Guest editorial

Immersive Learning: Current understandings and strategies for success

Introduction: How do immersive experiences influence learning?

Extended reality (XR), which includes augmented and virtual reality, is not new to the classroom, but it is increasingly feasible for a wider number of educators (Pellas *et al.*, 2021; Kaser *et al.*, 2019). This uptake is attributable to a combination of decreased hardware costs, increased performance and expanded software libraries. Importantly, these visualization platforms have profound implications for teaching and learning by providing the means to present physically inaccessible (i.e. distant, fragile, micro/macroscopic, dangerous, etc.) content in context, at human scale and in a way that's responsive to a wide range of body-centered interactions and familiar representational characteristics (Bowman and McMahan, 2007; Kersten-Pertel *et al.*, 2013; Whitlock *et al.*, 2020).

But deploying XR in the classroom isn't merely a technological endeavor. Learning theory is equally important to the student experience. Combined, a range of experiential, situated and embodied learning strategies demonstrate the value of a more targeted, modular approach to the curricular integration of XR-based learning objects. In this special issue, our aim is to document the work of both researchers and educational XR practitioners who are focusing their XR deployment strategies to achieve unique benefits. And, while individual contributors have succeeded here in narrowly focusing their respective XR deployment strategies, the deployment of effective immersive learning experiences do share requirements, including: an investment of time, resources, idiosyncratic implementation practicalities and a reimagining of assessment paradigms (as per Tscholl *et al.*, 2021 in this special issue). We have therefore set out to *triangulate* core aspects of immersive learning; to explore how the careful alignment of learning theories, practical considerations and technical affordances can strategically enable the application of XR to education – at the disciplinary level, but also across fields of study and potentially all levels of learning.

In an effort to balance the focused responses solicited from issue contributors with the general applicability of XR in the classroom, we set out here to answer the following questions:

Q1. What types of learning theories apply most readily to XR?

Q2. What types of learning activities are best supported by XR?

Q3. Where do technological affordances and practical concerns of XR align with these learning theories and activities?

Q4. How can instructors measure XR-assisted learning outcomes regardless of discipline?

Strategic use of immersive experiences requires an understanding of the theoretical, practical and technological considerations shaping educational XR. In this editorial, we will explore learning theories that are particularly salient in XR, review the current state of immersive technology and implications for implementation and finally consider how we can gauge the impact of XR on learning.

Information and Learning Sciences
Vol. 122 No. 7/8, 2021
pp. 433-441

2398-5348
DOI 10.1108/ILS-07-2021-262

Part 1: Learning theories relevant to XR

Any XR developer and enthusiast knows that the first question everyone asks is "Why XR?" (VR or AR). Initial research in whether or not XR supports learning often compares XR technologies to less immersive media such as textbooks, websites and videos (Hamilton *et al.*, 2021; Jensen and Konradsen, 2018; Pellas *et al.*, 2020). This type of comparison has two assumptions. The first assumption is that the comparison media (e.g. slides) is an example of a quality learning tool. The second assumption is that the delivery of the activity (e.g. from 2 D to XR) is equally suitable in either modality for the learning goal. Research needs to move beyond comparison of XR with 2 D alternatives to focus on the unique affordances of XR and to move away from "why" and into "how" to use XR as a learning tool.

Regarding the mechanics of immersive learning, Makransky and Petersen (2021) propose a model of learning that they call *The Cognitive Affective Model of Immersive Learning*. They argue that immersive virtual reality has two primary affordances: presence and agency. Presence, or the feeling of being physically in the environment, is established by the user's perceptions of the environment and the responsiveness of the environment to the user's actions. Agency is the degree of control the user has over the environment. The connection between presence and agency is echoed in other research in immersive learning (Johnson-Glenberg, 2018; Checa and Bustillo, 2020; Pellas *et al.*, 2020). In their review of VR in K12 settings, Pellas *et al.* (2020) assert that the level of presence in the environment is intrinsically linked to the degree of interactivity the user perceives. Checa and Bustillo (2020) note that more research is needed in the effect of presence and agency on learning to enable more strategic approaches in designing learning environments. However, additional contexts where presence and agency can be useful are implied by more established learning theories, which highlight different rationales for the motivation, resources and mechanisms of learning (Radianti *et al.*, 2020). As a way to imagine the types of activities that best match XR designs, we will focus now on three learning theories: experiential, embodied and situational.

