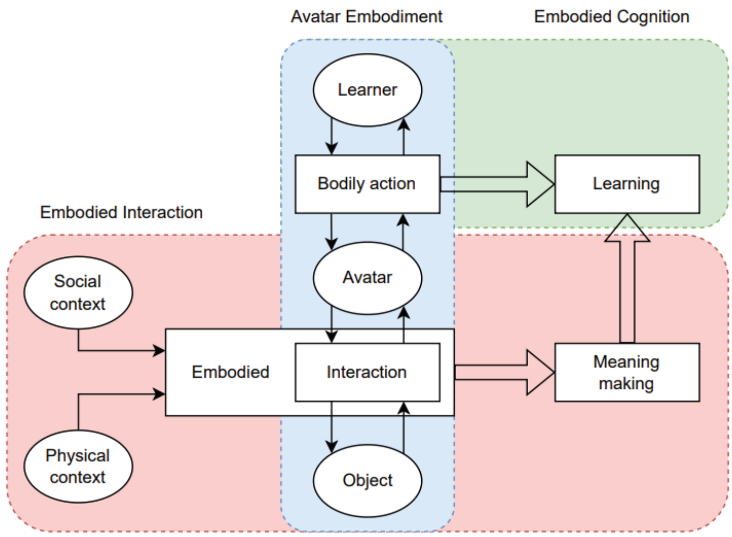


Figure 2. Representation of Framework for Embodied Learning Activities in VR (adopted from Chatain et al. (2023))

We adopted the embodied interaction design framework represented by Chatain et al. (2023) as shown in Figure 2. According to this framework, both physical and social contexts influence embodied interaction through the physical movements of the part of the body or whole body to interact with the virtual objects with the goal of meaning-making and ultimately learning. In the MaroonVR VRLE, the physical context such as the length of the cable used for tethering the HMD and the obstacles present in the real world make the learners teleport from one place to another by using the thumbstick present in the HHC rather than making any physical locomotory movements to navigate in the digital world. The social context such as the perception of various virtual objects (magnet and iron bar) present in the VRLE make the learners grab, drag, and drop using the grip button of HHC. Similarly, the virtual interfaces (buttons and sliders) present in the VRLE make the learners use the trigger button of HHC to manipulate the variables. The learners immersed in the VRLE extend their real physical hands (with HHC) to establish contact with the virtual objects and other interfaces (indicated by a color change) and interact with them constituting embodied interaction. The physical movement of the hands of the learners is represented by digital HHC (avatar) which the learners have to contextualize as their hands. The learners also move their physical heads to look at the plot (voltage or current) in the virtual graph, make meanings, and manipulate the parameters (coil turns, coil diameters, coil resistance, and magnetic strength) for the learning to occur.

In tandem with the creation of the VRLE to cultivate enriched embodied interactions, the design also adeptly incorporated a selection of multimedia learning theory principles, further enhancing the potential for improved learning outcomes. Numerous studies exploring the learning impact within VR environments have yielded a blend of results (Hamilton et al., 2021). This variance in outcomes might stem from the potential cognitive overload introduced by the multifaceted nature of learning in VR. Therefore, the VRLE and its interactions were meticulously structured to align with multimedia learning principles, aimed at mitigating the effects of cognitive overload linked to intrinsic, extraneous, and germane cognitive loads. Several multimedia learning principles were deliberately woven into the design:

1. The Pre-training Principle: This principle entailed the integration of a VR game named 'First Touch,' which allowed learners to familiarize themselves with the VR system and the corresponding interaction controllers.

2. The Self-pacing Principle: Learners were empowered to engage with the VRLE at their individualized pace, fostering a sense of self-guided progression.

3. The Signaling Principle: The learners were provided with several cues during VR intervention. For instances, the HHC avatar present in the VRLE signals the spatial movement of the hands of the learners, the change in colour of the virtual objects to blue colour indicate that the particular object is being touched and ready for interaction, and the vibrotactile haptic feedback indicate that the emf is induced.

Furthermore, the VRLE seamlessly incorporated the principle of temporal contiguity, ensuring that the aforementioned cues were temporally aligned signaling during the specific actions. The principles of spatial contiguity were equally applied, whereby textual information, including virtual object names and VR interfaces, were strategically co-located to their corresponding objects. This judicious amalgamation of multimedia learning principles into the VRLE's design is poised to optimize the learning experience, promoting comprehension and engagement while mitigating cognitive challenges associated with the immersive, multisensory nature of VR environments.

