Enacting Biomolecular Interactions in VR: Impact on Student Conceptual Understanding in Biochemistry

Prajakt PANDE[a&b*]
[a]*Southern Methodist University, Dallas, United States of America*
[b]*Roskilde University, Denmark*
*ppande@smu.edu

Abstract: Through the theoretical lenses of embodied and enactive learning, this paper reports the instructional effectiveness of immersive virtual reality (VR) in helping undergraduates learn core biochemistry concepts. The reported pretest-posttest quasi-experimental study investigated how student enactment and learning of biochemical interactions in a VR simulation designed for embodied and enactive learning compared with traditional slideshow lecture-based instruction in terms of student learning outcomes across a number of cognitive (conceptual learning) and affective (intrinsic motivation, self-efficacy, perceived learning) measures. Thirty-eight undergraduates (17 females) who volunteered to participate in the study randomly received either the VR simulation (19), or slideshow-based traditional (18) instruction. Preliminary statistical analyses revealed that embodied and enactive interactions in VR: (i) had a significant positive impact on conceptual understanding in contrast to traditional instruction, and (ii) significantly helped in improving self-efficacy and confidence among the students, but was indifferent from the traditional instruction on student scores in intrinsic motivation and perceived learning tests.

Keywords: Virtual Reality, Embodied Learning, Science Education, 4E Cognition, Technology-enhanced Learning, Immersion

1. Introduction

Immersive virtual reality (VR) – a technology that affords immersive, experiential, and real-life like interactions with dynamic virtual 3D models of objects in simulated environments – is becoming increasingly popular in STEM education (Radianti et al., 2020). VR allows learners to perceive, interact with, enact, and experience abstract STEM content in newer and innovative ways (Johnson-Glenberg, 2018; Skulmowski & Rey, 2018). However, research on the efficacy of VR as a tool for the learning-teaching of abstract scientific concepts is still evolving and varies considerably in relation to the educational level(s) at which VR was used (e.g. school, undergraduate; Jensen & Konradsen, 2018); the target content (e.g. visualization of abstract concepts; Checa et al., 2021), the degrees of VR's effectiveness (positive, mixed; Buttussi & Chittaro, 2017; Luo et al., 2021), and the nature of the VR experience (e.g. as facilitated by the hardware and software used; Luo et al., 2021).

In science education, the incorporation of VR as an instructional technology has generally led to favorable outcomes across several affective aspects of student learning (e.g. motivation, self-efficacy, enjoyment; Buttussi & Chittaro, 2018; Han, 2020; Pande et al., 2021) as well as knowledge-retention (e.g. Moro et al., 2017; Parong & Mayer, 2020), either in isolation, or in comparison with more traditional forms of instruction and/or other media. However, results related to content learning (e.g. particularly, conceptual understanding) have not been conclusive (e.g. Azer & Azer, 2016; Concannon et al., 2019; Klippel et al., 2020; Moro et al., 2017; Radianti et al., 2020; Zhao et al., 2021). Moreover, since majority of studies document the use of VR in controlled environments, the performance of VR in authentic education settings or classrooms, particularly over extended periods, remains unclear (ecological contexts; Pande et al., 2021; Zhao et al., 2021). The bulk of studies that documented the instructional applications of VR over the last ten years are concentrated within the more applied domains in higher science education such as medical, dentistry, and engineering education and have largely focused on procedural learning, training, or skills acquisition (Roy et al., 2017; Tang et al., 2020). Finally, the reports of instructional uses and effectiveness of VR are predominantly from studies conducted in (relatively) richer countries and regions, and such research among socio-economically underprivileged populations in developing nations (e.g. Brazil, India, South Africa) is still scarce.

This paper reports results from a pre-test post-test quasi-experimental pilot study involving undergraduates, from predominantly socio-economically underprivileged student population, at a semi-urban university college in India, which investigated cognitive (conceptual understanding) and affective effects of learning university biochemistry topics through an interactive VR simulation as compared to traditional slideshow-based scripted lecture.

