Investigating The Role of Gesture and Embodiment in Natural Sciences Learning Using Immersive Virtual Reality

Mafor PENN[a*] & Umesh RAMNARAIN[b]
[a]*Department of Childhood Education, University of Johannesburg, South Africa*
[b]*Department of science and technology Education, University of Johannesburg, South Africa*
*mpenn@uj.ac.za

Abstract: This study reports the findings of a qualitative case study on the role of embodiment and gesture in immersive virtual reality (IVR)-enhanced Natural Sciences (NS) learning. 32 NS pre-service teachers (PSTs) participated in the study, and qualitative data were gathered through observations and follow-up focus group semi-structured interviews. From a content analysis of observations and interviews, the following assertions were arrived at: Gesture and manipulation of virtual objects enhance spatial reasoning while fostering experiential and authentic learning experiences: Both bodily (physical) and virtual manipulations in IVR-enhanced learning have a positive effect on cognitive processes, and lastly that the combination of audio, visual and embodied actions together have a higher impact of long-term memory and retention of NS concepts. Some implications and future directions are also discussed in this paper.

Keywords: Cognition, Embodiment, Gesture, Immersive Virtual Reality (IVR), Natural Sciences learning, Spatial reasoning

1. Introduction

This study reports on the role of embodiment and gesture in Learning Natural Sciences (NS) concepts within immersive virtual reality (IVR) applications. The main aim of the study was to establish the actions that contribute to learning with IVR and other possible mechanisms that could enhance the formation of mental representations when learning NS concepts. The study investigated PSTs' (also referred to as students') experiences of gesture and embodiment in IVR-enhanced NS learning. PSTs in the context of this study are students in teacher education programmes who are being prepared to become in-service teachers (practising teachers) that will take up teaching jobs upon completion of a Batchelor of Education (B.Ed) qualification. In NS learning, there are several limitations in the way concepts are learned using two-dimensional (2D) representations. These limitations include the abstract nature of concepts and the fact that representational competencies are usually limited to 2D visualisation.

One of the practical solutions to enhancing visualisation and engagement in NS learning is the enforcement of hands-on and interactive inquiry-based learning (IBL) tasks which allows students to interact with learning artefacts and ask scientifically researchable questions (Crawford, 2014). The use of inquiry-based teaching and learning strategies in science education, though beneficial for students' learning experiences, has its limitations in the lack of human and other resources for enactment, time constraints for planning and execution of classroom inquiry processes, overcrowded classrooms for interactions associated with inquiry and teacher resistance to traditional didactics (Ramnarain, 2016).

From the perspective of some cognitive scientists, "the potential to engage spatial reasoning and action-based choices while immersing students in science knowledge and phenomena is amplified by new technologies that permit more physical and expressive body input" (Lindgren et al., 2016, p. 177).

Immersive virtual reality falls in this category and holds promise for Inquiry-based and interactive learning in virtual worlds situated within VR applications. Immersive virtual reality (IVR) refers to 3D-generated artificial environments in virtual worlds that mimic real-world environments and trick the user's mind with a feeling of actually being present in the virtual world (Merchant et al., 2014). The degree of immersiveness in a virtual world ranges in scale from low immersion to highly immersive VR environments (Georgiou & Kyza, 2018; Ratcliffe & Tokarchuk, 2020). Within highly immersive VR environments, the user can interact with virtual objects and be shut out of their immediate physical environment.

Immersion is the feeling of being physically present in a virtual world (Ratcliffe & Tokarchuk, 2020). When immersed in VR, users tend to be completely shut out of the physical reality around them as the virtual environment and stimuli are engrossing (Georgiou & Kyza, 2018). Immersion can be categorised into three main types, including tactical immersion, where the user is focused on the virtual manipulation of objects using tactile operations like moving the body and hands to attain specific goals. Strategic immersion is another dimension of immersion where cognitive structures are engaged in deep thought patterns that control action within VR. The last type is narrative immersion, where the user is absorbed in a story, and the sense of hearing is fully engaged in the virtual space.

