TITLE: Enhancing motivation to learn marine ecology and increase ocean literacy through Virtual Reality in Higher Education

AUTHORS: Sally A. Keith[1]*, Laura-Li Jeannot[1], Emma McKinley[2], Geraldine Fauville[3,4] 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, the effectiveness of VR for teaching and learning in higher education is poorly understood. Here, we use the *Explore* experience developed by The Hydrous (non-profit) 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 preference for realism. We found that undergraduate university 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

Understanding the potential benefits of Virtual Reality (VR) is an emerging research priority, with wide-ranging implications for education (Radianti *et al.* 2020; Conrad *et al.* 2024), cognition (Horváth *et al.* 2024), behaviour (Yaremych & Persky 2019; Fauville *et al.* 2020), and physical and mental wellbeing (Lundin *et al.* 2023; Robinson & Razak 2025). Key debates centre on what generates a convincing sense of "presence" and how multimodal sensory cues combine to create immersive, memorable experiences (Marucci *et al.* 2021) (Sanchez-Vives & Slater 2005). Efforts are increasing to test if VR can enhance knowledge retention, problem-solving, and conceptual understanding beyond traditional teaching approaches (Makransky & Petersen 2021; Conrad *et al.* 2024), and the extent to which skills or attitudes developed in virtual environments translate into real-world contexts (Calil *et al.* 2021; Mergen *et al.* 2024). Alongside these opportunities, questions remain about the psychological and physiological impacts of VR use, and how to ensure it is ethical (Raja & Al-Baghli 2025), inclusive, and accessible (Creed *et al.* 2024). These issues are especially relevant to environmental and ecological education, where VR's ability to situate learners in dynamic, threatened ecosystems offers unique potential to deepen understanding of complex systems and to encourage pro-environmental behaviour (PEB) (Fauville *et al.* 2020).

Here, we focus on VR as a tool to enhance student engagement and motivation in education. Evidence is emerging that VR is particularly useful in STEM disciplines that rely heavily on experiential learning and the visualisation of phenomena often invisible to the naked eye (Shute *et al.* 2017; Makransky *et al.* 2019b). However, research on the use of VR as a learning and teaching tool in Higher Education (HE) is limited (Radianti *et al.* 2020; Bermejo *et al.* 2023; Conrad *et al.* 2024).

VR in Ecology

VR environments have the potential to be particularly useful for learning about ecology, as they allow students to explore complex ecological systems, observe species interactions, and simulate fieldwork in ways that are often otherwise impractical due to logistical, financial, or safety constraints (Poland *et al.* 2003; Tarng *et al.* 2015; Morimoto & Ponton 2021; Ou *et al.* 2021). For instance, studies have shown VR to be well-received with students in secondary education, who achieved higher satisfaction and learning scores when exploring wetland ecosystems using a static 360° panoramic VR experience compared with their counterparts who used traditional materials including worksheets (Ou *et al.* 2021).

Examples of ecology using immersive VR, where participants interact with, and receive feedback from, the experience, like playing a computer game (see below for further explanation), are rare. Studies which assess its effects quantitatively are particularly scarce, yet there are two exceptions that focus specifically on marine systems. First, immersive VR that taught participants from school age to adults about ocean acidification increased knowledge and interest in learning and increase pro-environmental attitudes (Markowitz *et al.* 2018). In contrast, a VR experience built around a future conservation scenario for the high seas was not found to elicit more empathy towards the ocean than written information; however, there was no opportunity for interaction with the environment, which likely detracted from its impact (Blythe *et al.* 2021). Benefits of VR for learning in ecology and for motivating PEB are therefore expected given evidence from related fields, however the direct evidence is unclear. Considering the role of VR in HE is increasingly important for facilitating access to the natural world because opportunities for exposure to field experiences and their associated skills are decreasing rapidly (Morimoto & Ponton 2021), resulting in what some suggest is an “extinction of experience” among ecologists (Soga & Gaston 2025).