2. Theoretical Framework: Embodied Learning

This study draws its theoretical inspiration from the recent cognitive mechanism-accounts of science learning, especially the embodied and enactive (or what are often collectively referred to as 4E) cognition perspectives. These accounts of STEM learning assert that, regardless of how complex the target content (e.g. complex scientific concepts) is, one's learning (of that content) is constitutive of the various physical interactions they have with the different interactable forms of that content (e.g. scientific models like Bohr atomic model, representations such as equations; Landy et al., 2014; Pande & Chandrasekharan, 2017 & 2022). Put differently, these approaches systematically illustrate how seemingly abstract learning (e.g. conceptual understanding) originates from "doing", or from active bodily participation that engages our sense and movement capacities in relation to the nature of the content (Nathan, 2021; Kersting et al., 2023; Pande, 2021).

In the VR and technology-enhanced learning contexts, embodied and enactive learning theories imply that richer sensorimotor interactions and realistic bodily engagement with various forms of the content further enhance the chances of effective learning of scientific concepts (McGowin et al., 2022; Lindgren & Johnson-Glenberg, 2013; Kothiyal et al., 2014; Skulmowski & Rey, 2018), particularly in relation to other less active and immersive modes of instruction.

Consistent with theories of embodied and enactive learning which primarily account for content learning, theoretical and empirical works on affective aspects of learning have long emphasized how active (e.g. hands-on or bodily) engagement and participation are positively intertwined with one's interest, intrinsic motivation, self-efficacy, overall enjoyment, and other non-cognitive factors (e.g. Bandura, 2001; Maresky et al., 2019). Representing scientific concepts in accessible forms that facilitate bodily interaction, or actually *doing* or *enacting* a certain scientific phenomenon (e.g. chemical interactions between biomolecules) or set of procedures (e.g. lab protocol) that are otherwise difficult to access and imagine in the real world helps invoke the feeling of active engagement. High degrees of immersion and sense of presence, as in case of VR, further help enhances this feeling (Büssing et al., 2022; Chessa et al., 2019; Johnson-Glenberg, 2018). For instance, when navigating VR and interacting with virtual objects, many VR users feel as if they were interacting with the real world. Considerable amount of research in learning with VR has demonstrated that such a feeling often results in an increased interest, intrinsic motivation, engagement, and enjoyment (Maresky et al., 2019; Stepan et al., 2017; Teranishi & Yamagishi, 2018), which in turn has been linked to higher self-confidence/efficacy (Jang, 2008; Kahu et al., 2017).

3. The Study

This study explored whether enacting biochemical interactions in an immersive VR simulation designed for embodied learning yields better learning outcomes on abstract biochemistry concepts as compared to traditional slideshow-based traditional instruction.

A quasi-experimental two-group pretest–posttest design was employed.

A total of 38 undergraduate students (17 female) enrolled in various life sciences programs at a semi-urban university college, with a large proportion of students coming from socio-economically disadvantaged populations, in western India volunteered to participate in this study.

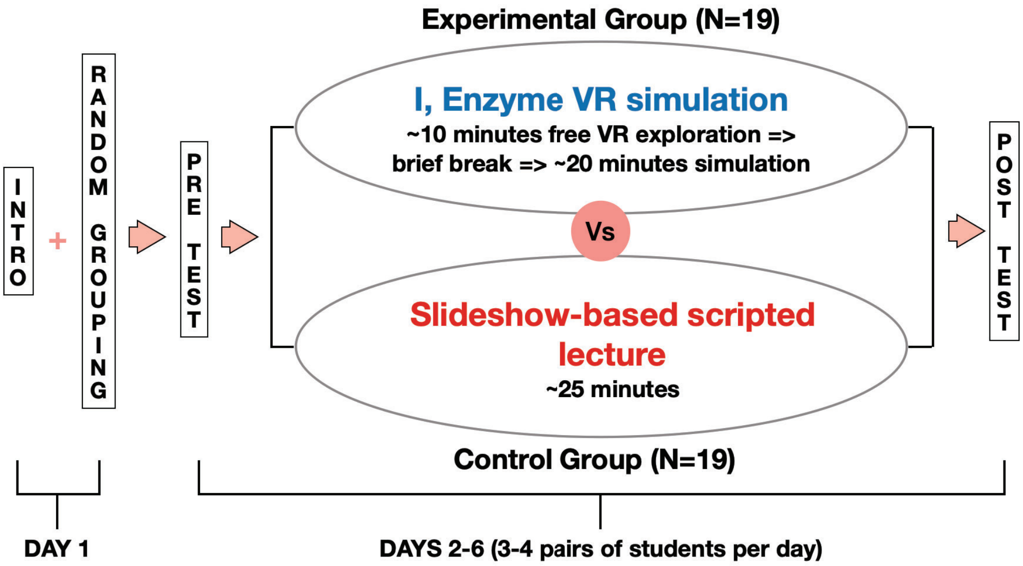

Figure 1. Study protocol.