According to Björk and Holopainen (2004), immersion can be classified as sensory-motoric, cognitive and emotional, respectively, in alignment with the broad categories above. However, in addition to these three, the pair suggest a fourth category referred to as spatial immersion, which describes the feeling of conviction and realness felt within the virtual world (Björk & Holopainen, 2004). These affordances of immersion in IVR have accrued several benefits for learning and cognitive processes in Science, Technology, engineering, and mathematics (STEM) disciplines.

For NS learning, in particular, benefits associated with IVR-enhanced learning include visualisation, the enhancement of spatial reasoning, interactivity, attention focusing, acquisition of conceptual and procedural knowledge, and a boost in affective constructs like motivation and interest in STEM (Parong & Mayer, 2018). For example, in studies like Parong and Mayer (2018), participants who studied in VR were reported to have gained more conceptual knowledge and practical skills in biology. In another IVR study by Al-Amri and Musawi (2020), which looked at 3D VR physics learning for eighth graders, it was reported that besides achievement in tests, students showed gains in the affective domain of motivation.

Despite the reported benefits and learning gains reported in IVR-enhanced learning, what remains a pertinent gap is establishing the factors within IVR environments that enhance better learning and retention of learned concepts. The current research focused on the perceived role of gesture and embodiment in IVR-enhanced NS learning. The following research questions were therefore posed to propel the inquiry;

- How do pre-service teachers perceive the role of gesture in IVR-enhanced NS learning?
- What is the role of embodiment in IVR-enhanced NS learning?

2. Theoretical underpinnings

2.1 Embodiment

One of the profound affordances of virtual reality (VR)-enhanced learning is embodiment, which is rooted in the theory of embodied cognition. Embodiment is defined as the role of sensorimotoric interactions in the cognitive process or the creation of knowledge (Castro-Alonso, Paas & Ginns, 2019; Lindgren et al., 2016). The theory of embodied cognition is related to experientialism which holds that all knowledge is embodied (Niebert, Marsch, & Treagust, 2012; Goldinger et al., 2016). Social cognitivism similarly has it that social interactions play a role in cognition and affect how people learn (Adam & Galinsky, 2012). However, some proponents of the theory of embodied cognition hold that embodiment is much more than popular theory say it is. Wilson and Golonka (2013), for example, categorically stated that:

> *Embodiment is the surprisingly radical hypothesis that the brain is not the sole cognitive resource we have available to us to solve problems. Our bodies and their perceptually guided motions through the world do much of the work required to achieve our goals, replacing the need for complex internal mental representations. (Wilson & Golonka 2013, p.1)*

As controversial and radical as this proposition by Wilson and Golonka (2013) sounds to the traditional cognitivist perspective, one cannot dismiss the inherent relationship between the sensory and motoric interactions in the human brain nor the principal role these interactions have in learning and the acquisition of long-term memory. Maturana and Varela (1991), describe cognition as an "interconnected system of multiple levels of sensori-motor subnetworks" (p. 206). This theoretical position leverages the traditional capacities of cognitivism, including attention, memory, affective cognition, and metacognition (Fiske & Taylor, 2013; Goldinger et al., 2016).

2.2 Embodiment and Gesture

Strongly associated with the principles of embodiment is "gesture." Cognitive scientists have proposed models to explain how abstract concepts emerge from concrete sensorimotor experiences (Lindgren & Johnson-Glenberg, 2013). In broader terms, this notion is supported by the cognitive semantics theory of conceptual metaphor (Lakoff & Johnson, 1980), which postulates that human reasoning is grounded in schemas generated from bodily movements and interactions that are created in the imagination to give structure to abstract inferences. Evidence from diverse studies like Goldin-Meadow (2014), Johnson-Glenberg and Megowan-Romanowicz (2017) and Pande (2021) that have examined how people gesture when they solve problems or talk shows further that thinking is embodied. Gesturing through bodily movements promotes cognitive processes and thinking.

