TITLE: Enhancing motivation to learn about the ocean through VR underwater field skills in a Higher Education setting

AUTHORS: Sally A. Keith[1]*, Laura-Li Jeannot[1], Emma McKinley[2], Geraldine Fauville[3] and Erika S. Woolsey[4,5]

AUTHOR AFFILIATIONS:

[1]Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK

[2]School of Earth and Environmental Sciences, Cardiff University, CF10 3AT, Wales, UK.

[3]Department of Education, Communication and Learning, University of Gothenburg, Gothenburg, Sweden

[4]The Hydrous, San Francisco, California, USA

[5]Virtual Human Interaction Lab, Stanford University, Palo Alto, California, USA

*corresponding author sally.keith@lancaster.ac.uk; ORCID 0000-0002-9634-2763

CO-AUTHOR EMAIL ADDRESSES: l.jeannot@lancaster.ac.uk; McKinleyE1@cardiff.ac.uk; geraldine.fauville@gu.se; erika@thehydro.us

ABSTRACT: Virtual Reality (VR) is increasingly recognised as a tool for enhancing engagement and motivation in education. This is particularly true where access to experiential learning is limited, as is often the case in marine ecology courses. However, evaluations of the effectiveness of VR as a teaching and learning tool in higher education is limited. Here, we use the *Explore* experience developed by The Hydrous combined with a post-experience questionnaire to test (1) the impact of the experience on self-reported motivation to learn, knowledge consolidation and motivation for pro-environmental behaviour (PEB); (2) the influence of small group discussion immediately after the experience (treatment) on these outcomes; and (3) whether individual motivation either to learn or for PEB could be predicted by sensory experience, cybersickness, ease of use, presence, or whether computer-generated imagery (CGI) detracted from the experience relative to if the footage had been real. We found that students (n=48) had overall positive responses to the VR experience regardless of whether they participated in a small discussion group, reporting increased motivation to learn, increased motivation for PEB and knowledge consolidation. Positive responses were predicted by positive sensory experience, with those students who reported stimulation (as opposed to overload) also experiencing the most positive outcomes in motivation and consolidation. Our study demonstrates that integrating VR into a real higher education course can enhance student motivation, support knowledge consolidation, and foster PEB. The findings align with learning theories suggesting that VR experiences promote active engagement, intrinsic motivation, and deeper cognitive processing. Our results highlight VR's potential as an effective tool in higher education, providing insights for future VR applications not only in marine science learning but also in fostering lifelong global citizenship.

KEYWORDS: coral reef, ecology, undergraduate, questionnaire, discussion, virtual reality, ocean literacy, empathy, immersive learning

INTRODUCTION

Virtual Reality (VR) has emerged as a powerful tool for enhancing student engagement and motivation in education, particularly in STEM disciplines that rely heavily on experiential learning and the visualisation of phenomenon often invisible to the naked eye (Makransky et al., 2019; Shute et al., 2017). However, research on the use of VR in Higher Education (HE) is limited (Bermejo et al., 2023; Radianti et al., 2020). VR environments have the potential to be particularly useful in ecology studies, as they allow students to explore complex ecological systems, observe species interactions, and simulate fieldwork in ways that are often otherwise be impractical due to logistical, financial, or safety constraints (Morimoto & Ponton, 2021; Ou et al., 2021; Poland et al., 2003; Tarng et al., 2015). Considering the role of VR in HE is particularly important for increasing access to the natural world because opportunities for exposure to field experiences and their associated skills are decreasing rapidly (Morimoto & Ponton, 2021), resulting in an "extinction of experience" among ecologists (Soga & Gaston).

Evidence suggests that the effectiveness of VR to increase motivation to learn is affected by presence — the psychological feeling of being in a different location (Sanchez-Vives & Slater, 2005) — and immersion, which refers to how well a user's physical movements and interactions are translated into the virtual space (Markowitz et al., 2018). When designed effectively, the psychological effects of these elements for increasing feelings of proximity to an event (i.e., Construal Level Theory (Trope & Liberman, 2010)) can make learning experiences more engaging and memorable, encouraging deeper cognitive processing of ecological concepts. However, immersion and presence must be balanced against ease of use, excessive sensory input leading to cognitive overload, and negative side effects of cybersickness (Radianti et al., 2020). The balance is likely to vary across different VR platforms and design choices, requiring careful consideration and testing for VR experiences (Radianti et al., 2020).

Beyond motivation to learn, VR-based experiences may also play a crucial role in consolidating previously taught material, fostering long-term knowledge retention (Radianti et al., 2020). The degree to which VR achieves increased motivation and consolidation in an ecological context is likely to depend on factors such as the realism of the virtual environment, interactivity, and alignment with course curricula. However, it remains unclear whether students prefer virtual ecosystems created with computer-generated imagery (CGI) or real-world 360-degree video footage, making it difficult to determine the most effective content design for ecological education. Additionally, given the intrinsic link between ecology and conservation, VR has the potential to enhance students' environmental stewardship (Blythe et al., 2021). While evidence suggests that immersive experiences can strengthen emotional connections to nature and encourage pro-environmental behaviour (PEB) (Calil et al., 2021; Sahabuddin & Makkasau, 2024), the extent to which VR fosters real-world conservation action remains an open question (Blythe et al., 2021). Addressing these gaps will be critical in optimizing the use of VR in university HE ecology courses, ensuring that virtual experiences are not only engaging but also pedagogically effective and impactful in shaping students' environmental perspectives.

Historically, VR experiences have been solitary. Therefore, we were interested in whether following the experience with small group discussions could enhance learning. Group discussions of this type provide the opportunity to critically reflect on the experience and link it more strongly to prior learning; yet, the effectiveness of combining small group discussions with a VR experience has been minimally tested. For instance, undergraduate nursing students found a discussion group after VR "expanded and deepened their learning", providing the opportunity to hear different perspectives on the experience, but this evaluation was limited to qualitative interviews with five students (Kuwabara et al., 2025).