XR technologies allow the user to learn through direct experience, well suited to framing the learning in the four step experiential learning process (Kolb, 2014). XR can bring the world to the classroom, thus bringing the students out into the world (Thompson, 2018). Fromm *et al.* (2021) suggested six principles to guide educators and designers. Three of the principles are useful for both educators and designers. Designers and educators should consider how the affordances of VR can be matched to learning objectives (principle of technical and pedagogical considerations) and should leverage the ability for VR to provide low stakes learning and practice for novices (principle of psychological comfort), by creating simulations that permit cycles of trying the VR simulation and applying what is learned to actual experience (principle of integration). Three principles are aimed at designers alone. Designers should create authentic experiences that allow learners to apply theoretical knowledge to practical situations (principle of knowledge contextualization), that enable both "concrete experience and active experimentation" (*p* 10) (principle of realism and interactivity) and using game-based learning to motivate learners (principle of gamification). These principles provide additional guidelines for developers of immersive learning activities.

In situated learning, learners experience the environment and enact the activities of a particular domain as if they were an apprentice (Lave and Wenger, 1991; Collins *et al.*, 1991). Situated learning has helped introduce new pilots to airplane cockpits, novice surgeons to operating rooms (Slater and Sanchez-Vives, 2016) and has even been used in training for fast food (or quick delivery) restaurants (Belani, 2020). Fromm *et al.*'s principle of "knowledge contextualization" matches well here, VR allows learners to step inside of a highly authentic yet virtual work environment to learn and practice skills essential to the job. In addition to authentic virtual environments, high levels of task authenticity can help learners realize situated learning, as discussed in this issue in Mikeska and Howell's study of preservice teachers' perceptions of their learning resulting from a virtual classroom simulation.

Learning with an authentic environment can be enhanced by including the physical activities that individuals would engage in, enabling embodied learning. According to the theory of embodied learning, learning is a full body, not a mind only activity, because cognitive processes are strongly linked to the senses (Weisberg and Newcombe, 2017). Furthermore, this stronger, body-centered link with the lesson may provide a more powerful learning experience because the learner becomes a part of the environment (Kiefer and Trumpp, 2012; Stolz, 2015), and the embodied framing can also offload cognition and thus reduce the cognitive load of the user (Weisberg and Newcombe, 2017). Embodied learning is linked to Fromm *et al.*'s principle of realism and interactivity where the immersive experience allows the learner to engage directly in activities that can help them learn. Embodied cognition can also be integrated into assessment of learning, as Tscholl *et al.* (2021) demonstrate in their study of students' physical intuitions about physics.

Radianti *et al.* (2020) suggest a "generalization of learning methods and design elements" in order to propagate best practices in immersive learning (p. 22). We contend that strategic implementation in XR should include interactive experiences where learning objectives are well suited to the two main affordances of XR: presence and agency. High levels of presence provide users access to experiential learning opportunities even within the limitations of the classroom wall as well as and the rich and realistic environments that support situated learning. Designing XR experiences for agency can include a full body approach to learning using embodied learning. Immersive experiences should be designed to give users authentic exposure to learning situations and enable ongoing practice of skills that educators can then use to bridge between virtual and actual experiences and facilitate transfer from the immersive experience into reality.

