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ORIGINAL RESEARCH

Go green: evaluating an XR application on biodiversity in German secondary school classrooms

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Abstract

One discussion in the context of education for sustainable development centers around the importance of suitable teaching materials for promoting pro-environmental attitudes. Especially applications that let learners travel to otherwise difficult to reach places seem promising for digital sustainability education that is both accessible and socially just. Applications for German-speaking learners are however rare, and it has often not been checked whether those that exist are fit for classroom use. Therefore, this paper focuses on an investigation of the Virtual Reality (VR) learning application "On Biodiversity's Tracks", developed by greenpeace, with a focus on the environment of the Amazon rainforest. In an experimental study, (1) VR-based and (2) traditional lesson conditions were compared in terms of their effects on self-appraisal of knowledge, interest, and attitude. Pre- and post-questionnaires were used to uncover between-subject and within-subject effects. 172 students at eight secondary schools in Germany were recruited. The results revealed that both experimental conditions were effective regarding increase of self-appraised knowledge. An increase in interest was barely found in either condition. Changes at the attitudinal level could mostly not be discovered. Further analyses highlighted that, unlike the experimental conditions, there were significant differences in self-rated learning outcomes between the types of schools. In general, our results indicate that VR learning applications can contribute to the teaching of topics such as sustainability and biodiversity in a target group-oriented and meaningful way. However, further research is needed to adequately assess VR learning effectiveness, especially regarding affective learning outcomes, due to their importance for sustainable behaviors of subsequent generations.

Keywords Biodiversity · Sustainable development goals · Virtual reality · Media pedagogy

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Introduction

It has been roughly nine years since the United Nations (UN) launched their agenda for 17 Sustainable Development Goals (SDGs). Their purpose is to serve as a general call to action to improve life on Earth (United Nations, 2015). Among those goals are the annihilation of poverty, establishing responsible methods of production and consumption, climate action, preserving life below water and on land, bringing peace, and establishing strong institutions. Many of the problems underlying those goals are interlinked: poverty leads to irresponsible resource extraction, leads to danger to life on land and climate change, leads to war, leads to poverty. The importance of this web of world affairs warrants generating awareness of the UN's SDGs. Many countries, among them Germany, have included the 17 SDGs as a guideline for school curricula (Læssøe et al., 2009; Singer-Brodowski et al., 2019). Ideally, knowledge conveyed in schools would contribute to turning students into responsible adults. This goes hand in hand with another SDG: quality education (United Nations, 2015). As of 2023, German K-12 schools have just about started going digital, due to the COVID-19 pandemic. German schools struggled with socio-economic disparities, expressed in the lacking access to digital devices for many working-class students (Giesinger, 2021; Kerres, 2022). Additionally, many teachers were still inexperienced in the proper use of digital media, which includes creating a fit between student needs and the way learning content is presented medially. This may raise engagement and interest in the topics to be learned (Brame, 2016).

One way of addressing the students' need for engaging classes could potentially be provided by Virtual Reality (VR), a form of highly immersive virtual environment (Makransky & Petersen, 2021), that has shown to improve students participation (Setyowati et al., 2023). VR is a promising learning technology that allows users to immerse themselves in three-dimensional environments. It offers an ethical way to experience virtual on-site learning while being physically safe and not disrupting local communities or ecosystems. Furthermore, it has the capability to enable interactive learning experiences, since it can actively involve the learner in the learning process by reacting dynamically to the learner's movement and behavior (Wu et al., 2020). For environmental education, VR is discussed as a feasible tool to allow individuals to engage in experiences that evoke the necessary level of concern and emotional engagement regarding climate change and biodiversity decrease, all while maintaining physical safety (Singer-Brodowski et al., 2022). Additionally, access to natural environments is constrained for a significant portion of the population, with projections indicating that an additional 2.5 billion people will reside in urban areas within the next 28 years (Bologna & Aquino, 2020; Intergovernmental Panel on Climate Change (IPCC, 2023). This trend will inevitably restrict experiences of nature to those with the requisite resources of time and money for travel. Simultaneously, ensuring that the majority of people experience natural reserves, such as the Amazon rainforest, is incompatible with effectively conserving these reserves. VR technology offers cost-effective and sustainable alternatives to enable first-person experiences while also safeguarding the environment. Previous research has highlighted its potential to foster environmental affection, enhance willingness to protect nature and biodiversity, and prevent harmful behaviors (Stenberdt & Makransky, 2023). Hence, VR learning applications can provide users a first-person perspective, enabling them to comprehend potential actions within a virtual world and engage with challenges and tasks. Hereby, this immersive experience can stimulate the exploration of knowledge, values, and emotions within the learning context (Kors et al., 2016). We assume that VR can provide a physically safe environment in which individuals can explore the biodiversity of foreign and distant habitats. By immediately experiencing natural environments, strong affective and cognitive processes can be explored, fostering self-reflection on one's role in our ecosystem (Stenberdt & Makransky, 2023).