One area of ecology that is particularly difficult to access, precluding the opportunity to develop field skills and undertake inspirational transformative experiences, is in the marine realm. The world's ocean covers more than 70% of the world's surface, hold 97% of

Earth's water, and play crucial roles in the health of the planet and the livelihood of humans by, for example, regulating the climate (Zanna et al., 2019), providing food (Costello et a., 2020), supporting a number of industries (OECD, 2016), and contributing to physical, mental and emotional well-being (White et al., 2010). In 2021, the UN Decade of Ocean Science for Sustainable Development (hereafter, the UN Ocean Decade) was launched in an attempt to reverse the decline of ocean health and restore human-ocean relationships. To achieve this, the UN Ocean Decade has positioned enhancing ocean literacy, defined as having an understanding of the ocean's influence on your and influence on the ocean, as a key mechanism for change. However, with roots firmly in the field of marine education, and increasingly within marine social sciences (McKinley et al., 2022), there is a need to raise awareness within ecology to foster the transdisciplinarity needed to achieve this. This will require efforts to increase ecology students' motivation to learn and connect with the oceans, even when access is limited. VR offers one way to achieve this goal.

While most of the research investigating the use of VR in education takes place in highly controlled settings, the naturalistic dimension of "VR in the wild" has been difficult to capture so far (Galeote et al., 2023). Indeed, the VR and education community is starting to call for more research on the feasibility, design and impact of VR in education in real-world settings (Fauville & Plechata, 2025; Wang & Bailenson, 2025). This study contributes to this call for research in the wild by investigating the impact a VR activity can have in a HE marine course. Students (n=48) on a 3rd year undergraduate Coral Reef Ecology module in a UK university took part in *Explore* - a 10-15 minute freely available underwater VR experience developed by non-profit company The Hydrous, US - using metaquest headsets. Students were asked to complete a voluntary questionnaire on their experience either before (control) or after (treatment) small group discussions that aimed to link the experience more strongly to module content and increase the level of the learning outcomes. Specifically, we asked whether: (1) the *Explore* experience led students to self-report an increase in motivation to learn, knowledge consolidation of course material, and motivation to engage in pro-environmental behaviour (PEB); (2) the inclusion of small group discussion immediately after the experience (treatment) enhanced these outcomes; and (3) self-reported motivation either to learn or for PEB could be predicted at an individual level by sensory experience, cybersickness, ease of use, presence, or CGI acceptance.

MATERIALS & METHODS

Materials

The VR experience was created by The Hydrous, a US based nonprofit on a mission to generate ocean literacy and ocean empathy for global marine stewardship, which leads "The Decade of Ocean Empathy," an official U.N. programme through the Decade of Ocean Science. As part of this programme, The Hydrous created *The Hydrous presents: Explor*e, an interactive CGI-based VR experience for the research project "Advancing Ocean Literacy with Immersive Virtual Reality," a collaboration between The Hydrous, Horizon Productions, and Stanford University's Virtual Human Interaction Lab, funded by the National Science Foundation (NSF) through the Advancing Informal STEM Learning (AISL) program. In *Explore*, the participant uses their hand controllers (they see their hands wearing dive gloves in the experience) to tag and track manta rays (Fig. 1) and identify them using a database, find global "hotspots" from outer space where corals are at risk of bleaching, and monitor species richness on a coral reef over time. The experience was developed for the HTC Focus 3 in 2021, and was later updated and improved for the Quest 2 in 2022. In 2021, it was an official selection for the Cannes World Film Festival, where it was the Grand Winner for Best Virtual Reality Short, and was also selected for the Tokyo International Short Film Festival. *Explore* is a free experience that can be downloaded by anyone with compatible VR headsets, and while The Hydrous has used and evaluated the experience with learners and educators in informal science centers and libraries, targeting middle and high school students, and its effectiveness in contributing to understanding of, and empathy for, the ocean for users (Inverness Research Inc., 2022), *Explore* has yet to be tested in a HE setting.

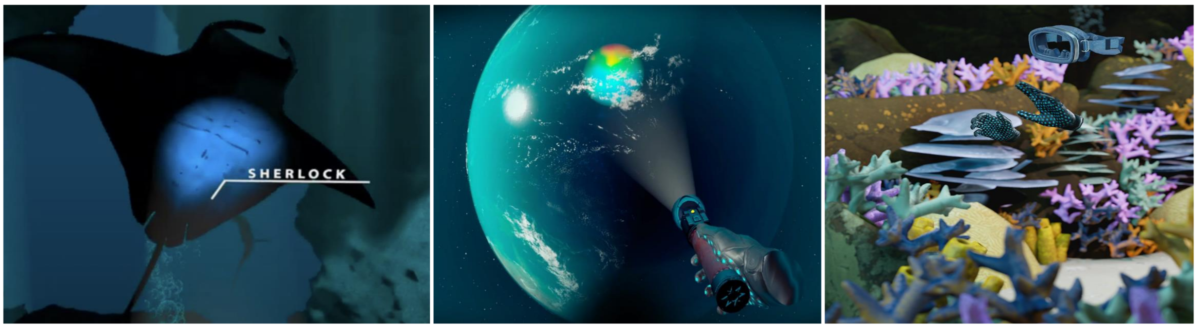

Figure 1. A screen grab of an *Explore* module in which the learner photographs manta rays and identifies them from their markings (left), a screen grab of a module in which the learner monitors sea surface temperatures from space (center) and a scene depicting the learner's hands and dive mask (right).

Methods

Participants: 48 students from a 3rd year undergraduate Coral Reef Ecology course participated in a virtual reality (VR) dive experience as part of their module content. Students were randomly allocated to either the control (16) or treatment (32) and asked to complete a questionnaire about their experience. As this was a real university cohort, gender and age were protected characteristics. Ethics approval was granted by the Faculty Research Ethics Committee at Lancaster University (reference FST-2024-4775-RECR-5).