5. Methodology

The IBD collection mechanism was put into operation within the MaroonVR VRLE, and a study was executed involving a group of 14 undergraduate engineering students. As the phenomena of electromagnetic induction is very familiar among the electrical engineering students, all the participants invited belonged to non-electrical engineering to avoid bias occurring due to prior knowledge. Prior to the commencement of the Virtual Reality (VR) intervention, we gathered relevant data encompassing participants' self-efficacy, self-regulation, and their existing understanding of electromagnetic induction phenomena (pre-test). Subsequently, during the VR intervention phase, the developed data collection mechanism automatically recorded comprehensive behavioral data. Following the conclusion of the VR intervention, we proceeded to amass data concerning learning outcomes (post-test).

6. Results and Discussion

The impact of VR intervention has resulted in a significant increase in the normalized learning gain and the results are already published in one of the previous articles (Prakash et al., 2023). Based on the mean value of the post-test scores the participants were categorized into high and low performers. Also, the embodied action events performed by the participants are extracted using the data logged in the IBD logger. An excerpt of the IBD data logger is depicted in Figure 3 for reference.

The data extracted from the VRLE involved the utilization of specific columns from the IBD logger, including 'Controller Index', 'Button', 'Button Action', 'Objects', and 'Timestamp'. These columns facilitated the extraction of action events executed by the participants. The action events such as Navigation, Magnet Handling, Iron Bar Handling, Setting Coil Turns, Setting Coil Diameter, Setting Magnetic Strength, Perspective Walking are extracted from the aforementioned IBD logger columns as shown in Table 1.

Controller Index	Button	Button Action	Button Pressure	Touchpad Axis	-	Touchpad Angle	Touchpad 2 Axis	-	Touchpad 2 Angle	Object	Time stamp
1	GRIP	unclicked	0	(0.0	0.0)	90	(0.0	0.0)	90	Magnet (VRT	6:14:13
1	GRIP	released	0	(0.0	0.0)	90	(0.0	0.0)	90	Magnet (VRT	6:14:13
1	GRIP	axis changed	0	(0.0	0.0)	90	(0.0	0.0)	90	Magnet (VRT	6:14:13
1	GRIP	untouched	0	(0.0	0.0)	90	(0.0	0.0)	90	Magnet (VRT	6:14:13
1	GRIP	touched	0	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:15
1	GRIP	pressed	1	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:15
1	GRIP	clicked	1	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:15
1	GRIP	axis changed	1	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:15
1	TRIGGER	untouched	0	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:16
1	GRIP	unclicked	0	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:16
1	GRIP	released	0	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:16
1	GRIP	untouched	0	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:16
1	GRIP	axis changed	0	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:16
1	BUTTON ONE	untouched	0	(0.0	0.0)	90	(0.0	0.0)	90	2 Turns Coil	6:14:16

Figure 3. An Excerpt of Interaction Behavioral Data Logger

The 'Controller Index' in the IBD logger identifies whether the interaction occurs with the right HHC or left HHC. The time duration of a specific action event is indicated by the entry in the 'Timestamp' between the 'Pressed' and 'Released' states in the 'Button Action' field. These action events, outlined in Table 1, encompass a wide range of interactions initiated by learners through their physical movements. These interactions vary, from actions like Magnet Handling, Iron Bar Handling, Setting Coil Turns, Setting Coil Diameter, and Setting Magnetic Strength—performed using specific body parts—to the comprehensive bodily engagement required for Perspective Walking. Magnet Handling, Iron Bar Handling, Setting Coil Turns, Setting Coil Diameter, and Setting Magnetic Strength primarily contribute to the goal of inducing emf and are categorized under 'Interaction.'