Part 2: Practical and technological considerations shaping educational XR

Now we will shift the focus from learning theory to the technology itself. XR provides a suite of affordances specific to virtual reality – head and body tracking technology combined with depth cues afforded by stereoscopic display technology, specifically – that allows students to engage in virtual learning environments using observational techniques that are already familiar to them. Under laboratory conditions, these technological affordances translate to improved performance on task types with generalized applicability across discipline and learning levels (Forsberg *et al.*, 2008; Kersten-Pertel *et al.*, 2013; Laha *et al.*, 2014; Ragan *et al.*, 2012). So instead of having to first learn an interface or control scheme, the XR user can turn their head, bend down or physically walk through a virtual environment to take in or engage with a variety of hyper realistic (and increasingly available) digital contents. As Thompson *et al.* (2021) conclude, in their contribution to this special issue, stereoscopic vision in particular can have a measurable "[P]ositive effect on conceptual learning" (12). The pedagogical usefulness of digital embodiment extends to include mixed reality applications as well as demonstrated by Tscholl *et al.* (2021) contribution to this issue.

Importantly, XR-based objects of study are themselves increasingly faithful to physical source material and technological advances associated with 3D scanning and capture technology (e.g. photogrammetry, MicroCT, structured light, etc.) are hereby informing the creation of virtual environments, as well as populating those environments with high-fidelity learning objects. In combination, these virtual environments and associated learning objects represent the same sorts of perceptual experiences students would encounter if they were in the field or a laboratory or in a museum archive (Pfarr-Harfst, 2016; Limp *et al.*, 2011). Combined into *scenes*, collections of high-definition 3 D objects can also simulate more sophisticated training scenarios, like those documented by Hannans *et al.* (2021) in this special issue, in addition to objects-of-study from scientific ".domains that whose [sic] primary dimensions are spatial" (Donalek, 2014, p. 2).

Beyond specialized professional training experiences, discipline-specific XR is still quite rare, but this isn't necessarily due to a lack of imagination or of available technology. Often, it's the *practical*, *logistical* and *economic* factors that have limited the broad introduction of XR into the K12 classroom (Cook *et al.*, 2019). Body-centered considerations related to simulator sickness, specifically, and human factors, generally, have also slowed uptake, while we are only now (in 2021) witnessing the availability of tetherless headsets, where cables no longer interfere with the immersive experience and PCs are no longer required to render XR experiences. In the absence of cables and outboard graphics processing, large-scale curricular integrations can support hundreds of students during relatively short time periods (Qin *et al.*, 2020). Nor are cost concerns hardware-specific. Even in situations where an instructor is able to deploy one headset per student, there's still a question about what to show. Educators cannot be expected to reinvent their syllabi simply to accommodate XR ambitions, but it's also not clear, which, if any, application ecosystem (e.g. Steam, Oculus Store, etc.) or specialized vendor software might readily target the learning outcomes of a preestablished lesson.

As an alternative, experimental classrooms have integrated single (or small sets of) learning objects from existing 3 D asset repositories, like Morphosource, Sketchfab,\ or the NIH 3 D Print Exchange and others; micro-experiences that make use of existing or easily produced contents, which might lack the sort of gamification or other functionality that students have come to expect of what is perceived as videogame technology (Lischer-Katz *et al.*, 2018; Dede *et al.*, 2017; Greene and Groenendyk, 2019; Jang *et al.*, 2017) [1]. These targeted integrations are supported by a small number of versatile "productivity-grade" XR applications – open ended sandboxes where data from any field can quickly enter and exit the virtual world, regardless whether that data represents a design idea, abstract data visualization or real-world object or specimen (Mills, 2020; Cook and Lischer-Katz, 2021).

As educators we are at a very significant point. While the private sector is employing hundreds of highly trained engineers and spending billions of dollars to ensure that high-production value entertainment products are surfaced on accessible headset hardware, students and teachers are resigned to accessible but mentally taxing content delivery platforms (e.g. Zoom) that can be implemented at scale in the COVID-era. But a handful of customizable XR applications now provide for drag-and-drop lesson design capabilities while current-generation portable headset hardware, like the Oculus Quest 2, affords the student with a generally comfortable viewing experience. Our mandate – as educators and researchers – is therefore two-fold: We do as the contributors to this special issue have done and construct (and encourage the construction of) targeted virtual experiences that blend seamlessly with the curriculum and, in the case of Tu *et al.* (2021), the physical world as well. We must also empower our students with the hardware and software to engage with these experiences. Fortunately, the technology already exists to move forward; the technical training, administrative support and energy to enact these changes will follow suit.