Treatment: To test whether student motivation and perception of consolidation of prior course material was enhanced by follow-on small group discussions around the experience, we assigned students to either control, where the discussion was delivered after filling out the questionnaire, or treatment, where the students engaged in the discussion before filling out the questionnaire. Discussion questions are provided in the Supplementary Material (Supplementary Material, Appendix 1).

VR delivery: Lancaster University's Data Immersion Suite (DIS) is equipped with a 270-degree wrap-around screen and 20 VR headsets, allowing immersive VR to be incorporated into teaching. We used the DIS to deliver *Explore* as the first use of VR in teaching at Lancaster University. Students were assigned to one of three groups. Groups were size limited due to the 23-person maximum capacity of the DIS. A briefing was provided in advance of the sessions outlining the use of VR in conservation by The Hydrous, describing risks and medical warnings, advice on how to use the headset and how to navigate the experience. For each session in the DIS, 14-16 students attended - some assigned to that group did not attend because they were unable to participate due to medical reasons identified in the briefing and were instead offered an alternative AR experience. The 270-degree wrap-around screens displayed videos recorded statically on coral reefs during the entire experience, providing a semi-immersive experience.

Students were assigned to "buddy pairs" to ensure one student could safely engage in the experience without walking into any obstacles and that help was available immediately if any students experienced nausea or dizziness. Buddy pairs also simulate the buddying within dive experiences (Richardson et al., 2008). The students then followed a series of instructions, read by their buddy (Supplementary Material, Appendix 2), to navigate the experience and complete the three tasks. After UV sterilisation of the headset for 3 minutes, the second member of the buddy pair engaged in the experience.

Small discussion groups were organised with 4-6 students and one coral reef researcher either before (treatment) or after (control) the questionnaire was filled out. Questions (see Appendix 1) were designed to link the VR experience to material taught earlier in the course. This included the advantages and disadvantages of different methods to measure coral richness, and to further explore topics raised through the experience such as the contexts in which it is useful to tag and track animals individually, among other topics.

Post experience questionnaire: The participants were invited to answer a short questionnaire following the VR experience. It consisted of eight questions with all answers using a likert scale from 1-10. The questionnaire was voluntary and anonymous, following all ethical guidelines including provision of a participant information sheet, consent form and debrief sheet. All questions were self-reported aspects of the students' experience. The survey included the following eight questions based on key aspects of VR experiences identified in HE (Bermejo et al., 2023; Huang et al., 2010; Makransky et al., 2019; Markowitz et al., 2018; Queiroz et al., 2022; Radianti et al., 2020; Sahabuddin & Makkasau, 2024):

1. *Learning Motivation:* "How do you feel that this experience has changed your motivation to learn about coral reef ecology?" (1 = strongly decreased, 10 = strongly increased)
2. *Knowledge Consolidation:* "How much did the experience consolidate and/or expand your learning from workshops 1 and 2? (1 = strongly decreased, 10 = strongly increased)"
3. *Sensory Experience*: How would you describe the sensory experience? (1 = negative (overloaded), 10 = positive (stimulated))
4. *Cybersickness*: "To what extent did you experience negative physical side effects such as nausea or dizziness?" (1 = none, 10 = severe)
5. *Ease of Use*: "How usable did you find the technology?" (1 = easy to use, 10 = difficult to use)
6. *Presence*: "To what extent did you feel immersed in the virtual experience?" (1= not at all, 10 = fully immersed)
7. *CGI Acceptance*: "To what extent do you think the use of CGI rather than real footage detracted from your emotional connection with the experience?" (1 = strongly detracted, 10 = not at all)
8. *Pro-environmental behaviour (PEB) Motivation*: "To what extent has this experience affected your motivation to protect the oceans and participate in conservation action?" (1 = strongly decreased, 10 = strongly increased)

Statistical analysis: Scores for cybersickness and ease of use were reversed to enable the 1-10 score to consistently range from most negative (1) to most positive (10). To analyse whether the VR experience had a positive effect on students' self-reported motivation to learn about coral reef ecology, knowledge consolidation, and motivation for PEB, we fitted Bayesian hierarchical models using the brms package in R (R Development Core Team, 2019). Bayesian models allow strong inference from small uneven sample sizes and have the advantage of visualising the full probability distribution rather than being restricted to a single p value. These models are widely used in ecology (Hooten & Hobbs, 2015).

Separate models were created for each key variable: motivation to learn (Q1), knowledge consolidation (Q2), and motivation for PEB (Q8). The models were specified as shown in (E1). Group was included as a random effect to account for potential group-level clustering.

$$Yi \sim Normal(\mu i, \sigma)$$

(E1) $\mu i = Intercept + (1 \mid Group)$

(E2) $\mu i = Treatment + (1 \mid Group)$

(E3) $\mu i = Sensory\ Experience\ +\ Cybersickness +\ Ease\ of\ use\ +\ Presence +$
$CGI\ acceptance\ +\ (1 \mid Group)$

Posterior distributions were estimated with 3,000 iterations, and convergence was monitored using standard diagnostics, including Rhat and effective sample size (Stan Development Team, 2016). For each model, we examined the posterior distribution of the intercept to assess whether it exceeded the midpoint of the scale (>5), corresponding to high confidence in a positive response from individuals. Hypotheses were tested using the hypothesis function, and results are reported as posterior probabilities. Posterior predictions were visualized for each variable using 1,000 draws from the posterior distribution.

We also investigated the effect of treatment against control for each of these variables, with identical model specifications and posterior checks (E2). We then focused on the predictors for motivation to learn about coral reef ecology, knowledge consolidation, and motivation for PEB. For this, five predictors were chosen: sensory experience, cybersickness, ease of use, presence and CGI acceptance (E3). The contribution of each predictor to the response variable was visualized using the posterior distributions of the coefficients of these predictors. Finally, students' perception of the use of CGI rather than real-world footage was evaluated by assessing the overall mean response from the posterior distribution of the intercept (E1).

ChatGPT was used to suggest a draft introduction and discussion structure for this manuscript.