Table 1. *Action Events extracted from the IBD logger*

Button	Objects	Action Event
Grip	Perspective Scene	Perspective Walking
	Magnet	Magnet Handling
	Iron Bar	Iron Bar Handling
Trigger	2, 4, and 6 Turns	Setting Coil Turns
	2, 4, and 6 Diameter	Setting Coil Diameter
	Magnetic Field Slider	Setting Magnetic Strength
Touchpad	-	Navigate

Participants were categorized as high or low performers based on post-test scores (Prakash et al., 2023). Analysis revealed no significant differences in pre-test scores (Mann-Whiteney $U = 16.5$, $p = .368$) or VR intervention duration (Mann-Whiteney $U = 13$, $p = .174$) at $p < .05$ between the two groups. However, there was a significant disparity in post-test scores (Mann-Whiteney $U = 0$, $p = .002$) at $p < .05$. Therefore, the high performers' ability to comprehend electromagnetic induction was examined using their bodily interactions in the VRLE. The percentage of embodied action event duration (Interaction, Navigation, and Perspective Walking) was calculated as $\frac{Duration\ of\ Action\ Event}{Total\ Duration\ of\ VR\ intervention}$ for both high and low performers. Figure 4 displays a comparison of the duration of embodied action events (Interaction: Magnet Handling, Iron Bar Handling, Setting Coil Turns, Setting Coil Diameter, Setting Magnetic Strength), Navigation, and Perspective Walking between high and low performers. Mann-Whitney U tests found no significant differences in the percentage of Interaction duration ($U = 15$, $p = 8$), Navigation ($U = 16$, $p = 8$), or Perspective Walking ($U = 15.5$, $p = 8$). Although Figure 4 indicates that high performers engaged in action events for a longer period, the no significance in the duration of embodied action events is likely due to the limited sample size.

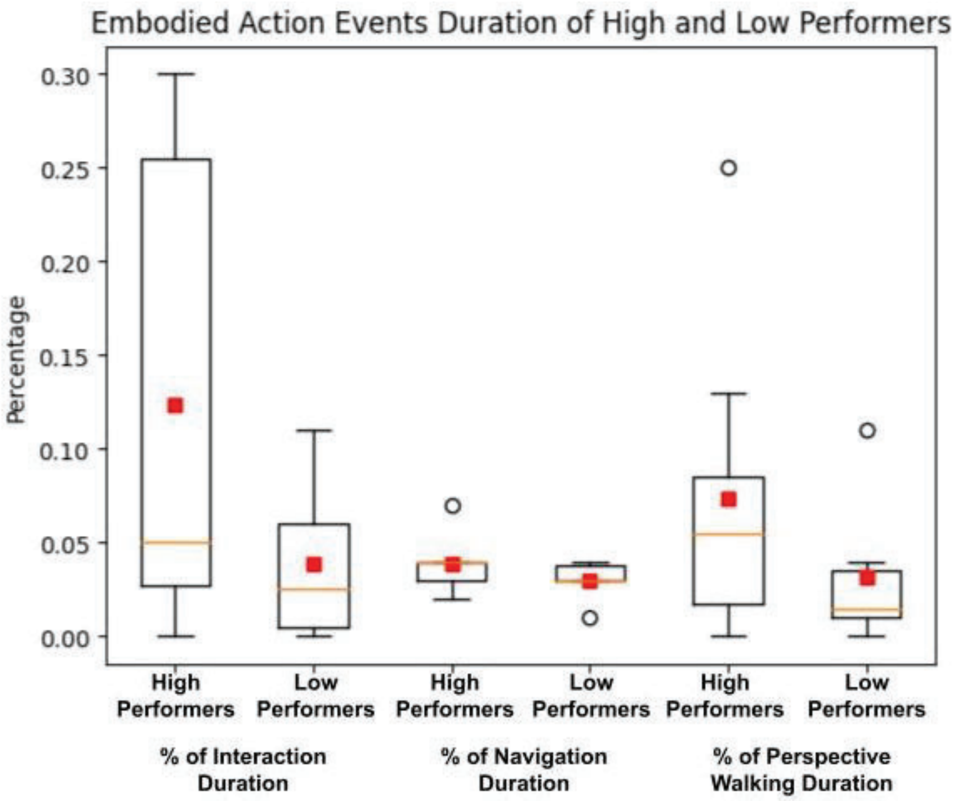


Figure 4. Distribution of Duration of Embodied Action Events

Interaction events like Magnet Handling and Iron Bar Handling involve tactile actions—touching, grabbing, dragging, and dropping virtual objects like magnets and iron bars in the VRLE. Meanwhile, events like Setting Coil Turns and Setting Coil Diameter entail adjusting coil parameters (number of turns, diameter, and resistance), and Setting Magnetic Strength focuses on modifying magnet field strength. To execute these actions (Magnet Handling, Iron Bar Handling, Setting Coil Turns, Setting Coil Diameter, and Setting Magnetic Strength), learners physically extend and manipulate their hands in the real world, activating corresponding events in the virtual environment. Perspective Walking, on the other hand, engages the entire body as learners physically walk to trigger the event. These actions enhance hands-on learning (Magana et al., 2017). The immersive VRLE experiences, combined with a first-person perspective, create a sense of situatedness. Additionally, vibrotactile feedback, triggered during emf generation, adds a tactile dimension. The interplay of bodily interactions in a highly situated environment, along with visual and tactile cues, results in embodiment during the conceptual learning of electromagnetic induction.