Nevertheless, it requires more research to derive when and under what circumstances VR is appropriate to ensure a profound understanding of environmental issues, increase public interest in such topics, and promoting pro-environmental attitudes and behavior (Petersen et al., 2020; Queiroz et al., 2023; Stenberdt & Makransky, 2023). Currently, the implementation and evaluation of VR in formal educational settings (e.g. schools) surrounding the learning about sustainability has yet to happen on a larger scale, since educational VR applications on the topic are quite rare, especially in the German language (Smutny, 2022). Thus, our article examines for the first time the utilization of a German-language and VR-based application on biodiversity in K-12 school classrooms. An experimental study was conducted to address the following research question: To what degree can VR applications improve students' self-appraised knowledge on, interest in and attitude towards environmental sustainability? With our present study, we aim to contribute to the discussion on the potential of VR technologies to foster sensible attitudes and behavior towards the environment and its sustainability.

Theory

Literature review

VR is utilized to create impactful and life-like experiences for users. It is a unique technology due to its ability to provide presence, the sensation of being present in the virtual environment, and agency, allowing users to interact autonomously (Makransky & Petersen, 2021). VR opens up an entirely new quality of learning and teaching as it facilitates a shift from information-centric to experiential learning (Plechatá et al., 2022a, 2022b).

Meta-analyses have demonstrated that VR-based instruction can yield superior learning outcomes compared to traditional educational methods (Coban et al., 2022; Wu et al., 2020). Across various educational settings, including K-6 (Villena-Taranilla et al., 2022), K-12, and higher education (Di Natale et al., 2020; Pellas et al., 2021), VR has shown effectiveness. Its efficacy is particularly notable in enhancing conceptual and procedural knowledge acquisition (Andreasen et al., 2019; Makransky et al., 2019a, 2019b), promoting knowledge transfer to real-world contexts (Araiza-Alba et al., 2021), and providing experiences that are otherwise unfeasible, hazardous, or costly in the physical world (Markowitz & Bailenson, 2021). Hence, making use of VR technology offers a wide variety of possible designs for learning scenarios (Elmqaddem, 2019; Fowler, 2015; Kavanagh et al., 2017).

It is noteworthy that a large portion of empirical studies on VR follows a comparative research design (Buchner, 2023; Mulders, 2023a). This means that VR is often compared with the instruction that has traditionally taken place, often referred to as traditional teaching. Traditional teaching is said to often involve the use of conventional media, which primarily refers to analog or print media, and less commonly includes other digital media such as PowerPoint-supported presentations. In our article, we adhere to the connotation of the latter terminologies.

When studies compare VR with other digital and/or analog methods, they often consider different learning outcomes. Common observed learning outcomes in VR environments include learning achievement (P. Kim, 2006), affective measures and engagement