RESULTS

Seven of the eight questions received a mean and median score >5, indicating an overall positive experience was self-reported (note that hereon in all measures are self-reported) for motivation to learn, knowledge consolidation and motivation for PEB (Fig.2, Table S1 Supplementary Material). The only exception was for Q7 CGI acceptance, which had a median of 5 and a mean of 5.13, with a large amount of variation in response. The greatest variation in responses were observed for ease of use and CGI acceptance, which both ranged from 1 to 10, followed by sensory experience and presence, which ranged from 2-10 (Fig. 2, Table S1). In contrast, motivation to learn and for PEB both ranged from 5-10 indicating that no negative responses were recorded (Fig. 2, Table S1).

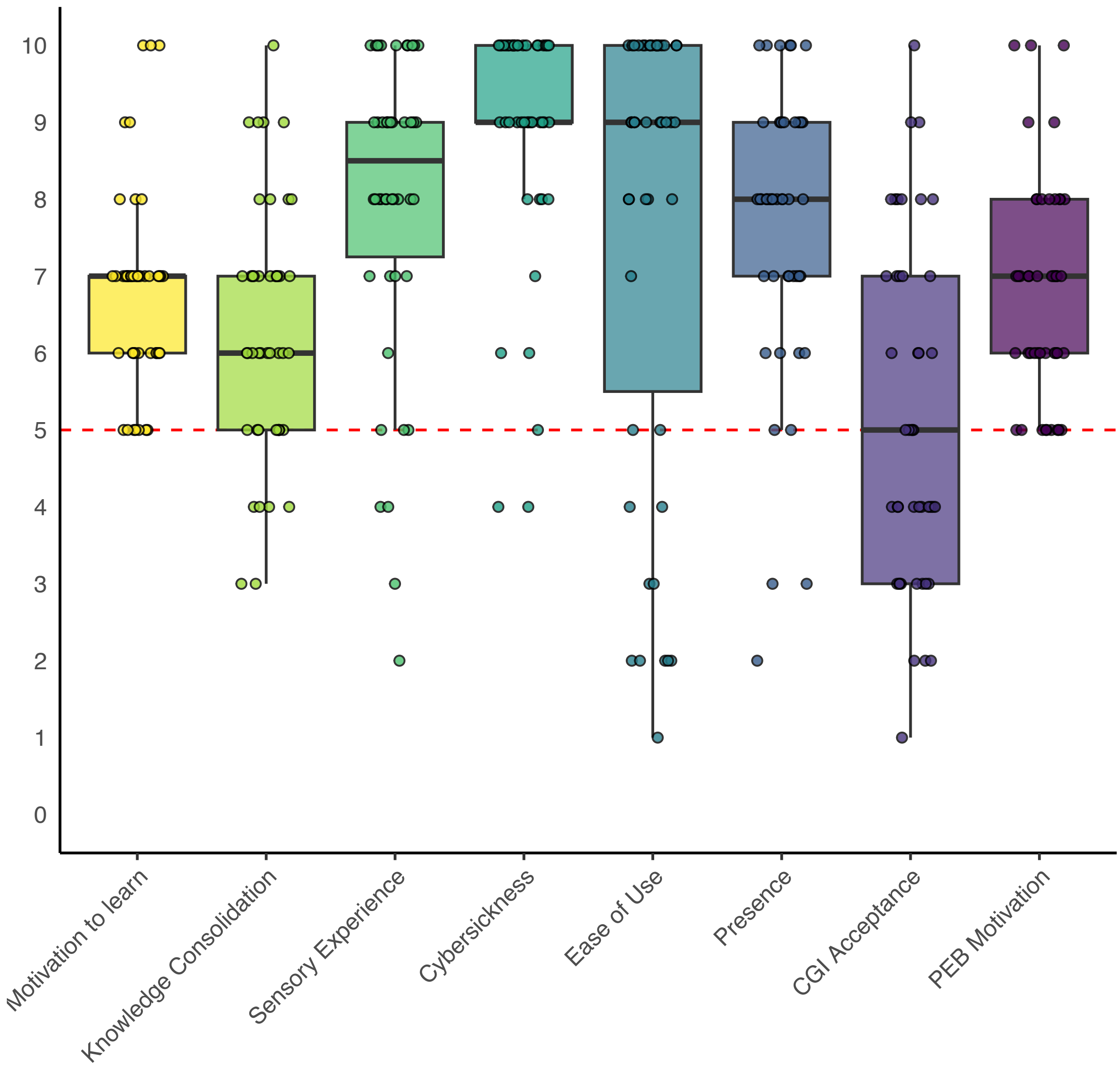

Figure 2. Responses to the eight questions of the post-experience survey pooled for treatment and control. Note that cybersickness has been reversed so positive values indicate lower cybersickness scores. Boxes represent an interquartile range (IQR) from 25%-75%, lines represent the median and whiskers extend to 1.5 times the IQR.

Specifically, there was a 99% likelihood of responses being higher than 5 for motivation to learn and for PEB, and for knowledge consolidation (Fig. 3), giving high confidence to positive responses. The effect of the small group discussion with a coral reef researcher (treatment) was negligible both for knowledge consolidation, and motivation for

PEB (likelihood of positive effect of treatment 45% and 48% respectively; Fig. 3). However, there was moderate evidence for a negative effect of the treatment, with an 81% likelihood of lower motivation to learn in the treatment group compared to the control group who only received the standalone experience without further contextualization (Fig. 3).