Learners control the virtual magnet, grabbing and moving it within a coil to induce emf, displayed in real-time on the virtual graph in the VRLE. Two avatar controllers, serve as the representation of the learner's hands, and learners perceive and use them as their own hands. The VR interfaces such as VR buttons and VR sliders are used to change the parameters of the coil and magnet. The VR buttons are pressed by the avatar touching by extending the physical hand and activating the trigger button of HHC. The VR sliders are operated by sliding movement of the physical hand after it is touched by the avatar. In addition, magnetic field lines with arrowheads are visible, originating from the magnet's north pole and extending toward the south pole. The magnetic field lines adapt dynamically as learners move the magnet. When learners move their hand (holding the virtual magnet) and observe the virtual graph for changes in induced emf, learning occurs through the sequence of *Context* => *Interaction* => *Bodily Action* => *Learning* (Figure 2). By extending their actual hand to make the avatar touch the virtual magnet (indicated by the magnet turning blue), grabbing it, and moving it in and out of the coil, learners experience vibrotactile haptic feedback in their hand, signifying that emf has been induced in the coil due to the magnet's movement (or hand movement). Consequently, learning in this scenario follows the path of *Context => Interaction => Bodily Action => Interaction => Meaning Making => Learning* (Figure 2). Thus the objects within the VRLE create a physical context that facilitates interactions aligned with bodily actions, fostering learning as illustrated in the framework shown in Figure 2.

7. Conclusion

We determined that embodied learning within the VRLE is facilitated through the engagement of embodied interaction activities. However, a deficiency exists within the current literature concerning the connection between embodied learning and these interaction activities, primarily due to the absence of an effective mechanism for logging such interactions. Consequently, we endeavored to devise an IBD mechanism capable of comprehensively recording all interaction traces, complete with timestamps. This data logging mechanism was seamlessly integrated into a VRLE, guided by the framework established for embodied interaction activities within a virtual environment. Furthermore, we successfully retrieved the embodied interaction activities executed by 14 participants, meticulously extracted from the interaction traces following VR intervention. Although, there was no significant difference in the duration of embodied action events, it was higher for the high performers. Our ongoing efforts will extend to extracting temporal and spatial attributes related to these activities, subsequently delving into the exploration of their interrelationship with embodied learning.

The implemented IBD logger has effectively captured bodily interactions, yet it has not encompassed visual interactions mediated through participants' gaze (noticing the virtual graph). Consequently, there is a necessity to incorporate provisions within the IBD logger to record virtual objects viewed by learners. Such an enhancement would facilitate the acquisition of more comprehensive embodiment data, enriching the analytical capacity. While the experiment successfully extracted action events stemming from learners' bodily actions, it's important to acknowledge certain limitations. The experiment was conducted with a relatively modest sample size, comprising only 14 participants. Additionally, the VRLE's instructional content centered around the physics concept of electromagnetic induction. Consequently, establishing the generalizability of any assertions derived from this study would necessitate further experimentation with larger and more diverse participant groups, encompassing a broader spectrum of subject matter.

In our forthcoming endeavors, we are poised to delve into a comprehensive analysis of the interplay between the extracted action events and the measured learning outcomes. Given that the action events are a direct outcome of interactions driven by bodily actions, this correlation analysis will effectively elucidate the intricate connection between embodiment and the resulting learning outcomes. This investigation into embodied action events will be instrumental in the development of a learner model tailored for optimizing performance, with the added capability of early prediction of learning outcomes based on learners' dynamic bodily interactions. The insights gleaned from these analyses carry significant implications for multiple stakeholders. Notably, they will offer valuable guidance to VRLE content developers, instructors, and learners alike, facilitating the effective integration of VR-based learning and teaching within classroom settings. As we venture into this exploration, we anticipate enriching the understanding of how embodied actions shape learning outcomes, thereby enhancing the overall effectiveness of VR-enabled educational experiences.

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