(Bodzin et al., 2024), or student satisfaction (Ryan & Poole, 2019). Regarding learning achievement, previous studies show some support for VR-based instruction. A study on 139 high school students revealed that VR could benefit knowledge transfer if used as a pre-training before the actual learning material was presented (Calvert & Hume, 2023). A research and development study showed better learning outcomes in a VR-based history class than in a class that used conventional media (Setyowati et al., 2023). Users of a VR-based game that trains people for the event of a flood overwhelmingly agreed or strongly agreed that they learned a lot though this kind of intervention (Araujo-Junior et al., 2024). Car painters in vocational training expressed that VR-based training supported acquisition of knowledge, competencies, and attitudes (Mulders et al., 2023; Tai et al., 2022). Students of a vocational school performed better on a knowledge test about wind turbines after a VR-intervention on the topic (Kapp et al., 2022). Training in VR may also increase knowledge about and intention to perform cardiopulmonary resuscitation (Liu et al., 2022). In a meta-analysis comprising 35 experimental or quasi-experimental studies, Wu et al. (2020) found that Head-mounted display (HMD)-based VR is more effective than desktop-based VR, especially for K-12 students and in science education. HMD generally refers to devices like VR-goggles that the user wears directly on their head. Other implementations of VR would be, for example, desktop-based VR, where learners navigate and view virtual environments though a computer screen and its periphery devices, or handheld VR, where users hold a handheld device as a viewport, but navigate through the motion of their own body (Wu et al., 2020).

Overall, current research trends indicate that VR-based instruction can be an effective support tool. Moreover, VR has shown positive effects on motivational and attitudinal factors as well. Bodzin et al. (2021) found that high school students expressed positive attitudes towards learning with VR technology and frequently experienced a flow state. The same authors measured high engagement and perceived learning in 139 participants using a desktop-based VR application (Bodzin et al., 2024). Another study revealed generally positive attitudes of undergraduate students towards participating in VR-based teaching (Hill & du Preez, 2021). Furthermore, it could be shown that students believe in the effectiveness of VR. HMD-based VR led to higher satisfaction in students and was more frequently recommended by them, while resulting in less knowledge gain than VR on a laptop (Mulders, 2023b). Also, students found learning about algorithms via a virtual world interesting and motivating and thought it helped them understand explanations better than a black board would have (Mateu & Alamán, 2013), although the setup included manipulation of real-world objects and was considered as Mixed Reality by the authors. Lin and Wang (2021) discovered that VR could help foster self-efficacy and partially intrinsic motivation in language learning. This points toward affective and motivational factors being a key strength of VR tools. However, attitudinal change often goes along with knowledge acquisition (Sinatra & Seyranian, 2015; Vaughn & Johnson, 2018). Lindgren et al. (2016) found that Mixed Reality that demands whole-body effort leads to greater positive attitude towards science than a desktop version of the same application. Painter apprentices showed an overall positive attitude towards VR training and retrospectively said that VR training supports knowledge, skills, and attitude acquisition equally (Mulders et al., 2023b). Another study found a non-significant positive change in attitude towards science in both 2D and 3D presentation of VR, where posttest attitude was strongly linked to pretest attitude (P. Kim, 2006).

Not all empirical research rates VR to be beneficial. In one study, university students learning about procedures in a biology lab using an HMD perceived higher presence than students in the desktop condition but performed worse on the following knowledge test and showed overall higher cognitive load (Makransky et al., 2019a, 2019b). This is in line with another study that finds increased spatial presence and cognitive load for immersive VR using an HMD compared to a desktop (Breves & Stein, 2022). HMD users in that study also reported higher levels of cybersickness, a subtype of motion sickness that includes symptoms like dizziness, nausea, or headaches.