Understanding the VR experience

Immersion and presence are two crucial factors in VR. Immersion relates to “the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant” and can be objectively quantified for any technological system (Slater & Wilbur 1997). Presence relates to the individual and subjective sense of being in the virtual environment experienced by the VR users (Slater & Wilbur 1997). The relationship between immersion and presence lies in the fact that presence can be enhanced by an increased level of immersion (Sanchez-Vives & Slater 2005).

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 are not the only factors that affect the VR experience. Ease of use (de Back *et al.* 2020), sensory input (Makransky *et al.* 2019b), and cybersickness (Makransky & Petersen 2021; Mareta *et al.* 2022) are also key considerations that influence the success of VR for learning. Trade-offs between multiple factors are likely to vary across different VR platforms and design choices, requiring careful consideration and testing for VR experiences (Makransky & Petersen 2021).

VR as a tool to enhance learning

Evidence suggests that VR can enhance motivation to learn relative to other media. Effectiveness of VR for safety training compared to both desktop simulation and to reading a traditional safety manual, demonstrated that VR provided the greatest enhancement for intrinsic motivation (Makransky *et al.* 2019a). 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 (Markowitz *et al.* 2018; Bermejo *et al.* 2023). However, with increased dependence on digital teaching materials and resources within HE, it remains unclear whether students prefer learning through experiences of virtual ecosystems created with computer-generated imagery (CGI) or real-world 360-degree video footage, or indeed what the impact of these different approaches might have on student learning, making it difficult to determine the most effective content design for ecological education. Additionally, given the intrinsic link between ecology and conservation, the use of VR as an education tool has the potential to enhance students' empathy and subsequent PEB (Blythe *et al.* 2021), together captured within the broader context of ocean literacy (McKinley *et al.* 2023). While evidence suggests that immersive experiences can strengthen emotional connections to nature and encourage PEB (Markowitz *et al.* 2018; 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 and scientific perspectives.

Historically, VR experiences have offered limited opportunity for collective or social learning during the experience yet collaborative tasks within a VR environment can improve learning (Petersen *et al.* 2023). However, most VR experiences do not have the functionality for group interaction within the task. Therefore, we were interested in understanding whether following the experience with small group discussions could enhance learning through a participation in collaborative task focused on the content of the VR but outside of the experience itself. 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 (Petersen *et al.* 2023). Despite this, some evidence suggests that this type of approach could enhance learning. For example, a small qualitative study with undergraduate nursing students (n=5) found a discussion group after VR “expanded and deepened their learning,” providing the opportunity to hear different perspectives on the experience (Kuwabara *et al.* 2025).

Encouraging Ocean Literacy

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 al.* 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 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 understanding the ocean’s influence on you, and your influence on the ocean, as a key mechanism for change. However, with roots firmly in the field of marine education and social sciences (McKinley *et al.* 2022), rather than in the natural sciences, transdisciplinarity within marine education is needed to realise the potential of ocean literacy. One aspect of this, is a need to increase ecology students’ motivation to connect with the ocean, in addition to advancing their scientific understanding, However, it can be challenging to create experiential learning opportunities since access to marine environments is severely limited. VR offers one mechanism through which this ocean connectedness (Nuojua *et al.* 2022) and ocean literacy can be fostered through ecological education, and is therefore worthy of deeper exploration.

Assessing VR in a real-world setting

While most of the research investigating the use of VR in education takes place in highly controlled settings, to date the naturalistic dimension of "VR in the wild" has been difficult to capture (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 alongside authentic teaching activities (Wang & Bailenson 2025). This study contributes to this call 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 at Lancaster University, UK – a top 15 research-led university - took part in *Explore* - a 10-15 minute freely available underwater VR experience developed by non-profit organization The Hydrous, US, using Meta Quest 3 headsets. To test whether a small group discussion influenced outcomes, students were asked to complete a questionnaire reflecting on their VR experience either after taking part in a discussion designed to link the experience more strongly to module content and deepen learning (treatment group), or without the discussion (control group). Specifically, we asked whether: (Research Question 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 PEB; (RQ2) the inclusion of small group discussion immediately after the experience (treatment) enhanced these outcomes relative to no small group discussion (control); and (RQ3) 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 preference for realism.