The study was conducted in accordance with the Declaration of Helsinki and the general ethical guidelines of the university/college where the study participants were recruited. All participating students were adults and were informed about the study's objectives prior to recruitment. Written consents were obtained from the participating students before the study.

Figure 1 above captures the study protocol. Due to the limited availability of VR equipment, the study was performed over a stretch of six days. On the first day, two sets of unique codes (e.g. VR1, VR2; SS1, SS2, etc.) were randomly distributed among all the 38 students. A code beginning with VR would assign a student to the VR biochemistry simulation (experimental/treatment) group (total 19 students; 9 female) whereas a code with SS would assign the student to the slideshow-based traditional lecture group (total 19 students; 8 female). The first day was also used to create a schedule that accommodated student availability. Between days 2-6, 3-4 pairs of students (with each pair composed of a VR student, and a slideshow lecture student) would visit the study site at different hours as scheduled. At the site they would: (1) first respond to a pre-test comprising of a brief demographic survey (age, gender, VR experience, major), a set of biochemistry questions (11 multiple-choice items to capture their conceptual understanding of the topic of the lesson) and affective questions deployed as 7-point Likert scales on intrinsic motivation (8 items; Monteiro et al., 2015) and self-efficacy (6 items; Makransky et al., 2016). After pre-test, the VR student in the pair would go to another room where they would put on the VR HMD and play the pre-loaded biochemistry simulation. The other student from the pair would, at the same time, receive a one-on-one detailed slideshow-based scripted lecture delivered by a university teacher presenting the same biochemistry content as the simulation.

On completion of their respective instruction, each student responded to a posttest comprising of the same set of items as in the pre-test plus 5 additional items on a 7-point perceived learning Likert scale (Lee et al., 2010). In addition, students in the VR group answered 18 items (7-point Likert scale; adapted from Franco & Peck, 2018) that measured the extent of embodiment they experienced when playing the simulation (analysis not included in this report).

3.1 Instructional material

A highly interactive VR simulation supporting the embodied learning and conceptual understanding of the biochemical mechanisms (specifically Nucleophilic Substitution of SN1 and SN2 reactions) involved in an enzyme-substrate interaction was designed and developed as part of a larger design-based research preceding this study.

Specifically, this VR simulation narrates the classic case of lysozyme – an enzyme/protein in human mucosal secretions that neutralizes harmful bacteria by breaking down peptidoglycan molecules in their cell walls. Through visual prompts (flashing arrows), text-based instructions, and dynamic haptic feedback (vibration), the VR simulation we designed allows a learner to (a) embody, i.e. become, lysozyme in its molecular form (visible as molecular arms whose movement is synced with the learner's; see figure 2a), (b) zoom into bacterial cell wall molecular structures (see Figure 2b), and (c) enact and learn about two types of reaction mechanisms, nucleophilic substitution 1 and 2 (SN1 and SN2), comprising lysozyme's biochemical function (see Figure 2c). The learners also see dynamic graphs and chemical equations that reflect the changing states of the biochemical reaction in real-time (see Figure 2d).