Gesture in this context refers to both the movements as a communicative form exhibited physically and the actions used to manipulate virtual objects in an IVR environment. The "gesture-enhancing-memory-trace" argument can also be framed as one of the levels of processing, which is a well-studied concept in cognitive psychology (Craik & Lockhart, 1972) in a similar position as "learning by doing". Some studies found that memory traces are improved when gesture is incorporated into the learning experience (Broaders et al., 2007; Goldin-Meadow, 2011). These findings imply that bodily movements (gesturing) within VR learning environments could be considered a "cross-modal prime" to facilitate cognitive activity like retrieval from long-term memory (Goldin-Meadow, 2014; Macedonia, 2019, Pande, 2021). In some studies, body movements have been aligned with certain learning domains, for example, learning about centripetal force and circular motion by performing circular movements instead of a linear stroke (Johnson-Glenberg et al., 2016). For the current study, the researchers assumed that motoric interactions in IVR will contribute to how PSTs learn and grasp NS concepts in 3D virtual learning environments (VLEs). The diagram in Figure 1 below shows the relationship between gesture, embodiment and learning as part of the conceptual framework of this study.

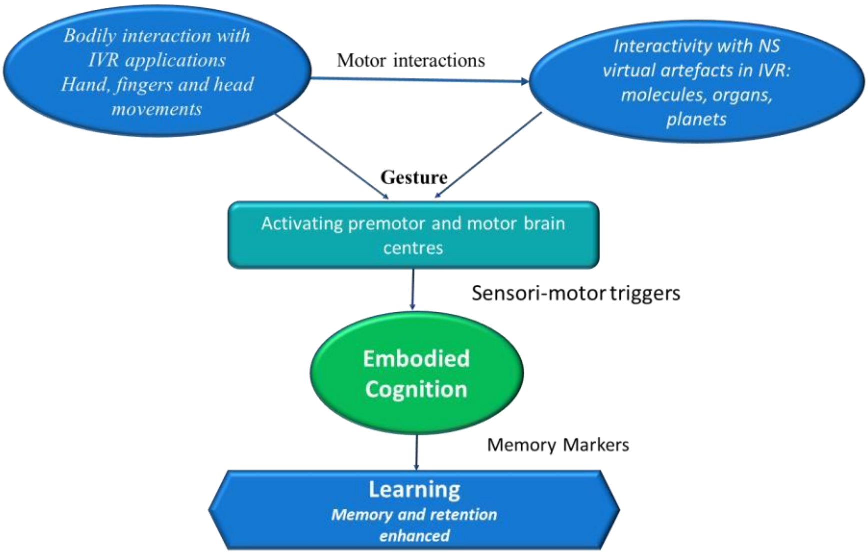

Figure1. Gesture, embodiment and learning

From Figure 1, bodily interactions in the physical (Hand, fingers and head gestures), which are motoric together with embodied actions in IVR, are all considered as gesture and will trigger sensorimotor activity. The assumption in the proposed framework is that these triggers enable embodied cognition and memory, leading to the learning and retention of NS concepts. In essence, the postulate is that embodiment has the ability to stimulate sensory responses in the pre-motor and motor brain centres, creating memory traces which aid memory and retention in the long term (Lindgren & Johnson-Glenberg, 2013; Lindgren et al., 2016). This means that the Participant PSTs in the study will learn better when their body movements and virtual gestures are employed in the learning process.

3. Methods

The research employed qualitative research methods in a case study design to gather data on PSTs' learning and interactions in IVR using observations and semi-structured focus group interviews as instruments for data gathering.

The study participants were purposively selected and included 32 Natural Sciences (NS) pre-service teachers (students) in the third year of a Bachelor of Education degree programme at a South African tertiary institution. Participants constituted twenty-one (n=21) males and eleven (n= 11) females, all of which were engaged in learning NS concepts with topics in biology, chemistry, and space science.