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. As part of this programme, The Hydrous created *The Hydrous Presents: Explor*e (hereafter shortened to *Explore*), an interactive CGI-based VR experience for the research project “Advancing Ocean Literacy with Immersive Virtual Reality,” a collaboration with Horizon Productions and Stanford University’s Virtual Human Interaction Lab, funded by the National Science Foundation through the Advancing Informal STEM Learning 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. In 2021, *Explore* 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 for free. As of September 2025, *Explore* has been used with more than 2,434 installs via Meta (Feb 2025). A preliminary evaluation of *Explore* revealed its potential to contribute to user’s understanding of ocean science and a better sense of what marine science work entails. Using *Explore* also enables connection with the ocean along with empathy towards it (Inverness Research Inc. 2022). However, so far, the impact of Explore has not been investigated in the context of HE.

Methods

Participants: 48 students from a 3rd year undergraduate Coral Reef Ecology course participated in a VR dive experience as part of their module content. The course is accessible to any undergraduate student within the Department of Lancaster Environment Centre, including those majoring in Ecology & Conservation, Zoology, Biology, Geography and Environmental Science. Students were randomly allocated to either the control (16, no small group discussion) or treatment (32, with small group discussion) and asked to complete a questionnaire about their experience. Group sizes were constrained by the need to run the minimum number of repeat sessions given room capacity, resulting in 3 groups where the third was randomly assigned to treatment or control. Although this results in an unbalanced number across groups, our use of Bayesian statistics accounts for any possible bias. As this was a real university cohort, gender and age were protected characteristics and so no participant demographic details were collected. Ethics approval was granted by the Faculty Research Ethics Committee at Lancaster University (reference FST-2024-4775-RECR-5).

Small group discussion as a 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 there was no small group discussion, or treatment, where the students engaged in small group discussion before filling out the questionnaire. Therefore, in the treatment, participation in small group discussions could potentially mediate post-experience self-reporting. Discussion questions are provided in Appendix S1 and linked to topics explored through the course. For example, students were asked to evaluate the use of quadrat methods versus transect methods for quantifying coral composition and abundance; and discuss in what scenarios these different methods are most useful. Questions also helped students to further explore topics raised through the experience such as the contexts in which it is useful to tag and track animals individually.

VR delivery: Lancaster University's Data Immersion Suite (DIS) is equipped with 20 Meta Quest 3 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, two of which took part in small group discussions before completing the questionnaire. A briefing was provided in advance of the sessions outlining the use of VR in ocean education and conservation by The Hydrous, describing risks and medical warnings, advice on how to use the headset, and how to navigate the experience using hand controllers and head movement. For each session in the DIS, 14-16 students attended. Wrap around screens (270-degrees) in the DIS displayed videos recorded from stationary cameras on coral reefs, providing a semi-immersive experience when not using the VR headsets.

Students were assigned to “buddy pairs” to ensure they could safely engage in the experience without walking into any obstacles and would receive help immediately if they experienced nausea or dizziness. Buddy pairs also simulate the buddying of divers during real life SCUBA dive experiences (Richardson *et al.* 2008). The students then followed a series of instructions, read by their buddy (See Appendix S1), to navigate the experience and complete the three tasks before swapping roles.

Small discussion groups were organised with 4-6 students and one coral reef researcher (treatment groups only. One experienced researcher was assigned to each discussion group to ask the questions, remind students of links to other aspects of the course and help ensure that all students had the space to participate without a few individuals dominating.