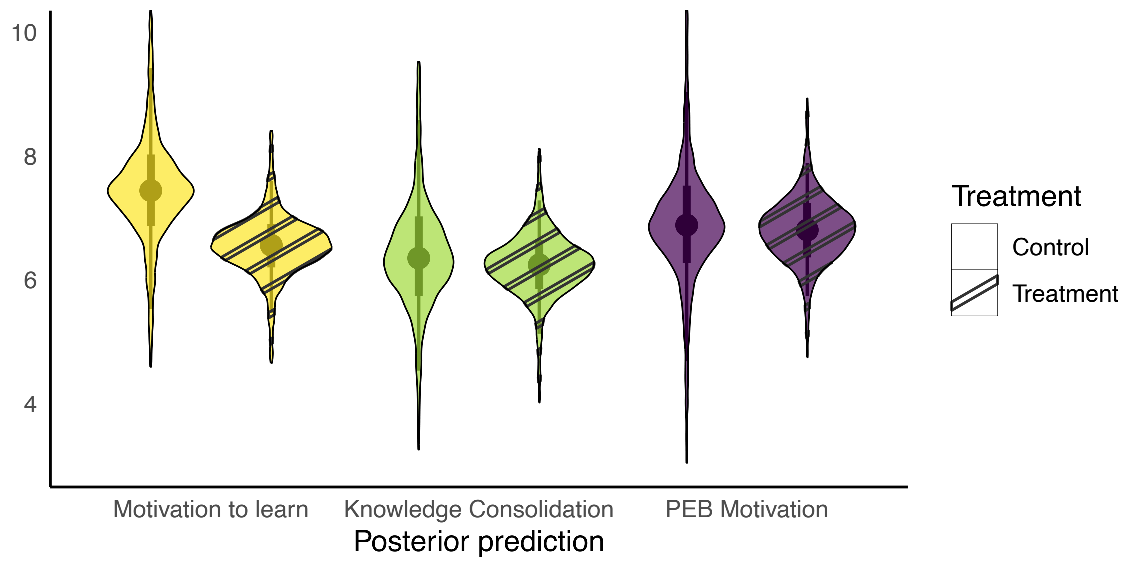

Figure 3. Violin plots (50% and 95% credible intervals) represent fitted values from Bayesian linear models. illustrate smoothed posterior density estimates of the predicted values for each treatment condition. See Fig. S1 for the same plot with data pooled for control and treatment.

The strongest positive predictor of motivation to learn, knowledge consolidation, and motivation for PEB was sensory experience, indicating that positive feelings of stimulation (as opposed to cognitive overload) were associated with positive outcomes (Fig. 4). Although there was a wide range of responses for ease of use, this factor had little effect on these outcomes. Unexpectedly, low reported cybersickness was a strong negative predictor of all three of these aspects, meaning that students who reported cybersickness were more likely to have a positive influence on motivation and knowledge consolidation. However, the variation in cybersickness was low, with few students experiencing adverse effects (mean =

8.91, median = 9; Table S1, Fig. 2) so despite the strong statistical effect, the psychological impact appears minimal.

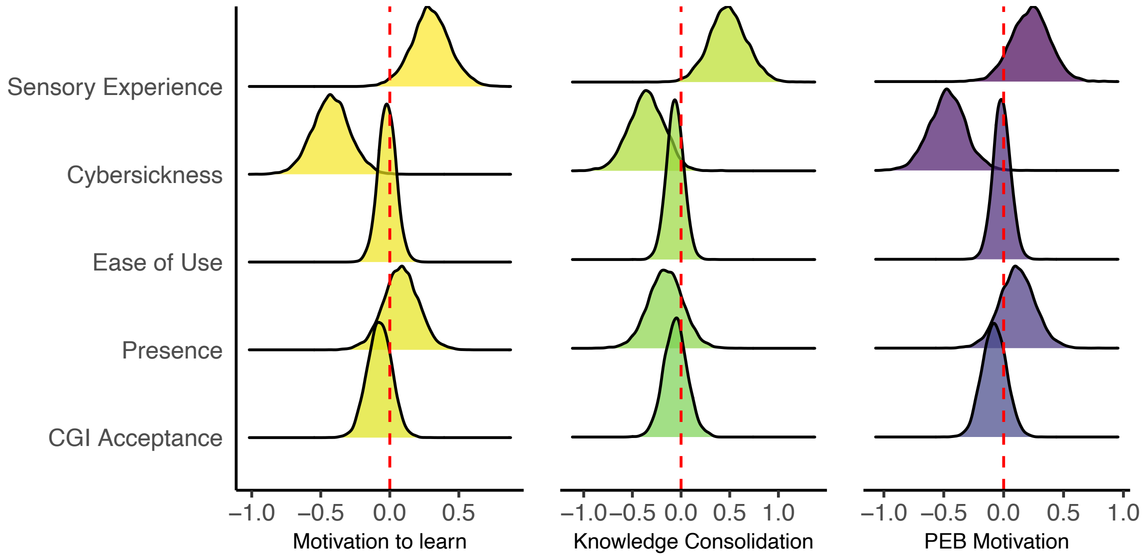

Figure 4. Posterior distributions of predictor contributions to motivation to learn, knowledge consolidation and PEB motivation. Ridge plots show the posterior distributions of the estimated coefficients for predictors in the Bayesian regression model. The x-axis represents the estimated effect size (posterior samples of the coefficients), and the y-axis denotes the predictors. The dashed red line at x=0 indicates no effect. Distributions to the right of this line suggest a positive contribution, while distributions to the left suggest a negative contribution.

Finally, students' opinion on the use of CGI within the VR experiences was the question that elicited the greatest diversity in response from 1 to 10 (Table S1). Slightly more students stated that CGI detracted from their experience (47.8% of students had a response < 5), while 39% were more favourable to CGI (response > 5) and 10.9% of students were neutral (response = 5).

DISCUSSION

Our findings indicate that integrating a VR experience into a 3rd-year HE undergraduate coral reef ecology course positively influenced the student learning experience. Students reported increased motivation to learn about coral reef ecology, enhanced knowledge consolidation from earlier in the course, and a greater motivation to engage in PEB. These findings highlight the potential for VR as an effective educational tool in ecological sciences within the HE context.