Once participants had been selected, they engaged in a six-week series of IVR-enhanced learning interventions using open-source biology, chemistry, and space science IVR applications. The *Oculus rift s* (a virtual reality head-mounted display) in combination with high-end *Asus* gaming laptops were used for this study. A VR application, *sharecarevr,* was selected and used for biology concepts. For chemistry, a mixed virtual and augmented reality (VAR) application, *jigspace*, was used, and for the solar system, another mixed VAR application, *ARsolar system*, was used. Three topics were targeted for learning outcomes, including the *"respiratory system"* for biology, *"combustion reactions"* for chemistry and *"composition of the solar system"* for space science. In planning and executing the learning interventions, lesson plans were first developed, and specific lesson objectives were set for each topic. An inquiry-based instructional model was considered the best teaching strategy for learning the selected NS topics in IVR. From contemporary literature, IBL modalities have proven to be most effective in IVR-enhanced learning as they allow students to participate actively in the knowledge creation process (Fegely et al., 2020; Wu et al., 2020). Because IBL instructional strategies promote interactivity and active learning, a characteristic prominent in IVR-enhanced learning, they become suitable strategies to employ in constructivist learning environments, as was the case in the current study. Participant PSTs used a guided-inquiry approach whereby they were able to engage, explore and interact with the different virtual artefacts.

The researchers developed an observation protocol for capturing different gestures and meanings based on the review of literature. The observation protocol was then used during interactive sessions to capture movements and spoken cues in the form of self-talk. Sessions were also video recorded and analysed again after each session for interpreting movements and gesture. Follow-up, semi-structured focus group interviews were conducted after the analysis of observation data as a means to get insights from participant PSTs on the meaning of their movements and interactivity in IVR after each session. The focus-group semi-structured interviews also provided room for data triangulations and validation of observed actions, which were unclear.

Semi-structured focus group interviews were audio-recorded, transcribed and analysed using thematic content analysis. Thematic content analysis is flexible and helps narrow large quantities of data into more precise and meaningful themes (Maguire & Delahunt, 2017). Thematic content analysis also provides a rich and detailed sum of all the data collected (Nowell et al., 2017), hence preferred for data analysis in the current study. Several strategies for qualitative data evaluation, including member checking, inter-coder (3 coders) reliability and an audit trail, were employed to ensure the quality of gathered data and meaningful interpretation (Nowell, 2017).

4. Results

Sample observation findings from the current study are presented in Table 1 below. The observation tool was used to record embodied actions of participant PSTs and also to provide meaning to each action recorded. PSTs were also requested to engage in self-talk during their immersive experiences with the goal of stating why they were making certain movements. Self-talk was preferred as the researchers did not have eye-tracking tools to track IVR engagements. Screes of the laptops were also being recorded by the researchers as PSTs' interacted in IVR. Table 1 below is a sample table from the observation data gathered. The table shows observed actions and how they were classified as a virtual or actual gesture. The verbal cue recorded explained why the PST was making this move, and the interpretation column was the researchers' meaning from the movements and cues.

Table 1. Observation protocol for interaction in IVR-enhanced learning

Observed bodily/virtual actions	**Gesture classification**	**Spoken cue (self-talk)**	**Interpretation**
Rotating head gestures	Physical gesture	Looking around to see	Creating a mental picture of a 3D image
Rotating hand gestures	Physical gesture	Looking at different angles	Establishing spatial dimensions
Annotations	Virtual gesture	Marking interesting features	Concept formation
Drag and zoom	Physical/Virtual gesture	Taking a closer look	Spatial image processing/visualisation
Pointer movements	Virtual gesture	Reflecting on a feature	Attention focusing
In-app screenshot	Virtual gesture	Keeping to re-engage after the session	Memorisation, repetition and remediation
Teleporting	Virtual gesture	Moving on to explore	Curiosity/inquiry tendencies

From Table 1, bodily actions observed as physical gestures included head rotations, hand swings (movements) and finger movements. Within the IVR environments for different VR applications, other gestures like using annotations with the aid of hand controllers, pointing, dragging, teleporting and zooming of virtual images were observed from the IVR learning interactions as part of gesture within the virtual environment.

From the self-talk data, PSTs associated different meanings with their bodily movements even as they spoke aloud. For instance, when participants were asked to provide reasons for head movements, their standard response was that they wanted to look around in the IVR environment in order to scale the environment and create mental representations of the virtual artefact. In an application like *sharecareVR*, participants used a pencil tool in the interface to make annotations on parts of the respiratory system as part of virtual gesturing. The spoken cue related to this action was that they were marking features of interest. Figure 2 below shows a PSTs' engagement in IVR on a two-by-two meters room scale.