Post experience questionnaire: The participants were invited to answer a short questionnaire (Appendix S1) following the VR (and discussion for treatment groups) experience. It consisted of eight questions with all answers using a Likert scale from 1-10 with each number choice labelled individually. Whilst less well used, evidence suggests that 10-point scales are favoured by respondents for ease of use and provide reliable data that are easily comparable (Preston & Colman 2000; Yadav *et al.* 2023). The questionnaire was voluntary and anonymous, following all ethical guidelines including provision of a participant information sheet, consent form and debrief sheet. All questions gathered self-reported data on aspects of the students’ experience. Knowledge consolidation related to the context of two workshops earlier in the course that involved coral and fish identification and survey skills via true to scale coral benthic photos (10 m x 1 m) and video transects. The questionnaire included the following eight questions based on key factors that influence VR experiences (Q3-7) and outcomes (Q1-2, Q8) in HE (see Introduction for justification):

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. *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

RQ1. Were self-reported outcomes and experiences positive? Scores for all questions were explored using descriptive statistics of median and mean for central tendency, and standard deviation, minimum and maximum to explore the spread of the data. Scales were reversed for cybersickness and ease of use to enable the 1-10 score to consistently range from most negative (1) to most positive (10).

RQ2. Was there an effect of small group discussion? To analyse whether there was an effect of treatment against control for the outcomes, we fitted Bayesian hierarchical models using the brms package in R (Bürkner 2017; 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 used normal distributions and Group (1-3) was included as a random effect to account for potential group-level clustering. 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 to assess the likelihood that small group discussions influenced responses from individuals. Posterior predictions were visualized for each variable using 1,000 draws from the posterior distribution.

RQ3. Could outcomes be predicted by experience? 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 models with identical specifications and posterior checks. One model was generated for each of the outcome variables – motivation to learn, knowledge consolidation, and motivation for PEB - with each using the same five potential predictors: sensory experience, cybersickness, ease of use, presence and CGI acceptance (drawing on insights from recent VR experience studies and theories, including Fauville *et al.* 2024; Weech *et al.* 2019; Makransky & Petersen 2021). The contribution of each predictor to the response variable was visualized using the posterior distributions of the coefficients of these predictors.

RESULTS

RQ1. Were self-reported outcomes and experiences positive?

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). The three outcome variables - motivation to learn, knowledge consolidation, and motivation for PEB – had a median of 7.0, 6.0 and 7.0 respectively (Fig.2, Appendix S1 Table S1). Motivation to learn and motivation for PEB both ranged from 5-10 indicating that 100% of the responses were positive (Fig. 2, Appendix S1 Table S1). Knowledge consolidation ranged from 3 to 10, with most students (82.6 %) reporting that the experience consolidated and/or expanded their learning (response > 5).

Students' opinion on the use of CGI within the VR experiences was one of the questions that elicited the greatest diversity in response from 1 to 10 (Appendix S1 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).

RQ2. Was there an effect of small group discussion?

Discussion with a coral reef researcher (treatment) had a negligible effect on both 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).

RQ3. Could outcomes be predicted by experience?

The strongest positive predictor of motivation to learn, knowledge consolidation, and motivation for PEB was sensory experience, indicating that positive feelings of stimulation 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.

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. The virtual reef environment may therefore have facilitated deeper cognitive processing and stronger conceptual understanding.

Predictors of VR outcomes

One of the unexpected findings was that the addition of 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), 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 (Makransky & Petersen 2021; 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.* 2019b). 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).

Our finding that higher self-reported cybersickness was associated was a more positive outcome for motivation to learn, knowledge consolidation, and motivation for PEB appears counterintuitive. Cybersickness was very mild for all participants. One reason it could have contributed to a positive experience is that it could have heightened sensory mismatch, mimicking feelings of being underwater and increasing feelings of presence; however, evidence for this idea is controversial (Weech *et al.* 2019), Alternatively, Arousal Theory suggests that mild discomfort during experiences framed as adventurous can increase memorability or perceived significance (Storbeck & Clore 2008).

Realism of the VR experience

An interesting aspect of student feedback was the acceptance of CGI in place of real-world imagery i.e., preference for realism. 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. This reaction suggests an appreciation for real-world marine environments and an understanding of their value beyond what VR can replicate. Indeed, evidence suggests lower acceptance of CGI imagery over recorded video for VR dive experiences among qualified divers compared to those without dive experience (Elsholz *et al.* 2025). This difference in perception from a real environment could also break the feeling of presence. An additional factor might rest in the "Uncanny Valley" theory proposed by Mori in the 1970s (Mori *et al.* 2012), which was suggested that feelings of discomfort are elevated by experiences that are close to real but not real, as the small imperfections elicit a cognitive response of disgust or avoidance as the human brain tries to rectify the experience with existing knowledge (Howard 2017). Although developed for response to humanoids, it can also be applied to environments and is exacerbated by high detail (Howard 2017).