The positive impacts observed in our study align with several established theories of learning and education. Constructivist approaches are strongly applicable to VR, highlighting situated learning and problem-based learning as key features that can improve learning outcomes (Huang et al., 2010) - both of which are captured in *Explore*. These approaches emphasise active engagement and experiential learning, supporting the idea that immersive experiences such as VR enable students to construct knowledge through direct interaction with their environment. Situated learning theory (Lave & Wenger, 1991) also supports the notion that learning is most effective when it takes place in contexts that resemble real-world applications and has supporting evidence specifically related to VR (Huang et al., 2010). By providing students with a virtual yet realistic reef environment, the VR experience may therefore have facilitated deeper cognitive processing and stronger conceptual understanding.

One of the unexpected findings was that small group discussions did not significantly impact reported knowledge consolidation. However, sensory experience and the absence of cybersickness were significantly higher in the treatment group, suggesting that these factors may have played a role in shaping student responses. Rather than the small group discussions, the variability in experiences—particularly negative aspects such as cybersickness—may have influenced learning outcomes. This suggests that VR can still be a valuable learning experience even without extensive structuring or supplementary discussions to enhance student learning and knowledge retention. Our finding aligns with Self-Determination Theory (Ryan & Deci, 2000)(Deci & Ryan, 1985)(Ryan & Deci, 2000), which highlights the importance of intrinsic motivation to learn based on interest and enjoyment, alongside autonomy in learning. By allowing students to engage independently with the virtual environment, the experience likely supported such intrinsic motivation. While some students experienced mild cybersickness, this did not appear to negatively influence motivation to learn or engage in PEB, or knowledge consolidation. This reinforces the idea that, even when individual experiences vary, the overall educational value of VR remains strong.

Moreover, both cybersickness and sensory experience emerged as significant predictors of motivation to learn and motivation for PEB. Importantly, the overall positive sensory experience suggests that cognitive overload, which has been identified as a potential drawback in other VR learning environments (Morimoto & Ponton, 2021), was not a significant issue in our implementation of the *Explore* experience. This is an encouraging outcome, as cognitive overload has been previously linked to reduced learning efficacy in VR settings compared to 2D equivalents (Makransky et al., 2019). This finding reinforces the idea that well-designed VR experiences can enhance learning without exceeding cognitive processing limits, supporting research showing that immersive environments can enhance engagement and retention when cognitive demands are balanced effectively (Morimoto & Ponton, 2021).

An interesting aspect of student feedback was the acceptance of CGI in place of real-world imagery. Some students felt that CGI detracted from the experience, and on personal communication, at least one of those students had experienced SCUBA diving and therefore recognised the limitations of digital representation. Paradoxically, this reaction suggests a deep appreciation for real-world marine environments and an understanding of their value beyond what VR can replicate. This idea is supported by the concept of experiential learning (Kolb, 2015), which suggests that direct, hands-on experiences foster deeper learning. At the same time, the inclusion of charismatic marine species such as manta rays, which cannot be guaranteed or directed during real underwater filming, was likely a strong motivational factor, demonstrating the potential for CGI to enhance engagement. Further, while 360º video is likely to look more realistic, it may have limitations in *feeling* more realistic. Most strikingly, 360º video can provide 3 degrees of freedom (i.e. roll, pitch, and yaw rotational head movement) whereas CGI virtual environments allow for 6 degrees of freedom, adding three degrees of translational body movement along 3 axes (surge, heave, and sway). In addition, having the ability to control what you see and do in the VR experience, as well as seeing your hands or embodying an avatar, are more conducive to CGI environments than 360º video, and these affordances (interaction and embodiment) are associated with better learning outcomes and increased feelings of presence, agency, and empathy in virtual environments (Herrera et al., 2018; Petersen et al., 2022; Slater & Sanchez-Vives, 2016).

While our results suggest meaningful benefits of VR experiences in HE teaching situations, we acknowledge several limitations. Due to the design of the study being purposefully as minimally invasive as possible to capture VR in HE in a naturalistic setting, we were unable to conduct a pre-survey, limiting our ability to assess changes relative to baseline knowledge or motivation. Such trade-offs in control are required if we are to rewild our educational research. Additionally, our sample size was relatively small (although larger than many other research in this area) and limited to a single cohort, reducing the generalisability of our findings, despite providing valuable insights. Finally, as this study was conducted in a real-world educational setting, multiple external variables may have contributed to the observed outcomes including the time of day that students participated in the session, whether the allocated buddy during the VR experience was a well-known to the participant, individual learning characteristics, or the extent to which students were enjoying the course in general. However, we believe that this study contributes to calls to conduct more “wild” experiments for the use of VR in education.

These findings also build towards widening accessibility for ocean experiences (McKinley et al., 2023). Availability of content that aligns with ocean literacy principles and key features of VR – like presence, interaction, and embodiment – are limited and researchers, educators, and developers have called for more educational content and investigation into the use of immersive media for learning (Pimentel et al., 2022). This study therefore helps inform the future design and real-world application of extended reality (XR) technologies like virtual and augmented realities for marine science education and in higher learning environments. The VR experience led students to report increased motivation to engage in PEB, which contributes to the lifelong learning goal towards global citizenship.

Overall, this study, conducted in real-world HE setting, highlights the potential for VR as a valuable educational tool for coral reef ecology, fostering motivation, supporting knowledge consolidation, and fostering intentions to undertake PEB. While challenges such as cybersickness and individual acceptance of CGI must be considered, our results suggest that VR can be a powerful way to engage students in ecological learning.

DECLARATIONS

Availability of data and materials: All data and code generated or analysed during this study are available on GitHub here https://github.com/llljeannot/VR/tree/main.

Funding: UKRI funded Diverse Marine Values project (NE/V017497/1) for funding to support EM.

Acknowledgements: Thank you to Rucha Karkarey, Javier Gonzalez-Barrios, Victoria Marchment for helpful discussions and for helping to run the experience. Thank you to David McBride and Paul James for coordinating the event and managing the use of the Data Immersion Suite. Thank you to the Digital Education Team at Lancaster University for help with developing the discussion around the experience. Thank you to Horizon Productions, Jason McGuigan, and Monica Arés.