In sustainability education, VR technology has been increasingly utilized. It is said to be a promising technology for educating individuals about sustainability issues and pro-environmental practices (Markowitz & Bailenson, 2021; Taufik et al., 2021). There is a growing body of literature examining the effects of VR on sustainability education (e.g. Scurati et al., 2021). VR has been positioned as an alternative to other interventions such as printed information material or public campaigns (Nisa et al., 2019), demonstrating promising transferability of behavior and knowledge from simulated to real-world settings (Araiza-Alba et al., 2021). For instance, Taufik et al. (2021) emphasize its effectiveness in teaching consumers new behaviors, Markowitz and Bailenson (2021) as well as Ahn et al. (2014) highlight its utility in promoting pro-environmental behavior, and Di Natale et al. (2020) underscore its role in contextualizing school learning. Moreover, users often report finding VR more engaging than conventional instructional materials, and it has been successful in generating interest (Makransky & Mayer, 2022). In an experimental study (desktop-based vs HMD-based VR), Makransky and Mayer (2022) investigated how the level of immersion of a virtual field trip influences the VR's effectiveness in a classroom setting, using a climate-change-related trip to Greenland. They discovered that the field trip experienced using HMDs led to greater presence, enjoyment, interest, and retention compared to using desktops. Plechatá et al., (2022a, 2022b) conducted another study and found that VR can increase students' intentions to engage in pro-environmental behavior, as well as their knowledge and ability to transfer that knowledge. In a study by Markowitz et al. (2018), another VR simulation for environmental education was examined by testing different users: high school students, college students, and adult participants. Their findings indicated that the simulation not only enhanced knowledge about ocean acidification but also increased interest in the topic. However, studies with inconclusive or negative findings regarding the effectiveness of VR for sustainability education also exist. For example, Spangenberger et al. (2022) examined whether embodying a tree in VR increased nature connectedness. While increased immersion raised nature connectedness, they found no differences in the effectiveness of the two media types. Similarly, Soliman et al. (2017) investigated whether watching a nature video using HMDs increased nature relatedness and pro-environmental behaviors. They found that while it did increase nature relatedness, it did not enhance pro-environmental behaviors. Furthermore, like Spangenberger et al. (2022), they found no difference in the effectiveness between technologies (HMD vs desktop).

Previous research suggests that VR can effectively support sustainability education due to its ability to create a sense of presence, and agency. Regarding the impact of presence, prior studies indicate that HMD-based VR might have the same impact on pro-environmental behavior (Stenberdt & Makransky, 2023) or nature connectedness (Spangenberger et al., 2022) as less immersive technology (e.g. desktop-based VR), provided the same level of presence. In our study, we utilize a VR application for mobile devices (e.g. tablets) that shows the habitat of humans and animals living at the Amazon rainforest. The application was developed by the non-profit organization greenpeace. In an experimental study, we compared this VR application to a traditional teaching lesson using conventional media. We examined its effects on three learning outcomes: self-assessed knowledge, interest, and attitudes.

Hypotheses Our literature review found that utilizing VR technology in a learning environment usually increases learning achievement or perceived learning (Araujo-Junior et al., 2024; Kapp et al., 2022; Liu et al., 2022; Mulders et al., 2023b; Setyowati et al., 2023; Tai et al., 2022). Additionally, many studies (e.g. Coban et al., 2022; Wu et al., 2020) have been able to demonstrate the superiority of VR compared to other conventional media representations. Therefore, it can be assumed that the VR application developed by greenpeace will be able to create similar effects.

H1a Self-assessed knowledge of students in the VR condition will increase between the pretest and the posttest.

H1b The difference in self-assessed knowledge between pretest and posttest will be higher in the VR group than in the control group.

The literature review also showed that VR is an effective way to increase students' interest in the topic at hand or class in general (Lin & Wang, 2021; Mateu & Alamán, 2013). Therefore, it can be assumed that the VR application will be able to increase interest in biodiversity and sustainability.

H2a Interest of students in the VR condition will increase between the pretest and the posttest.

H2b The difference in interest between pretest and posttest will be higher in the VR group than in the control group.

The previous findings on attitudinal change in VR imply that attitudinal change via VR technology is generally possible (Bodzin et al., 2021; Hill & du Preez, 2021; P. Kim, 2006; Lindgren et al., 2016; Mulders et al., 2023b). With the literature encountered, it can be assumed that the VR application will lead to a more positive attitude towards biodiversity and sustainability.

H3a Attitude of students in the VR condition will be more positive in the posttest than in the pretest.

H3b The difference in attitude between pretest and posttest will be higher in the VR group than in the control group.