Figure 2. PST engaged with IVR using head and hand motions

From Figure 2, the PST participant moves around in VR and engages in diverse physical and virtual gestures. Post-observation of IVR learning engagements, six semi-structured focus group interviews were conducted with all the participant PSTs to establish the role of bodily movements and gestures in their learning experiences. The following four main questions were used for semi-structured focus group interviews with participant PSTs:

- Why do you move your heads, hands, and fingers when immersed in the HDM?
- In your own words, are there any benefits for your movements and gestures when immersed in VR?
- Are there any other features of the VR applications you have engaged with that help you learn concepts?
- How can you rate the retention of learned concepts you have interacted with in IVR?

From a combination of the observation and interview data, it was clear that there were several dimensions of bodily (head, hand and finger movements) and virtual gestures, including pointing, rotation, zooming, dragging, and annotating virtual structures and images. In-app screenshots were also taken for relearning, remediation, and repetition. From the coding and analysis of the post-observation focus group interviews, three main themes were generated to answer the main research questions on the role of embodiment and gesture in IVR-enhanced NS learning.

4.1 Embodiment and gesture enhance the formation of mental representations

PSTs indicated that the ability to move one's body while immersed in VR and the actions that can be taken within IVR are essential for close examination of virtual artefacts. These movements changed the perception that PSTs had about the NS concepts being learned and enhanced their formation of mental images or representations. For example, P15 (a Pseudonym) indicated that *"I was able to interact freely with the molecules involved in the combustion of methane using jigspace in VR, I move, I zoom and even drag objects closer. This makes it easier for what I have seen to remain in my memory for long periods of time."*Another participant PST P12 in the same focus group supported P15 saying, *" I feel the same way. In my case, I could move around in a human lung by moving my head and looking at each structure carefully. I am not sure I will be able to forget the images of the different parts of the respiratory system for the longest time."* In the first focus group, P2 reported a similar experience: *"In the Solarsytem app, I felt like I was moving from one planet to another; being able to rotate the different planetary bodies as I studied their characteristics gave me a clear picture of each one of the planets. I always hated this topic, but IVR gave me a different perspective".*

These excerpts and other similar ones led to the assertion of this theme. It is evident from these findings that embodiment and gesture both in the physical and virtual spaces have a positive effect on cognitive processes, spatial reasoning and the formation of mental representations/schemas.

4.2. Embodiment and gesture enhance interactivity and experiential learning

Findings also revealed that embodied interactions within IVR spaces supported experiential learning. The PST participants revealed that freedom of movement within IVR, whereby they could use bodily gestures like head, hand and finger movements to explore molecules, organs and planets, made the learning in IVR memorable and real. For example, P21 said that *"my virtual interactions were interesting, especially in sharecareVR where I could teleport to the internal structure of an organ, move it around and really see it up close. This keeps a clear picture in my mind of the experience and the particular structure."* P 30 in the same focus group said, *"the whole VR-enhanced learning makes me interact with the things I am learning. For example, as I went into space in VR, the experience was good, but it went to another level when I realised I could drag planets, zoom in on them, rotate them and study them as if I was physically present in space.*" These experiences attest to some of the aspects of experiential learning and the feeling of presence that is associated with IVR. PSTs indicated that the learning experiences were real, and they felt like they had been present in the learning experience.

In validating the role of physical gesture as well, PSTs indicated that because they were able to interact using their body movements in IVR, for instance, pushing fingers forward using thumb sticks or rotating a structure with a hand gesture, gave a natural feeling to the experiences as though they were in the real world experiencing the actions. For example, P31 said that *"when I stretched my hand out to* *touch or pinch an object in VR, I felt a feedback as though the object was actually in my hand. This made the learning experience more authentic".*

Asking about other learning aids in the IVR environment, PSTs indicated that some applications like the *jigspace* VR had textual information which aided their thinking, *sharecarevr* had labels on organ structures, while *ARsolar* system had planetarium text on the composition and characteristics of each planet in the solar system. These assertions suggest that embodiment is not a standalone system for learning concepts. There is a need for other kinds of representations that could support the learning process.