REFERENCES

Bermejo, B., Juiz, C., Cortes, D., Oskam, J., Moilanen, T., Loijas, J., Govender, P., Hussey, J., Schmidt, A. L., Burbach, R., King, D., #039, Connor, C., & Dunlea, D. (2023). AR/VR Teaching-Learning Experiences in Higher Education Institutions (HEI): A Systematic Literature Review. *Informatics*, *10*(2), 45. https://www.mdpi.com/2227-9709/10/2/45

Blythe, J., Baird, J., Bennett, N., Dale, G., Nash, K. L., Pickering, G., & Wabnitz, C. C. C. (2021). Fostering ocean empathy through future scenarios. *People and Nature*, *3*(6), 1284-1296. https://doi.org/https://doi.org/10.1002/pan3.10253

Calil, J., Fauville, G., Queiroz, A. C. M., Leo, K. L., Mann, A. G. N., Wise-West, T., Salvatore, P., & Bailenson, J. N. (2021). Using Virtual Reality in Sea Level Rise Planning and Community Engagement—An Overview. *Water*, *13*(9), 1142. https://www.mdpi.com/2073-4441/13/9/1142

Fauville, G., & Plechata, A. (2025). Environmental Education in Virtual Reality. In J. Plass, R. Mayer, & G. Makransky (Eds.), *The Handbook of Learning in Virtual Reality*.

Galeote, D. F., Legaki, N. Z., & Hamari, J. (2023). Text- and game-based communication for climate change attitude, self-efficacy, and behavior: A controlled experiment. *Computers in Human Behavior*, *149*, Article 107930. https://doi.org/10.1016/j.chb.2023.107930

Herrera, F., Bailenson, J., Weisz, E., Ogle, E., & Zaki, J. (2018). Building long-term empathy: A large-scale comparison of traditional and virtual reality perspective-taking. *PLoS ONE*, *13*(10). https://doi.org/10.1371/journal.pone.0204494

Hooten, M. B., & Hobbs, N. T. (2015). A guide to Bayesian model selection for ecologists. *Ecological Monographs*, *85*(1), 3-28. https://doi.org/https://doi.org/10.1890/14-0661.1

Huang, H.-M., Rauch, U., & Liaw, S.-S. (2010). Investigating learners' attitudes toward virtual reality learning environments: Based on a constructivist approach. *Computers &*

Education, *55*(3), 1171-1182. https://doi.org/https://doi.org/10.1016/j.compedu.2010.05.014

Inverness Research Inc. (2022). *Advancing Ocean Science Literacy Through Immersive Virtual Reality Project: Summative Evaluation Report*. https://static1.squarespace.com/static/587968346a4963fff6c09a9c/t/64079354b88d974171f57b50/1678218068423/AOSL+SumEvalReport+FINAL+18Jul22.pdf

Kolb, D. A. (2015). *Experiential Learning: Experience as the Source of Learning and Development*. Pearson Education. https://books.google.co.uk/books?id=o6DfBQAAQBAJ

Kuwabara, Y., Ogata, A., Tanaka, T., Nishida, T., & Sasaki, I. (2025). Qualitative Assessment of Undergraduate Nursing Students' Perceptions of Combined Virtual Reality and Group Discussion Learning Interventions: A Focus Group Study. *Evidence-Based Nursing Research*, *7*(1).

Lave, J., & Wenger, E. (1991). *Situated Learning: Legitimate Peripheral Participation*. Cambridge University Press. https://books.google.co.uk/books?id=CAVIOrW3vYAC

Makransky, G., Terkildsen, T. S., & Mayer, R. E. (2019). Adding immersive virtual reality to a science lab simulation causes more presence but less learning. *Learning and Instruction*, *60*, 225-236. https://doi.org/https://doi.org/10.1016/j.learninstruc.2017.12.007

Markowitz, D. M., Laha, R., Perone, B. P., Pea, R. D., & Bailenson, J. N. (2018). Immersive Virtual Reality Field Trips Facilitate Learning About Climate Change [Original Research]. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.02364

McKinley, E., Burdon, D., & Shellock, R. J. (2023). The evolution of ocean literacy: A new framework for the United Nations Ocean Decade and beyond. *Marine Pollution Bulletin*, *186*, 114467. https://doi.org/https://doi.org/10.1016/j.marpolbul.2022.114467

McKinley, E., Kelly, R., Mackay, M., Shellock, R., Cvitanovic, C., & van Putten, I. (2022). Development and expansion in the marine social sciences: Insights from the global community. *iScience*, *25*(8), 104735. https://doi.org/https://doi.org/10.1016/j.isci.2022.104735

Morimoto, J., & Ponton, F. (2021). Virtual reality in biology: could we become virtual naturalists? *Evolution: Education and Outreach*, *14*(1), 7. https://doi.org/10.1186/s12052-021-00147-x

Ou, K.-L., Chu, S.-T., & Tarng, W. (2021). Development of a Virtual Wetland Ecological System Using VR 360° Panoramic Technology for Environmental Education. *Land*, *10*(8), 829. https://www.mdpi.com/2073-445X/10/8/829

Petersen, G. B., Petkakis, G., & Makransky, G. (2022). A study of how immersion and interactivity drive VR learning. *Computers & Education*, *179*, 104429. https://doi.org/https://doi.org/10.1016/j.compedu.2021.104429

Pimentel, D., Fauville, G., Frazier, K., McGivney, E., Rosas, S., & Woolsey, E. (2022). *An Introduction to Learning in the Metaverse*. M. Treehouse.

Poland, R., Baggott la Velle, L., & Nichol, J. (2003). The Virtual Field Station (VFS): using a virtual reality environment for ecological fieldwork in A-Level biological studies—Case Study 3. *British Journal of Educational Technology*, *34*(2), 215-231. https://doi.org/https://doi.org/10.1111/1467-8535.00321

Queiroz, A. C. M., Fauville, G., Herrera, F., Leme, M. I. d. S., & Bailenson, J. N. (2022). Do Students Learn Better With Immersive Virtual Reality Videos Than Conventional Videos? A Comparison of Media Effects With Middle School Girls. *Technology, Mind, and Behavior*, *3*(3). https://doi.org/10.1037/tmb0000082

R Development Core Team. (2019). *R: A Language and Environment for Statistical Computing v3.6.1.* In R Foundation for Statistical Computing.