Method

Background

Greenpeace is a transnational non-profit organization that aims at peacefully protecting the earth's climate and environment. They have recently developed "On Biodiversity's Tracks" (German translation "Der Artenvielfalt auf der Spur"), a virtual environment designed for classroom use that allows students to explore various places like the Amazon rainforest, the Great Barrier Reef, or a supermarket, and viewing information on the people, animals, items, and environment there. This is framed to expand the students' knowledge, as well as express the importance of the SDGs, raise interest in them, and aims to change attitudes and behaviors (greenpeace, 2022).[1]

Design

This study set out to evaluate the greenpeace VR application (Greenpeace, 2022) regarding its ability to (1) increase students' self-appraised knowledge of and (2) interest in, as well as (3) its ability to improve students' attitude towards sustainability and biodiversity. In a broader sense, this study also evaluated the general use of VR technology in a classroom setting in comparison to traditional lessons using conventional teaching materials. Complementary to this between subject design, pre- and post-intervention online questionnaires were used in a within subject research design to assess direct effects. The test condition (VR-based vs traditional lesson/control group) served as the independent variable. Increase in self-appraised knowledge and interest, as well as attitude improvement were the dependent variables.

Participants

Datasets of a total of 172 students at eight schools in five German federal states were usable. Students were aged between 12 and 19 years ($M = 13.54$, $SD = 1.09$), with one 19-year-old being an outlier, putting them into seventh to ninth grade. Outliers regarding age were students currently seeking refuge in Germany, whose competency levels were assessed by the schools to be at those grade levels. Out of the 172 students, 66 (38.4%) identified as female, 102 (59.3%) as male, and three (1.7%) as non-binary, while one participant did not answer this question. Schools were approached directly by greenpeace and notified their teachers about the possibility to participate in this experimental study. Teachers that agreed to participate with one or more of their classes were given a sheet containing information about the experiment (see Appendix A). Parents and students were given the same information and the opportunity to opt out of the study. Classes entered test conditions as a group, however teachers with multiple classes were asked to conduct one experimental and one control group each.

In total, 108 students in eight classes were assigned to the VR condition, while 64 students in four classes entered the control condition. German secondary schools can be classified as follows (Ashwill, 1999; Salden & Hertlein, 2020): (1) General school (*Hauptschule*) is usually attended by students with below average grades whose parents often have a low level of education. Students in this school type are also more likely to have an immigration background (Freitag & Blaeschke, 2021; Nold, 2010). They pursue practical, hands-on careers after completing their education. These schools often emphasize basic academic skills and vocational preparation, leading to apprenticeships or vocational training (Pietsch & Stubbe, 2007). (2) Middle school (*Realschule* or *Mittelschule*) is usually attended by students with average grades. Such schools offer a more balanced curriculum, blending academic and practical subjects, and is designed for students who may continue into vocational training or pursue further education (Pietsch & Stubbe, 2007). (3) The academic track high school (*Gymnasium*) allows students to enter tertiary education after completing its exit exam and is frequently attended by students with above average grades.

[1] The app can be found under https://artenvielfalt-auf-der-spur.de/

This school type represents the most academically rigorous secondary school (Pietsch & Stubbe, 2007). Parents of students in this school type are often well educated (Freitag & Blaeschke, 2021; Nold, 2010). (4) High school or comprehensive school (*Gesamtschule*) attempts an egalitarian approach of unifying all of those school types, similar to an American high school, while the combined school (*Oberschule*) only combines general school and middle school. This school type allows students to follow a flexible learning path based on their individual performance and interests. Such schools promote a broad-based education and provide various graduation options.

In our study, the largest group of students ($n = 62$) attended the academic high school track. Another 57 attended high school. The remaining 53 attended either middle school, general school, or the combined school.

Instruments

A preliminary version of both questionnaires was tested with seven students (aged between 12 and 14 years). This piloting sample took between 4 and 13 min to work the pretest, and 18–23 min to work the posttest. One student with dyslexia was unable to finish the posttest. Some of the items were adapted for legibility and easier to understand language. Upon reviewing the material for the VR group, teachers raised concerns that they would not be able to adapt the regular material of their control group classes to convey the exact same information. To accommodate the teachers, the knowledge questions pertaining to specific learning content from the VR application were dropped from the control group post-questionnaire. These included items like "Which resources are being extracted from the Amazon rainforest?".