Part 3: Measuring the impact of immersive learning

As we've seen, to successfully leverage the specific affordances associated with XR requires that an instructor thoughtfully aligns the curriculum with the pedagogical, practical and technological considerations of the tool. Importantly, each aspect of immersive learning is (and must be) measurable to some extent, so downstream analysis can be performed by researchers to determine where exactly a given XR integration succeeded or failed and how such experiences might be refined and expanded.

Yet the assessment mechanisms that researchers have developed to investigate XR differ fundamentally from traditional, in-class methods, which, as contributors Tscholl *et al.* (2021), note "[R]ely on representational formats enveloped into task contexts that, at best, superficially resemble the situations people encounter in their everyday lives". So, while the following data gathering methods represent potential research agendas, they may be challenging for educators as they do require a conceptual shift from "paper-and-pencil" measurement techniques to a body-centered set of data gathering methods.

To begin, eye-movement can be tracked with increasing granularity using third third-party technologies that integrate with headset hardware (Sipatchin *et al.*, 2021). Emerging primarily from engineering fields like computer science and human computer interaction, task load and performance outcomes both represent validated metrics for determining the efficacy of XR in the classroom (LaViola *et al.*, 2017; Bharathan *et al.*, 2013; Hart, 2006). In the laboratory, data gathering is often automated through the use of customized software, but, as Tu *et al.* (2021) show in the current special issue, video analysis can also be employed to track performance of students completing a given task.

Importantly, these methods require that instructors deploy XR in conjunction with narrowly defined assignments or modules, with specific start and end points, which allows performance to be measured across quantitative dimensions related to time and accuracy of output. To maximize rigor, researchers measuring performance or task load will also need to implement and track control group performance, which presents experimental design challenges unique to XR, since equivalent course content distribution methods (e.g. lecture, textbook, multimedia) themselves vary with regards to efficacy (see: Part 1, above).

Qualitative instruments and self-reports are another established way to gather data and measure the impact of XR in the classroom. Interrelated constructs have also been deployed successfully, at the pilot or preliminary research stage, including data gathering tools designed to gauge engagement and self-efficacy of student users (Mills, 2020; Brinkerhoff, 2006). Coded observational techniques, like those employed by Brenner *et al.* (2021) in this special issue, represent another rich, if labor intensive, qualitative data gathering strategy. Stepping away from a focus on course material, it's also possible (and important) to test the usability of a given XR implementation as well as the prior spatial abilities of student users, including video game experience, as these factors might confound data gathered via other means (Brooke, 2013; Kennedy *et al.*, 1993; Yoon, 2011; Jang *et al.*, 2017; Wagner *et al.*, 2021).

Concluding remarks

The articles included here represent a viable way forward for educational XR, and moreover, it's increasingly clear that contemporary deployments can only be successful to the extent that their integration can be circumscribed, gauged and disseminated. As the authors in this issue have demonstrated, when learning objectives are well matched to the affordances of XR, the applications of XR transcend discipline, learning level and specific hardware platforms. Although potential applicability is capacious, there are touchstones; common, foundational elements that define each and every XR integration such as the role of presence and agency, the ability to support experiential, situated and embodied learning and the potential for giving learners access to virtual experiences as "safe spaces" for learning and practice. Would-be XR-assisted instructors, designers and researchers must familiarize themselves with the learning theory, technology and data gathering tools necessary to both implement and achieve strategic learning with XR.