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/https://doi.org/10.1016/j.compedu.2019.103778

Richardson, D., Kinsella, J., & Shreeves, K. (2008). *The Encyclopedia of Recreational Diving*. PADI.

Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist*, *55*(1), 68-78. https://doi.org/10.1037/0003-066X.55.1.68

Sahabuddin, E. S., & Makkasau, A. (2024). Utilization of virtual reality as a learning tool to increase students' pro-environmental behavior at universities: A maximum likelihood estimation approach. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(12), em2540. https://doi.org/10.29333/ejmste/15654

Sanchez-Vives, M. V., & Slater, M. (2005). From presence to consciousness through virtual reality. *Nature Reviews Neuroscience*, *6*(4), 332-339. https://doi.org/10.1038/nrn1651

Shute, V., Rahimi, S., & Emihovich, B. (2017). Assessment for Learning in Immersive Environments. In D. Liu, C. Dede, R. Huang, & J. Richards (Eds.), *Virtual, Augmented, and Mixed Realities in Education* (pp. 71-87). Springer Singapore. https://doi.org/10.1007/978-981-10-5490-7_5

Slater, M., & Sanchez-Vives, M. V. (2016). Enhancing Our Lives with Immersive Virtual Reality [Opinion]. *Frontiers in Robotics and AI*, *3*. https://doi.org/10.3389/frobt.2016.00074

Soga, M., & Gaston, K. J. Extinction of experience among ecologists. *Trends in Ecology & Evolution*. https://doi.org/10.1016/j.tree.2024.12.010

Stan Development Team. (2016). rstanarm: Bayesian applied regression modeling via Stan. http://mc-stan.org/. .

Tarng, W., Ou, K.-L., Yu, C.-S., Liou, F.-L., & Liou, H.-H. (2015). Development of a virtual butterfly ecological system based on augmented reality and mobile learning technologies. *Virtual Reality*, *19*(3), 253-266. https://doi.org/10.1007/s10055-015-0265-5

Trope, Y., & Liberman, N. (2010). Construal-level theory of psychological distance. *Psychological Review*, *117*(2), 440.

Wang, P., & Bailenson, J. (2025). Virtual Reality as a Research Tool. In L. v. S. Reimer & A. Florack (Eds.), *The Routledge Handbook of Communication and Social Cognition*.

White, M., Smith, A., Humphryes, K., Pahl, S., Snelling, D., & Depledge, M. (2010). Blue space: The importance of water for preference, affect, and restorativeness ratings of natural and built scenes. *Journal of Environmental Psychology*, *30*(4), 482-493. https://doi.org/https://doi.org/10.1016/j.jenvp.2010.04.004

SUPPLEMENTARY MATERIAL

APPENDIX 1 Small group discussion questions

1. What are the advantages and disadvantages of using photo identification for individuals (a) for manta rays, (b) for smaller reef fish species?
2. When would it be useful to be able to track individuals? What ecological questions could be explored?
3. What ecological elements of the reef might be affected by having different regional coral species compositions?
4. Why might you expect different regions to harbour a different species pool?
5. Evaluate the use of quadrat methods versus transect methods for quantifying coral composition and abundance? In what scenarios are these different methods most useful?
6. Design one additional VR-based task to add to these three, aimed at undergraduate students.

APPENDIX 2 Student Instructions for *Explore* Navigation

INSTRUCTIONS (*read aloud to your buddy*)

1. *If you feel unwell at any point, stop immediately*
2. Is it ok for me to steer you by your shoulders if needed? (*get permission for physical contact if required*)
3. Place the chair on the marker and sit down.
4. Put headset on, adjust for comfort. For the straps at the back, move them away from each other to tighten, and together to loosen. The Velcro on the top of your head will adjust the tilt.
5. Here are the hand controllers (*hand them to your buddy*).
6. Select apps icon on far right of the bar using the button under your front index finger (either hand will work).
7. Select “The Hydrous Explore” app using your front index finger. Note that once you select this app, you should experience full immersion and will no longer be able to see the room. *REMEMBER - If you feel unwell at any point, stop immediately*
8. Once you have it ready to go, let me know if you would like to stand up. I will spot you to ensure you stay safe. (*Push back the chair so it is out of their way*).
9. You will see four cards come up. <u>Ignore Immerse</u> and work through each of the other three tasks in turn by selecting them with the front index finger.

10. If you need to go back, push down the indented button on the top of the hand controller. Select quit to close *Explore*.
11. At the end, please give me the hand controllers (*take the controllers from them*), I will get the chair and sit you down. Now remove the headset.
12. *If you need help at any point, please raise your hand!*

Troubleshooting

If your buddy can see the room again in the background, try moving them back towards their original marker on the floor. If needed, select “create new boundary” and look all around you (360 degrees) to remap the space.

If you get stuck on the manta ray task, make sure you have photographed all four individuals (look for the question marks).

Table S1: Summary statistics for questionnaire responses to questions Q1 through Q8 on a 10-point Likert scale (1–10) provided by participants after the VR experience. For each question, the mean, median, standard deviation (SD), minimum (min), and maximum (max) are reported. Note that scales are reversed relative to the survey for Q4 Cybersickness and Q5 Ease of use.

Question	Mean	Median	SD	Max	Min
Q1. Motivation to learn	6.83	7.0	1.29	10	5
Q2. Consolidation	6.28	6.0	1.63	10	3
Q3. Sensory experience	8.00	8.5	2.02	10	2
Q4. Cybersickness	8.91	9.0	1.59	10	4
Q5. Ease of use	7.65	9.0	3.01	10	1
Q6. Presence	7.65	8.0	1.86	10	2
Q7. CGI acceptance	5.13	5.0	2.23	10	1
Q8. Motivation for PEB	6.82	7.0	1.42	10	5