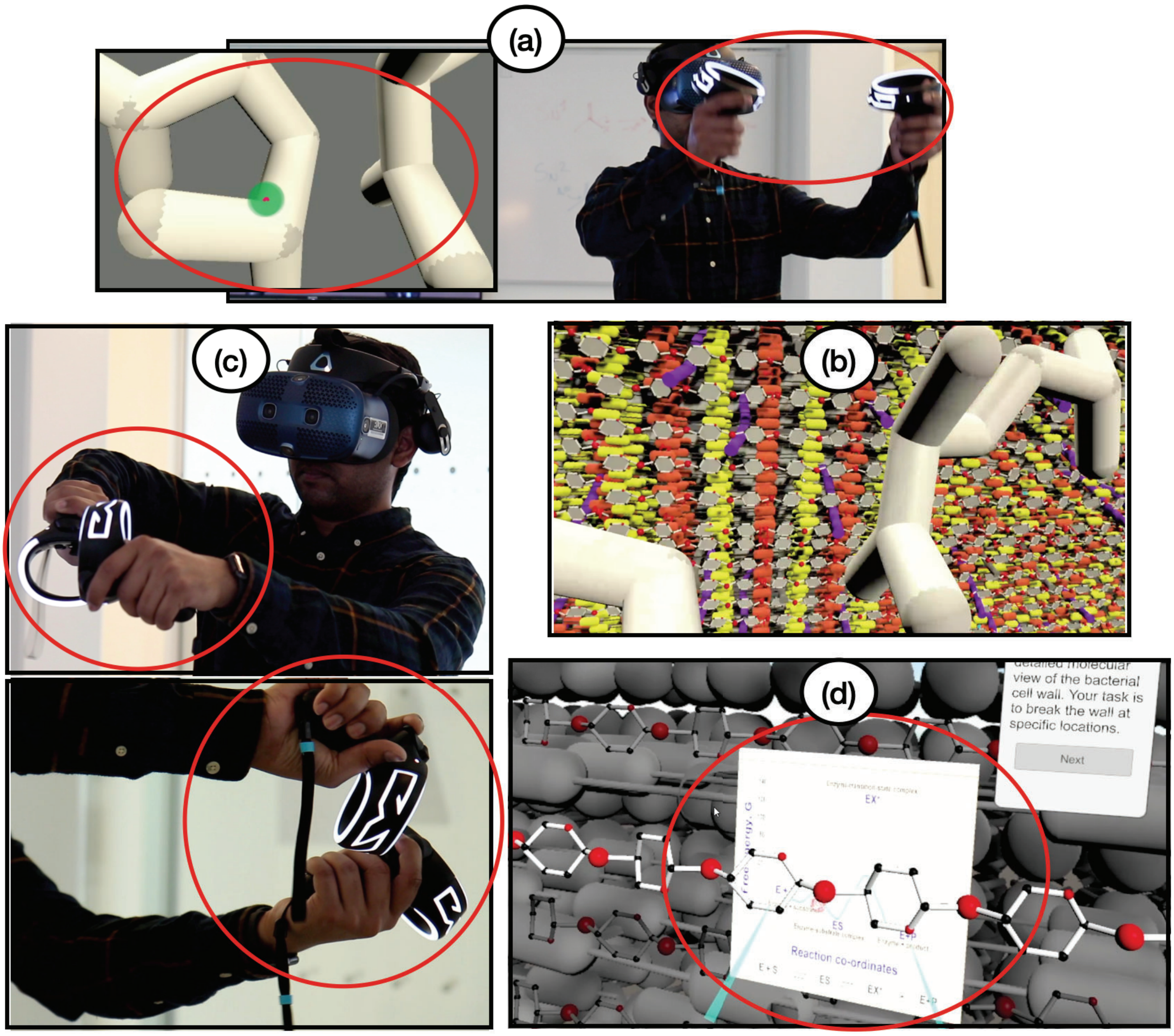

Figure 2. Snippets from the VR simulation: (a) On the right, a learner can be seen lifting their arms (controllers) to embody (i.e. become) the enzyme. On the left is the learner's view of

embodied enzyme arms in a skeleton/stick molecular model. (b) A zoomed-in colorful molecular view of peptidoglycan polymer bacterial cell wall (with learner's view of embodied enzyme arms in a skeleton/stick molecular model in the foreground). (c) Learner's enaction of the two chemical reaction mechanisms using two different body movements: (Top) Nucleophilic Substitution 1 (SN1) reaction by an abrupt and jerky twisting the right hand/controller in clockwise direction. (Bottom) Activation of Nucleophilic Substitution (SN2) reaction mechanism by abruptly twisting both hands/controllers in anti-clockwise direction. (d) Dynamic graph and chemical equations as seen on a white panel in the background.