Matthew Cook
Harvard Library, Harvard University, Cambridge, Massachusetts, USA, and
Meredith Thompson
The Education Arcade, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Note

1. Morphosource.org;Sketchfab.com;https://3dprint.nih.gov/

References

Belani, M. (2020), April. “Evaluating virtual reality as a medium for vocational skill training”, in *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1-8.

Bharathan, R., Vali, S., Setchell, T., Miskry, T., Darzi, A. and Aggarwal, R. (2013), “Psychomotor skills and cognitive load training on a virtual reality laparoscopic simulator for tubal surgery is effective”, *European Journal of Obstetrics and Gynecology and Reproductive Biology*, Vol. 169 No. 2, pp. 347-352.

Bowman, D.A. and McMahan, R.P. (2007), “Virtual reality: how much immersion is enough?”, *Computer*, Vol. 40 No. 7, pp. 36-43.

Brenner, C., DesPortes, K., Ochoa Hendrix, J. and Holford, M. (2021), “GeoForge: investigating integrated virtual reality and personalized web sites for collaboration in Middle school science”, *Information and Learning Sciences*.

Brinkerhoff, J. (2006), “Effects of a long-duration, professional development academy on technology skills, computer self-efficacy, and technology integration beliefs and practices”, *Journal of Research on Technology in Education*, Vol. 39 No. 1, pp. 22-43.

Brooke, J. (2013), “SUS: a retrospective”, *Journal of Usability Studies*, Vol. 8 No. 2, pp. 29-40.

Checa, D. and Bustillo, A. (2020), “A review of immersive virtual reality serious games to enhance learning and training”, *Multimedia Tools and Applications*, Vol. 79 Nos 9/10, pp. 5501-5527.

Collins, A., Brown, J.S. and Holum, A. (1991), “Cognitive apprenticeship: making thinking visible”, *American Educator*, Vol. 15 No. 3, pp. 6-11.

Cook, M., Lischer-Katz, Z., Hall, N., Hardesty, J., Johnson, J., McDonald, R. and Carlisle, T. (2019), “Challenges and strategies for educational virtual reality”, *Information Technology and Libraries*, Vol. 38 No. 4, pp. 25-48.

Cook, M. and Lischer-Katz, Z. (2021), “Practical steps to an effective virtual reality course integration”, *(forthcoming) in College and Undergraduate Libraries. Special Issue*.

Dede, C.J., Jacobson, J. and Richards, J. (2017), “Introduction: virtual, augmented, and mixed realities in education”, in *Virtual, Augmented, and Mixed Realities in Education*, (pp. 1-16). Springer, Singapore.

Donalek, C., Djorgovski, S.G., Cioc, A., Wang, A., Zhang, J., Lawler, E., Yeh, S., Mahabal, A., Graham, M., Drake, A. and Davidoff, S. (2014), “Immersive and collaborative data visualization using virtual reality platforms”, *In Proceedings of 2014 IEEE International Conference on Big Data, IEEE*, pp. 609-614.

Forsberg, A., Katzourin, M., Wharton, K. and Slater, M. (2008), "A comparative study of desktop, fishtank, and cave systems for the exploration of volume rendered confocal data sets", *IEEE Transactions on Visualization and Computer Graphics*, Vol. 14 No. 3, pp. 551-563.

Fromm, J., Radianti, J., Wehking, C., Stieglitz, S., Majchrzak, T.A. and Vom Brocke, J. (2021), "More than experience? On the unique opportunities of virtual reality to afford a holistic experiential learning cycle", *The Internet and Higher Education*, Vol. 50, p. 100804.

Hamilton, D., McKechnie, J., Edgerton, E. and Wilson, C. (2021), "Immersive virtual reality as a pedagogical tool in education: a systematic literature review of quantitative learning outcomes and experimental design", *Journal of Computers in Education*, Vol. 8 No. 1, pp. 1-32, doi: 10.1007/s40692-020-00169-2.

Hannans, J., Colleen, N. and Kristin, J. (2021), "See it, hear it, feel it: embodying a patient experience through immersive virtual reality", *Information and Learning Sciences*, Vol. 122 No. 7/8.