On the flip side, 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 in *Explore*, demonstrating the potential for CGI to enhance engagement. The other two modules in *Explore* took place in outer space and featured time travel, respectively, and collecting real-world footage for such locations and features would be costly, time-consuming, or impossible. 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 (Slater & Sanchez-Vives 2016; Herrera *et al.* 2018; Petersen *et al.* 2022). This idea is supported by the concept of experiential learning (Kolb 2015), which suggests that direct, hands-on experiences foster deeper learning.

Limitations and future steps

While our results suggest meaningful benefits of VR experiences in HE teaching situations, we acknowledge limitations and opportunities for future research. The study design was intentionally minimally invasive to capture VR in HE in a naturalistic setting, meaning we were unable to conduct a pre-survey, limiting our ability to assess changes and impact relative to baseline knowledge or motivation. However, such trade-offs, where it is necessary to relinquish some control to obtain data from a real teaching setting, are required if we are to rewild our educational research. Additionally, our sample size was limited due to the nature of the study itself. Indeed, instead of conducting a study in controlled conditions in a laboratory, we decided to pilot the implementation of VR in an existing course. This sample size reflects some of the constraints imposed by this kind of *in situ* implementation. However, while our sample size is relatively small, it does not differ much from the mean sample size (n=54) reported in a meta-analysis of VR studies in education (Wu *et al.* 2020). We also acknowledge that we had only one question to measure each construct, where ideally multiple questions would be used to ensure validity. Given that this was a new addition to the module content coupled with the relatively small sample size and voluntary nature of the questionnaire completion, it was determined that keeping the questionnaire as short as possible would result in a higher response rate whilst also allowing us to explore a range of variables. This study, therefore, provides useful initial insights as to the opportunities for the integration of VR into HE settings, and lays the foundation for a larger exploration of the impact of VR on PEB.

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 *in situ* experiments for the use of VR in education.

These findings also build towards widening accessibility to the ocean (McKinley *et al.* 2023). Availability of content that aligns with both the 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; Fauville *et al.* 2025). This study therefore helps inform the future design and real-world application of extended reality (XR) technologies like VR, and indeed augmented realities for marine science education and in HE environments. The VR experience led students to report increased motivation to engage in PEB, which contributes towards enhanced 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, engendering ocean literacy, supporting knowledge consolidation, and fostering motivation and intentions to undertake PEB. While challenges such as cybersickness and individual acceptance of CGI must be considered when using VR experiences as a teaching resource, our results suggest that VR can be a powerful way to engage students in ecological learning that enhances their ocean literacy.

DECLARATIONS

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

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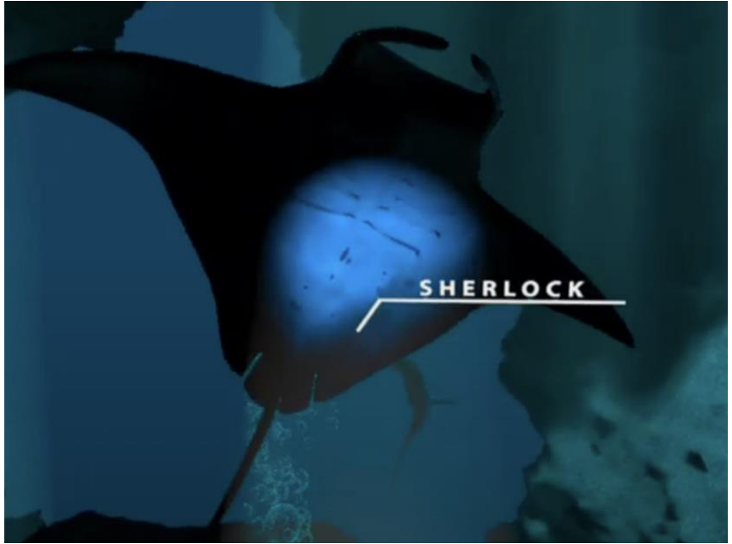
FIGURE CAPTIONS