The VR simulation was deployed using an HTC Vive Cosmos headset tethered to a DELL gaming laptop.

The traditional slideshow-based traditional instruction presented this lysozyme-peptidoglycan interaction, biochemical mechanisms, and other relevant concepts as covered in the VR simulation through a set of static diagrams, animations, and textual information in a self-paced format (i.e. students could choose to view/review the slides at their will), accompanying a scripted verbal lecture. The lecturing teacher was specifically trained to avoid using iconic gestures and/or body language related to the presented content/concepts, and strictly adhere to the verbal instruction provided in the script. This would prevent the students in this group from getting additional cues or support in imagining concerned biochemical phenomena/concepts.

3.2 Expected Outcomes

Following from the theoretical framing of embodied, enactive, and action-based learning, we expected the VR simulation to outperform slideshow-based lecture instruction by helping the students dynamically visualize, enact, and experience the enzyme-substrate interactions and thus conceptually understand the content better. Similarly, we hoped that this would make the VR group more motivated as well as self-confident for navigating and learning about the complex/abstract biochemical concepts after the intervention in comparison to the other instruction (where students would be unsupported in imagining how lysozyme-peptidoglycan interactions would "look" and "feel" like). We also expected the average perceived learning scores for the VR group to be higher than those for the slideshow lecture group.

3.3 Analysis

One student identifying themselves as a man dropped out from the VR group soon after trying the simulation for several minutes due to cybersickness-related issues. This rendered the effective sample size to a total of 37 participants (19 and 18 in the VR and Slideshow-based lecture groups, respectively).

All statistical analyses were performed using IBM SPSS Statistics 28.

First, descriptive statistics were calculated for pre and post test scores (independent and dependent variables) for each group. Baseline tests showed that the groups did not differ significantly in terms of any of the collected demographic variables (age, gender, prior VR experience).

ANCOVA was employed to compare means of the two study groups to assess their comparative learning effectiveness, while controlling for the groups' respective pre-test performances to make sure that the differences, if any, did not arise from pre-existing group differences, across the mentioned conceptual understanding and affective learning outcomes. Assumptions of ANCOVA were assessed, including linearity, homogeneity of regression slopes, independence, and normality. These assumptions were found to be sufficiently met for the analysis.

The main ANCOVA analyses were conducted with each dependent variable (i.e. post-test scores for conceptual understanding, intrinsic motivation, and self-efficacy) as the outcomes, controlling for the respective covariate (i.e. pre-test scores for conceptual understanding, intrinsic motivation, and self-efficacy, respectively).

Finally, an independent samples t-test was performed to compare the mean perceived learning scores of the two groups. Analyses of VR group's responses to the self-report embodiment questionnaire are not included in this paper.

4. Results

4.1 Descriptive statistics

The means and standard deviations are presented in Table 1.

Table 1. *Descriptive statistics*

	Variables	Pre-test		Post-test	
		Mean	SD	Mean	SD
VR	Conceptual understanding	0.21	0.14	0.45	0.22
	Intrinsic motivation	4.41	0.89	4.99	1.09
	Self-efficacy	4.23	0.72	5.73	0.81
	Perceived Learning	-	-	5.37	1.18
Slideshow-based lecture	Conceptual understanding	0.22	0.13	0.27	0.17
	Intrinsic motivation	4.53	0.65	4.87	0.99
	Self-efficacy	4.05	0.41	5.02	0.96
	Perceived Learning	-	-	5.16	1.15

4.2 ANCOVA Results

On conceptual understanding-related learning outcomes, the ANCOVA model revealed a significant effect of group on the dependent variable, mean post-test conceptual learning score ($F(1, 34) = 5.884$, $p = 0.021$), while controlling for the covariate, mean pre-test conceptual learning score. The effect size as indicated by the partial eta squared was considerably big with a value of 0.148.

For intrinsic motivation, ANCOVA did not result in a significant group effect for the dependent variable, mean post-test intrinsic motivation rating ($F(1, 34) = 0.445$, $p = 0.509$), while controlling for the covariate, mean pre-test intrinsic motivation rating.