Hart, S.G. (2006), "NASA-task load index (NASA-TLX); 20 years later", *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 50 No. 9, pp. 904-908.

Jang, S., Vitale, J.M., Jyung, R.W. and Black, J.B. (2017), "Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment", *Computers and Education*, Vol. 106, pp. 150-165.

Jensen, L. and Konradsen, F. (2018), "A review of the use of virtual reality head-mounted displays in education and training", *Education and Information Technologies*, Vol. 23 No. 4, pp. 1515-1529, available at: https://link.springer.com/article/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*, Vol. 5, p. 81.

Kaser, D., Grijalva, K. and Thompson, M. (2019), *Envisioning Virtual Reality: A Toolkit for Implementing VR in Education*, Lulu Press, Inc.

Kersten-Pertel, M., Chen, S.J.S. and Collins, D.L. (2013), "An evaluation of depth enhancing perceptual cues for vascular volume visualization in neurosurgery", *IEEE Transactions on Visualization and Computer Graphics*, Vol. 20 No. 3, pp. 391-403.

Kennedy, R.S., Lane, N.E., Berbaum, K.S. and Lilienthal, M.G. (1993), "Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness", *The International Journal of Aviation Psychology*, Vol. 3 No. 3, pp. 203-220.

Kiefer, M. and Trumpp, N.M. (2012), "Embodiment theory and education: the foundations of cognition in perception and action", *Trends in Neuroscience and Education*, Vol. 1 No. 1, pp. 15-20, doi: 10.1016/j.tine.2012.07.002.

Kolb, D.A. (2014), *Experiential Learning: Experience as the Source of Learning and Development*, FT press.

Laha, B., Bowman, D.A. and Socha, J.J. (2014), "Effects of VR system fidelity on analyzing isosurface visualization of volume datasets", *IEEE Transactions on Visualization and Computer Graphics*, Vol. 20 No. 4, pp. 513-522.

LaViola, J.J., Jr, Kruijff, E., McMahan, R.P., Bowman, D. and Poupyrev, I.P. (2017), *3D User Interfaces: theory and Practice*, Addison-Wesley Professional.

Lave, J. and Wenger, E. (1991), *Situated Learning: Legitimate Peripheral Participation*, Cambridge university press.

Limp, F., Payne, A., Simon, K., Winters, S. and Cothren, J. (2011), "Developing a 3-D digital heritage ecosystem: from object to representation and the role of a virtual museum in the 21st century", *Internet Archaeology*, Vol. 30 No. 30, pp. 1-38.

Lischer-Katz, Z., Cook, M. and Boulden, K. (2018), "Evaluating the impact of a virtual reality workstation in an academic library: methodology and preliminary findings", *Proceedings of the Association for Information Science and Technology*, Vol. 55 No. 1, pp. 300-308.

Makransky, G. and Petersen, G.B. (2021), "The cognitive affective model of immersive learning (CAMIL): a theoretical research-based model of learning in immersive virtual reality", *Educational Psychology Review*, pp. 1-22.

Mills, N. (2020), "11 Engagement and immersion in virtual reality narratives. Student engagement in the language classroom".

Pellas, N., Mystakidis, S. and Kazanidis, I. (2021), "Immersive virtual reality in K-12 and higher education: a systematic review of the last decade scientific literature", *Virtual Reality*, pp. 1-27.

Pellas, N., Dengel, A. and Christopoulos, A. (2020), "A scoping review of immersive virtual reality in STEM education", *IEEE Transactions on Learning Technologies*, Vol. 13 No. 4, doi: 10.1109/TLT.2020.3019405.

Pfarr-Harfst, M. (2016), "Typical workflows, documentation approaches and principles of 3D digital reconstruction of cultural heritage", In *3D Research Challenges in Cultural Heritage II*, Springer, Cham, pp. 32-46.