Figure 1. 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). Images are from the VR experience *The Hydrous presents: Explore* ("*Explore*"). The left two images are screenshots from within-headset gameplay and the right image is a promotional illustration. *Explore* was created by The Hydrous, a U.S. based 501(c)3 nonprofit, in partnership with Horizon Productions and The Stanford University Virtual Human Interaction Lab, with funding from the National Science Foundation, HTC, and Meta. *Explore* is owned by The Hydrous and available to play for free with a Quest VR headset. Co-author EW is the CEO & Chief Scientist of The Hydrous and grants permission to publish these images as part of this research.

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.

Figure 3. Violin plots (50% and 95% credible intervals) represent fitted values from Bayesian linear models and illustrate smoothed posterior density estimates of the predicted values for each treatment condition.

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.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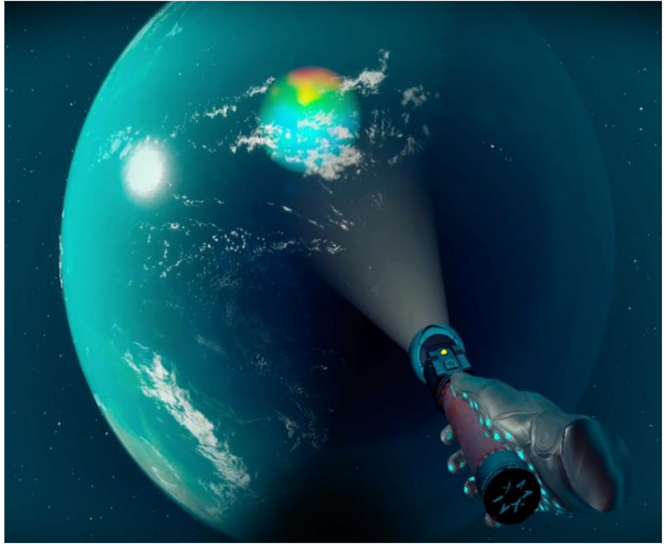
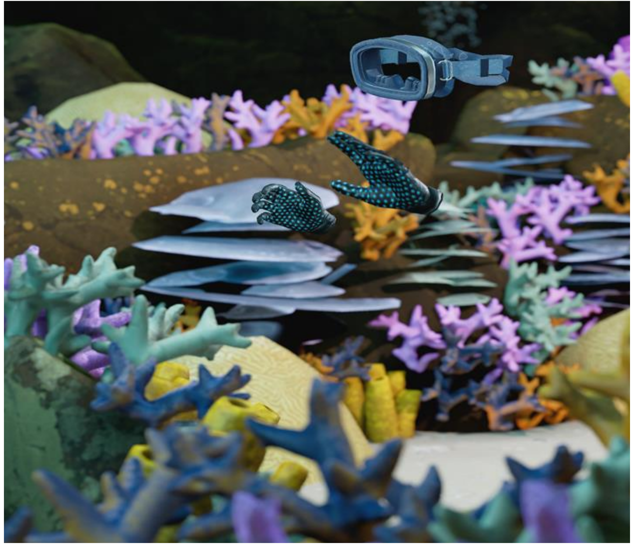