For self-efficacy, the ANCOVA model revealed a significant effect of group on the dependent variable, mean post-intervention self-efficacy rating ($F(1, 34) = 5.086$, $p = 0.031$), when controlling for the covariate, mean pre-test self-efficacy rating before the intervention. The effect size as indicated by the partial eta squared was considerably big with a value of 0.13.

Finally, a two-tailed independent samples t-test assuming equal variances revealed that the two groups did not differ in terms of post-intervention perceived learning scores at $p = 0.582$.

5. Summary and Conclusion

This research examined the learning effectiveness of a highly interactive VR simulation designed to support embodied learning of complex biochemical phenomena and concepts through enactive experiences of certain chemical interactions between two biomolecules. The simulation learning-teaching efficacy was tested in contrast to the traditional PowerPoint slideshow-based instruction concerning the same conceptual content.

ANCOVA analyses were employed to allow for a more robust assessment of the instructional impact of embodied and enactive VR interactions. Additionally, a t-test was used to evaluate differences between groups on post-intervention perceived learning scores.

Conceptual understanding-related results underscore the effectiveness of embodied interactions in VR to foster enhanced conceptual understanding among learners. The substantial observed effect size ($\eta^2 = 0.148$) suggested that embodied VR interactions had a noteworthy impact on post-test conceptual learning scores; thus, strongly aligning this finding with theoretical expectations. It is probable that deliberately controlling the slideshow group's exposure to embodied cues (e.g. natural/accidental iconic gestures performed by a teacher during instruction) by training the teacher to stick to the verbal script contributed to this sizable group effect. This opens up a potential research direction.

The analysis did not yield a significant group effect on post-test intrinsic motivation ratings, implying that VR and slideshow-based scripted lecture did not affect participants' intrinsic motivation directly to the same extent. Nor was there any group difference in terms of post-intervention perceived learning. Yet, there was a significant effect of group on post-intervention self-efficacy ratings, particularly suggesting that VR positively impacted participants' self-efficacy beliefs and their confidence. The effect size ($\eta^2 = 0.13$) indicated a noteworthy magnitude of the VR's impact on post-intervention improvements in self-efficacy. It is not clear why results on intrinsic motivation and perceived learning were inconsistent with our expectations, particularly considering that interest and intrinsic motivation are often believed to be the roots of self-efficacy (Jang, 2008; Kahu et al., 2017); previous work has demonstrated an overall positive relationship between VR experience and affective engagement in comparison to traditional instructional methods.

This preliminary set of analyses merely scratch the surface of the complex relationships between VR-facilitated embodied and enactive interaction, conceptual understanding, and affective aspects related to learning. Further analyses of data may yield important insights into these relationships, and help provide a comprehensive picture on embodied VR's instructional effectiveness. More probing is needed specifically to understand how enactment in VR is affecting intrinsic motivation and perceived learning, and if prior VR experience and/or novelty effect are playing any roles in such settings.

Acknowledgements

Sincere thanks to my former research team (Biljana Mojsosksa, Morten Erik Moeller, Praveen Ramasamy, Per Meyer Jepsen, Jonathan Hvass) at Roskilde University Denmark for collaborating with me on the design and development of the embodied VR simulation used in this study. Special thanks to Søren Larsen for his administrative support during the simulation design and development. Special thanks to the undergraduate students for participating in this study, as well as their amazing professors and college staff for making this pilot study possible.

References

Azer, S. A., & Azer, S. (2016). 3D Anatomy Models and Impact on Learning: A Review of the Quality of the Literature. *Health Professions Education*, *2*(2), 80–98. https://doi.org/10.1016/j.hpe.2016.05.002

Bandura, A. (2001). Social Cognitive Theory: An Agentic Perspective. *Annual Review of Psychology*, *52*(1), 1–26. https://doi.org/10.1146/annurev.psych.52.1.1

Buttussi, F., & Chittaro, L. (2018). Effects of Different Types of Virtual Reality Display on Presence and Learning in a Safety Training Scenario. *IEEE Transactions on Visualization and Computer Graphics*, *24*(2), 1063–1076. https://doi.org/10.1109/TVCG.2017.2653117