4.3. Embodiment and gesture enhance memory and retention

Recorded experiences also indicated that due to the formation of metal representations and the interactivity in IVR, PSTs could retain concepts learned for a longer period. They credit this to the ability to visualise and gesture in IVR. P11 indicated that *" I have always been good at memorising things which I forget shortly, but I realised that in IVR, I don't need to memorise the things are just fixated in my mind because I touched and played with them in VR*." This and similar opinions led to the conclusion that gesture in IVR holds promise for the way NS concepts are learned and retained in long-term memory.

5. Discussions and conclusions

Based on the findings of this study, it is clear that the role of gesture in IVR-enhanced NS learning is critical for authentic, experiential and interactive learning. In fact, the findings from this study concur with those of studies like Johnson-Glenberg et al. (2016) and Johnnson-Glenberg & Megowan-Romanowicz, (2017), which suggest that for learning to take place, the body should move rather than just focus on reading and imagining concepts. Findings from Pande and Chandrasekharan (2017) and Abrahamson et al. (2020) also allude to the fact that embodiment and gesture, which may be external, can enhance mental representations and cognitive processes. The findings of the current research also suggest that the combination of actions, interactions, visualisation and thinking are critical for learning NS concepts. These findings are also congruent with the results of studies like Alibali and Nathan (2018) and have implications for how learning interventions are designed for maximum learning gains.

In answering the research questions on the role of gesture and embodiment in IVR-enhanced NS learning, findings from the current study suggest that embodiment is undisputedly relevant for concretising scientific concepts and fostering cognition in IVR-enhanced NS learning. Gesticular movements which propel the process of embodiment were suggested by PSTs to be the actual triggers of their thought processes and spatial reasoning when learning concepts in IVR. Both physical and virtual gestures were seen to have a role in long-term memory and retention, a finding supported by Goldinger et al. (2016).

Based on these findings, it is recommended that IVR-enhanced learning in any STEM discipline be characterised by interactive gesture-provoking applications that will ensure students have an experiential learning opportunity where they can interact with the learning content. Further research on the role of embodiment in IVR-enhanced science learning could be conducted on a larger scale using a mixed methods design. For practitioners in science education, the role of embodied learning and gesture can be compared in traditional inquiry-based settings against virtual laboratory settings in IVR to establish the effects on learning.

Acknowledgements

We want to thank participant pre-service teachers who come to the hub daily amid lockdowns to participate in this study.

References

Abrahamson, D., Nathan, M. J., Williams-Pierce, C., Walkington, C., Ottmar, E. R., Soto, H., & Alibali, M. W. (2020, August). The future of embodied design for mathematics teaching and learning. In *Frontiers in Education* (Vol. 5, p. 147). Frontiers Media SA.

Adam, H., & Galinsky, A. D. (2012). Enclothed cognition. *Journal of experimental social psychology*, *48*(4), 918-925.

Al Amri, A. Y., Osman, M. E., & Al Musawi, A. S. (2020). The effectiveness of a 3D-virtual reality learning environment (3D-VRLE) on the Omani eighth grade students' achievement and motivation towards physics learning. *International Journal of Emerging Technologies in Learning (Online), 15*(5), 4.

Alibali, M. W., & Nathan, M. J. (2018). Embodied cognition in learning and teaching: Action, observation, and imagination. In International handbook of the learning sciences (pp. 75-85). Routledge.

Bjork, S., & Holopainen, J. (2004). *Patterns in game design (game development series)*. Charles River Media, Inc..

Broaders, S. C., Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2007). Making children gesture brings out implicit knowledge and leads to learning. *Journal of Experimental Psychology: General, 136*(4), 539.

Castro-Alonso, J. C., Paas, F., & Ginns, P. (2019). *Embodied cognition, science education, and visuospatial processing*. In Visuospatial processing for education in health and natural sciences (pp. 175-205). Springer, Cham.

Craik, F. I., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of verbal learning and verbal behavior*, *11*(6), 671-684.

Crawford, B. A. (2014). *From inquiry to scientific practices in the science classroom*. In handbook of research on science education, volume II (pp. 529-556). Routledge.

Fegely, A. G., Hagan, H. N., & Warriner III, G. H. (2020). A practitioner framework for blended learning classroom inquiry-based virtual reality lessons. *E-Learning and Digital Media*, *17*(6), 521-540.