The pretest consisted of demographic questions on school form, home state, age, and gender, as well as three 5-point Likert-scale items to gauge prior experience with environmental protection and sustainable development and one 5-point item for student self-appraisal (comparable to the assessment in Leonard & Fitzgerald, 2018) of knowledge on these topics (Table 1). In addition, two items measuring interest in the Amazon rainforest and biodiversity as well as three items on attitudes towards the development in the Amazon rainforest were assessed, all of them 7-point Likert-items. To measure "green" consumer values of the students, defined by Haws et al., (2014, p. 337) as "the tendency to express the value of environmental protection through one's purchases and consumption behaviors", all six 5-point Likert-items of the Green-Scale (Haws et al., 2014), more specifically a translation by Spangenberger (2021), were adapted and implemented. Finally, the 10 5-point Likert-items of the scale for Common Attitudes Towards Environmental Protection and Sustainable Development (German translation *Allgemeine Einstellungen zum Umweltschutz und einer Nachhaltigen Entwicklung*, or *Umweltschutzskala*, USS, Rieß & Mischo, 2008; Waltner et al., 2021) were included to further measure attitudes. For all Likert-scales, ranges and scale anchors were retained from the original questionnaires.

For the posttest, the self-appraisal items for experience, but not the one for self-assessed knowledge, were dropped. Students were asked the same questions regarding their interest as in the pretest. The control group received slightly different versions of the questionnaires. Any in-text references to the VR application were replaced with references to the lesson as a whole. The items on app-specific learning gains as mentioned above were excluded from the control group questionnaire. It should be noted that the questionnaires contained more items than were analyzed for the present paper. Both the pre- and posttest questionnaire can be found in the appendix (see Appendix B).

Table 1 Sample items for self-appraised knowledge, knowledge, interest, attitude, Green Scale (Haws et al., 2014; Spangenberger, 2021), and Environmental Protection Scale (Rieß & Mischo, 2008; Waltner et al., 2021)

Instrument	Item		Answer options
	English	German	
Self-assessed knowledge (1 item)	"How substantial would you rate your knowledge on the Amazon rainforest?"	"Wie gut schätzt du dein Wissen zum Amazonas-Regenwald ein?"	"1 no knowledge – 5 rich body of knowledge"
Knowledge (4 items, VR only)	"Which resources are being extracted from the Amazon rainforest?"	"Welche Rohstoffe werden aus dem Amazonas-Regenwald gewonnen? "	Free text
Interest (2 items)	"To what degree are you interested in the Amazon rainforest?"	"Wie sehr interessierst du dich für den Amazonas-Regenwald?"	"1 not at all – 7 very strongly"
Attitude (3 items)	"To what degree do you think that the situation in the Amazon rainforest affects us and our environment in Europe?"	"Wie sehr glaubst du, dass die Lage im Amazonas-Regenwald uns Menschen und unsere Umwelt in Europa betrifft?"	"1 not at all – 7 very strongly"
Green Scale (6 items)	"My purchase habits are affected by my concern for our environment."	"Meine Einstellung zu unserer Umwelt beeinflusst meine Kaufgewohnheiten."	"1 fully disagree – 5 fully agree"
Environmental Protection Scale (10 items)	"I am concerned when I think about the environmental and social conditions under which we and future generations will likely have to live."	"Es beunruhigt mich, wenn ich daran denke, unter welchen ökologischen und gesellschaftlichen Verhältnissen wir und die nachfolgenden Generationen wahrscheinlich leben müssen."	"1 fully disagree – 5 fully agree"

Procedure

Teachers received a briefing with precise instructions on February 15th, 2023, and were given the opportunity to ask further questions in case of uncertainty. Experiments started no longer than two weeks after the teachers' briefing and concluded roughly a month after the briefing was held. The investigation was completed on March 27th, 2023. The lessons were conducted independently by the teachers in both conditions. Researchers were not present at any time.