Büssing, A. G., Thomsen, D., & Braun, N. (2022). Linking technology usage to instructional quality: Immersive virtual reality increases presence, positive emotions, and cognitive activation. Authors Preprint Accessed at: https://osf.io/preprints/p9esz/.
Checa, D., Miguel-Alonso, I., & Bustillo, A. (2021). Immersive virtual-reality computer-assembly serious game to enhance autonomous learning. *Virtual Reality*. https://doi.org/10.1007/s10055-021-00607-1
Concannon, B. J., Esmail, S., & Roduta Roberts, M. (2019). Head-Mounted Display Virtual Reality in Post-secondary Education and Skill Training. *Frontiers in Education*, *4*. https://doi.org/10.3389/feduc.2019.00080
Gonzalez-Franco, M., & Peck, T. C. (2018). Avatar embodiment. towards a standardized questionnaire. *Frontiers in Robotics and AI*, *5*, 74
Han, I. (2020). Immersive virtual field trips in education: A mixed-methods study on elementary students' presence and perceived learning. *British Journal of Educational Technology*, *51*(2), 420–435. https://doi.org/10.1111/bjet.12842
Jang, H. (2008). Supporting students' motivation, engagement, and learning during an uninteresting activity. *Journal of Educational Psychology*, *100*(4), 798–811. https://doi.org/10.1037/a0012841
Jensen, L., & Konradsen, F. (2018). A review of the use of virtual reality head-mounted displays in education and training. *Education and Information Technologies*, *23*(4), 1515–1529. https://doi.org/10.1007/s10639-017-9676-0
Johnson-Glenberg, M. C. (2018). Immersive VR and Education: Embodied Design Principles That Include Gesture and Hand Controls. *Frontiers in Robotics and AI*, *5*. https://doi.org/10.3389/frobt.2018.00081
Kahu, E., Nelson, K., & Picton, C. (2017). Student interest as a key driver of engagement for first year students. *Student Success*, *8*(2), 55–66. https://doi.org/10.5204/ssj.v8i2.379
Kersting, M., Amin, T. G., Euler, E., Gregorcic, B., Haglund, J., Hardahl, L. K., & Steier, R. (2023). What is the role of the body in science education? A conversation between traditions. *Science & Education*, 1-40.
Klippel, A., Zhao, J., Oprean, D., Wallgrün, J. O., Stubbs, C., la Femina, P., & Jackson, K. L. (2020). The value of being there: toward a science of immersive virtual field trips. *Virtual Reality*, *24*(4), 753–770. https://doi.org/10.1007/s10055-019-00418-5
Kothiyal, A., Majumdar, R., Pande, P., Agarwal, H., Ranka, A., & Chandrasekharan, S. (2014). How does representational competence develop? Explorations using a fully controllable interface and eye tracking, In C.-C. Liu, Y. T. Wu, T. Supnithi, T. Kojiri, H. Ogata, S. C. Kong & A. Kashihara (Eds.), *Proceedings of the 22nd International Conference on Computers in Education,* 738-743. Japan: APSCE.
Landy, D., Allen, C., & Zednik, C. (2014). A perceptual account of symbolic reasoning. *Frontiers in psychology*, *5*, 275.
Lee, E. A. L., Wong, K. W., & Fung, C. C. (2010). How does desktop virtual reality enhance learning outcomes? A structural equation modeling approach. *Computers & Education*, *55*(4), 1424-1442.
Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by Embodiment. *Educational Researcher*, *42*(8), 445–452. https://doi.org/10.3102/0013189X13511661
Luo, H., Li, G., Feng, Q., Yang, Y., & Zuo, M. (2021). Virtual reality in K-12 and higher education: A systematic review of the literature from 2000 to 2019. *Journal of Computer Assisted Learning*, *37*(3), 887–901. https://doi.org/10.1111/jcal.12538
MCGOWIN, G., FIORE, S. M., & ODEN, K. Towards a Theory of Learning in Immersive Virtual Reality: Designing Learning Affordances with Embodied, Enactive, Embedded, and Extended Cognition. *Bridging the XR Technology-to-Practice Gap: Methods and Strategies for Blending Extended Realities into Classroom Instruction*, 35.
Maresky, H. S., Oikonomou, A., Ali, I., Ditkofsky, N., Pakkal, M., & Ballyk, B. (2019). Virtual reality and cardiac anatomy: Exploring immersive three-dimensional cardiac imaging, a pilot study in undergraduate medical anatomy education. *Clinical Anatomy*, *32*(2), 238–243. https://doi.org/10.1002/ca.23292
Makransky, G., Thisgaard, M. W., & Gadegaard, H. (2016). Virtual Simulations as Preparation for Lab Exercises: Assessing Learning of Key Laboratory Skills in Microbiology and Improvement of Essential Non-Cognitive Skills. *PLOS ONE*, *11*(6), e0155895. https://doi.org/10.1371/journal.pone.0155895
Monteiro, V., Mata, L., & Peixoto, F. (2015). Intrinsic Motivation Inventory: Psychometric Properties in the Context of First Language and Mathematics Learning. *Psicologia: Reflexão e Crítica*, *28*(3), 434–443. https://doi.org/10.1590/1678-7153.201528302