Fiske, S. T., & Taylor, S. E. (2013). *Social cognition: From brains to culture*. Sage.

Georgiou, Y., & Kyza, E. A. (2018). Relations between student motivation, immersion and learning outcomes in location-based augmented reality settings. *Computers in Human Behavior, 89*, 173-181.

Goldinger, S. D., Papesh, M. H., Barnhart, A. S., Hansen, W. A., & Hout, M. C. (2016). The poverty of embodied cognition. *Psychonomic bulletin & review, 23*(4), 959-978.

Goldin-Meadow, S. (2014). How gesture works to change our minds. *Trends in neuroscience and education, 3*(1), 4-6.

Johnson-Glenberg, M. C., Megowan-Romanowicz, C., Birchfield, D. A., & Savio-Ramos, C. (2016). Effects of embodied learning and digital platform on the retention of physics content: Centripetal force. *Frontiers in psychology, 7*, 1819.

Johnson-Glenberg, M. C., & Megowan-Romanowicz, C. (2017). Embodied science and mixed reality: How gesture and motion capture affect physics education. *Cognitive research: principles and implications, 2*(1), 1-28.

Lakoff, G., & Johnson, M. (1980). Conceptual metaphor in everyday language. *The Journal of Philosophy*, *77*(8), 453– 486. doi:10.2307/2025464

Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment: Six precepts for research on embodied learning and mixed reality. *Educational researcher, 42*(8), 445-452.

Lindgren, R., Tscholl, M., Wang, S., & Johnson, E. (2016). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. *Computers & Education, 95*, 174-187.

Macedonia, M. (2019). Embodied Learning: Why at school, the mind needs the body. *Frontiers in Psychology, 10*(2098), 1-8.

Maguire, M., & Delahunt, B. (2017). Doing a thematic analysis: A practical, step-by-step guide for learning and teaching scholars. *All Ireland Journal of Higher Education*, *9*(3), 3351-33513.

Maturana, H. R., & Varela, F. J. (1991). *Autopoiesis and cognition: The realisation of the living* (Vol. 42). Springer Science & Business Media.

Merchant, Z., Goetz, E. T., Cifuentes, L., Kenney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education. *Computers & Education, 70*, 29–40.

Niebert, K., Marsch, S., & Treagust, D. (2012). Understanding needs embodiment: A theory-guided reanalysis of the role of metaphors and analogies in understanding science. *Science Education, 96*(5), 849–877. doi: 10.1002/sce.21026

Nowell, L. S., Norris, J. M., White, D. E., & Moules, N. J. (2017). Thematic analysis: Striving to meet the trustworthiness criteria. *International journal of qualitative methods*, *16*(1), 1-13, 1609406917733847.

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. *Journal of Educational Psychology, 110*(6), 785-797. doi:10.1037/edu0000241

Pande, P., & Chandrasekharan, S. (2017). Representational competence: towards a distributed and embodied cognition account. *Studies in science education*, *53*(1), 1-43.

Pande, P. (2021). Learning and expertise with external scientific representations: an embodied and extended cognition model. *Phenomenology and the Cognitive Sciences*, *20*(3), 463-482.

Ramnarain, U. (2016). Understanding the influence of intrinsic and extrinsic factors on inquiry-based science education at township schools in South Africa. *Journal of research in science teaching, 53* (4), 598-619. doi: 10.1002/tea.21315

Ratcliffe, J., & Tokarchuk, L. (2020, August). Evidence for embodied cognition in immersive virtual environments using a second language learning environment. In *2020 IEEE Conference on Games (CoG)* (pp. 471-478). IEEE.

Wilson A.D., & Golonka, S. (2021). Embodied cognition is not what you think it is. *Frontiers in Psychology, 4*(58), 1–13. DOI: 10.3389/fpsyg.2013.00058 [PubMed: 23382719]

Wu, B., Yu, X., & Gu, X. (2020). Effectiveness of immersive virtual reality using head-mounted displays on learning performance: A meta-analysis. *British Journal of Educational Technology, 51*(6), 1991-2005