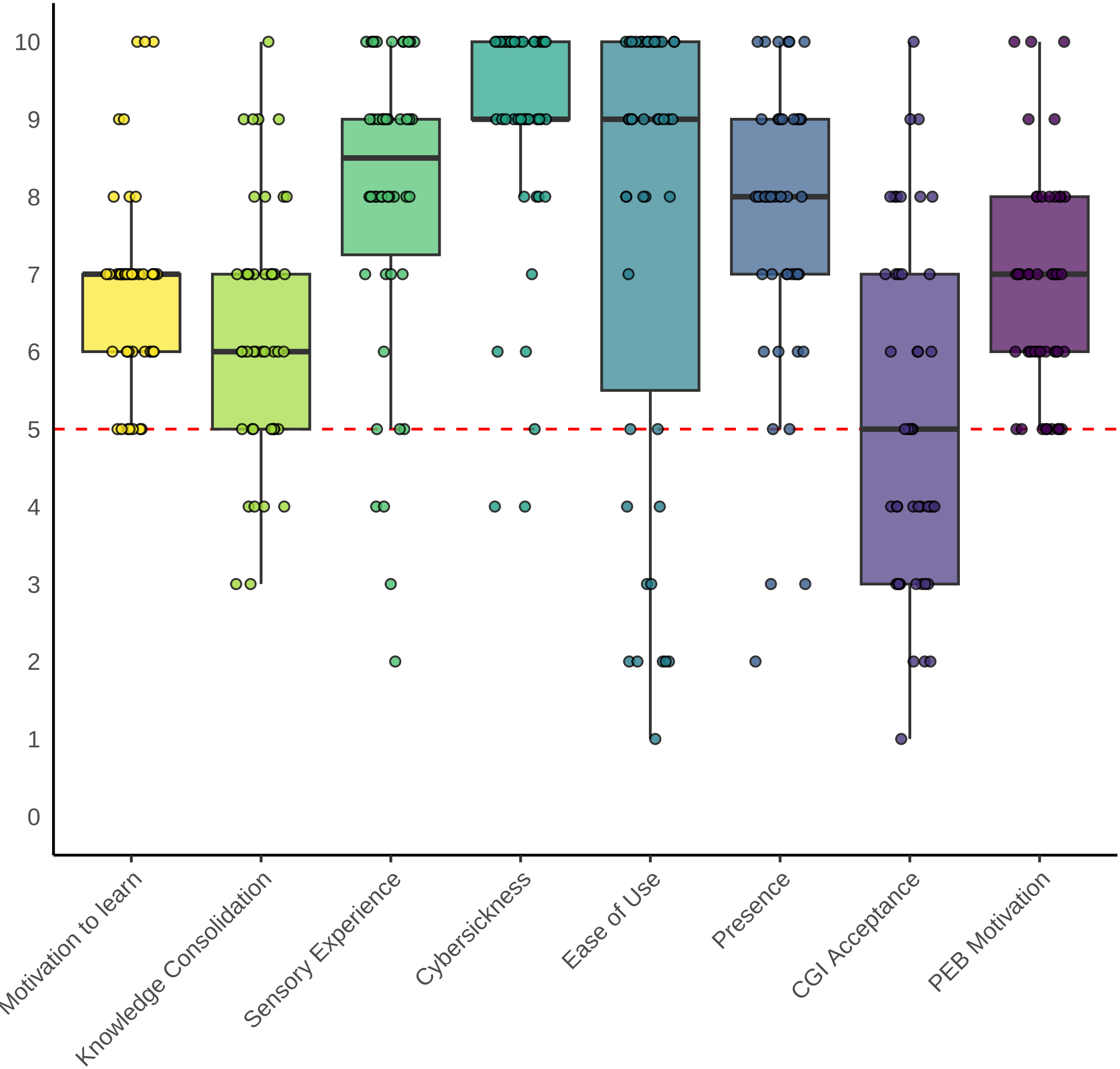

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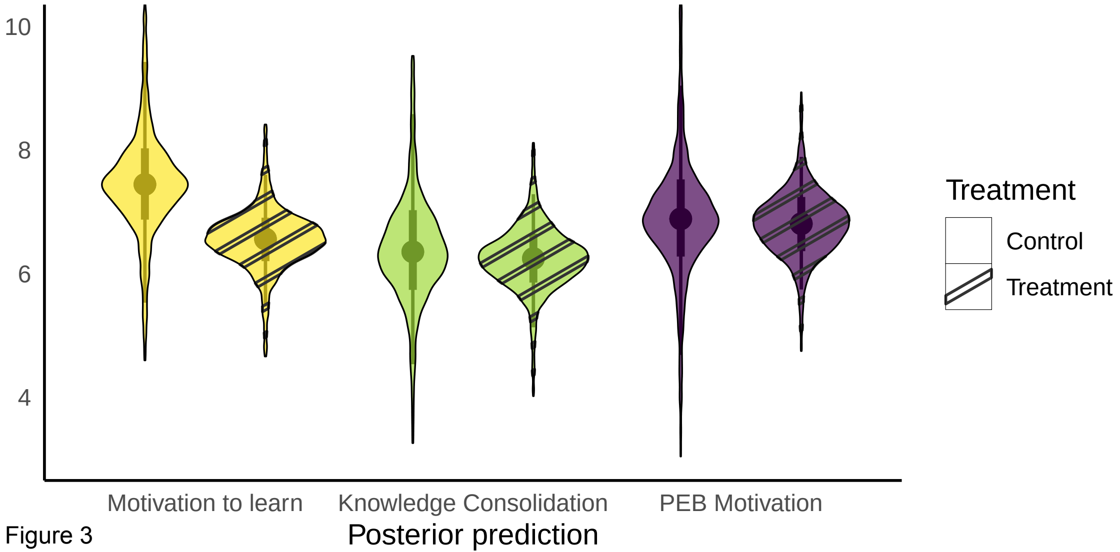
Motivation to learn
Knowledge Consolidation
Sensory Experience
Cybersickness
Ease of Use
Presence
CGI Acceptance
PEB Motivation

Figure 2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Motivation to learn
Knowledge Consolidation
PEB Motivation
Posterior prediction
Treatment
Control
Treatment

Figure 3

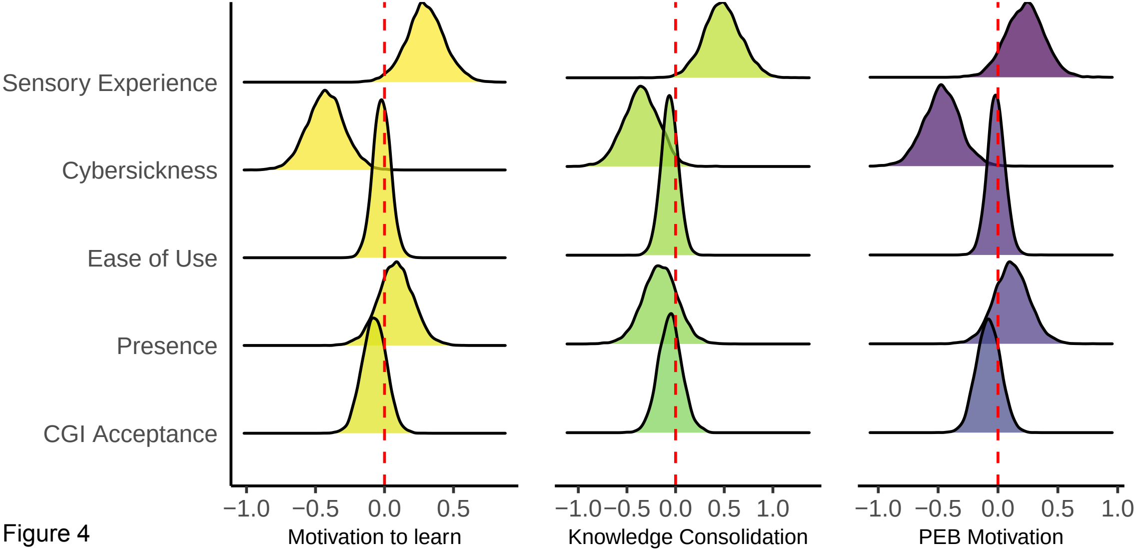
Sensory Experience
Cybersickness
Ease of Use
Presence
CGI Acceptance
−1.0 −0.5 0.0 0.5
Motivation to learn
−1.0 −0.5 0.0 0.5 1.0
Knowledge Consolidation
−1.0 −0.5 0.0 0.5 1.0
PEB Motivation

Figure 4

Journal: ***Ecosphere***

Title: Enhancing motivation to learn marine ecology and increase ocean literacy through Virtual Reality in a Higher Education setting

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

APPENDIX S1

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.

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. Knowledge 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