Qin, T., Cook, M. and Courtney, M. (2020), "Exploring chemistry with wireless, PC-Less portable virtual reality laboratories", *Journal of Chemical Education*, Vol. 98 No. 2.

Radianti, J., Majchrzak, T.A., Fromm, J. and Wohlgenannt, I. (2020), "A systematic review of immersive virtual reality applications for higher education: design elements, lessons learned, and research agenda", *Computers and Education*, Vol. 147, p. 103778.

Ragan, E.D., Kopper, R., Schuchardt, P. and Bowman, D.A. (2012), "Studying the effects of stereo, head tracking, and field of regard on a small-scale spatial judgment task", *IEEE Transactions on Visualization and Computer Graphics*, Vol. 19 No. 5, pp. 886-896.

Sipatchin, A., Wahl, S. and Rifai, K. (2021), "Eye-Tracking for clinical ophthalmology with virtual reality (VR): a case study of the HTC vive pro eye's", *Healthcare*, Vol. 9 No. 2, p. 180.

Slater, M. and Sanchez-Vives, M.V. (2016), "Enhancing our lives with immersive virtual reality", *Frontiers in Robotics and AI*, Vol. 3, p. 74.

Stolz, S.A. (2015), "Embodied learning", *Educ. Philos. Theory*, Vol. 47, p. 47, doi: 10.1080/00131857.2013.879694.

Thompson, M. (2018), "Making virtual reality a reality in today's classrooms", *The Journal: Transforming Education Through Technology*, available at: https://thejournal.com/articles/2018/01/11/making-virtual-reality-a-reality-in-todays-classrooms.aspx

Thompson, M., Cigdem, B., Tutwiler, M., Melat, A., Josephine, M., Annie, W., Philip, T., Richard, E., Dan, R., Judy, P. and Eric, K. (2021), "Stereoscopic views in a virtual reality game positively affect learning compared to an equally interactive 2D game", *Information and Learning Sciences*, Vol. 122 Nos 7/8.

Tscholl, M., Morphew, J. and Lindgren, R. (2021), "Inferences on enacted understanding: using immersive technologies to assess intuitive physical science knowledge", *Information and Learning Sciences*.

Tu, X., Georgen, C., Danish, J. and Enyedy, N. (2021), "Elementary students learning science in a MR environment by constructing liminal blends through action on props", *Information and Learning Sciences*.

Wagner, J., Stuerzlinger, W. and Nedel, L. (2021), "The effect of exploration mode and frame of reference in immersive analytics", *IEEE Transactions on Visualization and Computer Graphics*.

Weisberg, S.M. and Newcombe, N.S. (2017), "Embodied cognition and STEM learning: overview of a topical collection in CR: PI", *Cognitive Research: Principles and Implications*, Vol. 2 No. 1, p. 38, doi: 10.1186/s41235-017-0071-6.

Whitlock, M., Smart, S. and Szafir, D.A. (2020), "Graphical perception for immersive analytics", *In 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, *IEEE*, pp. 616-625.

Yoon, S.Y. (2011), "Psychometric properties of the revised purdue spatial visualization tests: visualization of rotations (the revised PSVT: R)", Purdue University.

Further reading

Alliez, P., Bergerot, L., Bernard, J.F., Boust, C., Bruseker, G., Carboni, N., Chayani, M., Dellepiane, M., Dell'unto, N., Dutailly, B. and Gautier, H. (2017), "Digital 3D objects in art and humanities: challenges of creation, interoperability and preservation", *White paper*. In *Digital 3D Objects in Art and Humanities: challenges of creation, interoperability and preservation*, p. 71.

Cook, M. and Lischer-Katz, Z. (2019), "Integrating 3D and virtual reality into research and pedagogy in higher education", *Beyond Reality: Augmented, Virtual, and Mixed Reality in the Library*, pp. 69-85.

Trelease, R.B. and Rosset, A. (2008), "Transforming clinical imaging data for virtual reality learning objects", *Anatomical Sciences Education*, Vol. 1 No. 2, pp. 50-55.