Moro, C., Štromberga, Z., Raikos, A., & Stirling, A. (2017). The effectiveness of virtual and augmented reality in health sciences and medical anatomy. *Anatomical Sciences Education*, *10*(6), 549–559. https://doi.org/10.1002/ase.1696
Nathan, M. J. (2021). *Foundations of embodied learning: A paradigm for education*. Routledge.
Pande, P. (2021). Learning and Expertise with Scientific External Representations: An Embodied and Extended Cognition Model, *Phenomenology and the Cognitive Sciences*, (20), 463-482. doi: https://doi.org/10.1007/s11097-020-09686-y
Pande, P., & Chandrasekharan, S. (2017). Representational competence: towards a distributed and embodied cognition account, *Studies in Science Education*, 53(1), 1-43. UK: Routledge. https://doi.org/10.1080/03057267.2017.1248627
Pande, P. & Chandrasekharan, S. (2022). Expertise as Sensorimotor Tuning: Perceptual Navigation Patterns Mark Representational Competence in Science, *Research in Science Education*, 52, 725-747, https://doi.org/10.1007/s11165-020-09981-3
Pande, P., Thit, A., Sørensen, A. E., Mojsoska, B., Moeller, M. E., & Jepsen, P. M. (2021). Long-term effectiveness of immersive vr simulations in undergraduate science learning: Lessons from a media-comparison study. *Research in Learning Technology*, *29*. https://doi.org/10.25304/rlt.v29.2482
Parong, J., & Mayer, R. E. (2020). Cognitive consequences of playing brain-training games in immersive virtual reality. *Applied Cognitive Psychology*, *34*(1), 29–38. https://doi.org/10.1002/acp.3582
Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education*, *147*, 103778. https://doi.org/10.1016/j.compedu.2019.103778
Roy, E., Bakr, M. M., & George, R. (2017). The need for virtual reality simulators in dental education: A review. *The Saudi Dental Journal*, *29*(2), 41–47. https://doi.org/10.1016/j.sdentj.2017.02.001
Skulmowski, A., & Rey, G. D. (2018). Embodied learning: introducing a taxonomy based on bodily engagement and task integration. Cognitive research: principles and implications, 3(1), 1-10.
Stepan, K., Zeiger, J., Hanchuk, S., del Signore, A., Shrivastava, R., Govindaraj, S., & Iloreta, A. (2017). Immersive virtual reality as a teaching tool for neuroanatomy. *International Forum of Allergy & Rhinology*, *7*(10), 1006–1013. https://doi.org/10.1002/alr.21986
Tang, K. S., Cheng, D. L., Mi, E., & Greenberg, P. B. (2019). Augmented reality in medical education: a systematic review. *Canadian Medical Education Journal*. https://doi.org/10.36834/cmej.61705
Teranishi, S. & Yamagishi, Y. (2017). Educational Effects of a Virtual Reality Simulation System for constructing Self-Built PCs. In J. Johnston (Ed.), *Proceedings of EdMedia 2017* (pp. 1214-1222). Washington, DC: Association for the Advancement of Computing in Education (AACE).
Zhao, G., Fan, M., Yuan, Y., Zhao, F., & Huang, H. (2021). The comparison of teaching efficiency between virtual reality and traditional education in medical education: a systematic review and meta-analysis. *Annals of Translational Medicine*, *9*(3), 252–252. https://doi.org/10.21037/atm-20-2785