Each teacher opened the lesson with a short greeting and introduction to the lesson's topic. Following this, students used their smart devices to scan a QR-code that led them to the pretest implemented with the online survey tool *SoSciSurvey*. Afterwards, teachers provided a learning impulse with a short lecture on the 17 SGDs. The procedure then differs depending on the test condition: Whereas the control groups continued the lesson as prepared by their teacher, the VR groups began exploring the greenpeace VR application.

In the control groups, the teachers were asked to prepare the lesson on the Amazon rainforest themselves. The teachers were allowed to design the lesson freely, but they were advised in advance to conduct the lesson in a teacher-centered manner and to use printed materials. Hence, it can probably be assumed that the traditional lessons followed a teacher-centered, direct instruction model, grounded in behaviorist learning theory (e.g. Adams & Engelmann, 1996; Gagné, 1974). This approach emphasized structured content delivery, where the teacher guided the learning process using printed materials, offering less autonomy to the students.

In contrast, the VR condition was underpinned by constructivist learning principles, specifically discovery learning (e.g. Bruner, 1961; Clark, 2018), allowing students to actively explore the material in a self-directed and interactive manner. Following this approach, the VR groups used their own devices (here: tablets or smart phones) to start the greenpeace VR application with a focus on exploring the environment of the Amazon rainforest. Each student had one mobile device. They were encouraged to work on the application independently and on their own. Headphones were used to avoid distracting each other. The exploratory VR application functions as follows: After scanning a QR code, students see a globe on their devices. Using the touch function of their devices, they then select South America on the globe and travel to the Amazon rainforest, where they explore the living environment of various people and animals there. The virtual world is characterized by auditory (e.g. rainforest sounds, human voices) and visual content (e.g. intact vs non-intact rainforest) and can be freely explored by the students. Different interactions with virtual agents (e.g. native people, animals) are possible. An impression is given in Fig. 1. The exploration of the 360-degree environment is done through body movements (i.e. physically moving the device left and right, tilting it up and down) and reactions towards actions on their screens (e.g. speech bubbles by natives), which can be responded to with touch gestures. This explorative part of the lesson was only marginally accompanied by teachers (e.g. in case of technical difficulties). However, the teachers had no prior training regarding the use of VR technologies, but due to the voluntary nature of the study, it can be assumed that the teachers are used to work with digital technologies.

After approximately 20–25 min, students in both groups worked the posttest. The teachers then asked the students to discuss prospects of sustainability in small groups

Fig. 1 Screenshot from the greenpeace VR application on the Amazon rainforest. English translation of the speech bubble: What are you doing? What is important to you as a young woman?

until the end of the lesson. The duration of the entire lesson was about 90 min, or two 45-min standard lessons in German schools. As a follow-up, eight focus group interviews with the classes in the experimental condition were held within two weeks of completing the VR-based lesson. Results of those focus groups are reported on in another paper (Mulders et al., 2023) and will only be referenced for context during the interpretation of the present quantitative results.

Analytic process

Python (McKinney, 2022) and *R* (Fox et al., 2023; Jarek, 2012; Navarro, 2021; Revelle, 2023; Rosseel et al., 2023; Signorell et al., 2023; Yentes & Wilhelm, 2021) were used for data cleaning and subsequent analysis. The original dataset contained 630 cases, where pre- and posttest entries were separated. Cases belonging to the same participant were merged, empty and incomplete cases and those where a pretest could not be matched to a posttest were excluded from analysis, leaving us with 287 participants. Additionally, a check for straight-lining was implemented by checking for variance on the last page of each questionnaire that contained Likert scales and excluding cases where variance equaled 0 (Y. Kim et al., 2019; Leiner, 2019). While lack of variance by itself does not necessarily imply straight-lining, the pages in question contained multiple different scales (the Green Scale and Environmental Protection Scale). This procedure deleted another 115 cases, leading to the final 172 participants. Table 2 shows internal consistencies for the instruments used in this study, all of which were satisfactory.

Results

Descriptive statistics

For each scale with more than one item, the average score was computed. Upon a preliminary analysis, students from the combination school control condition were found to have significantly lower self-assessed prior knowledge than students from the academic track and combination school experimental conditions ($F(5, 165)=2.81$; $p=0.018$). Similarly, the academic track experimental group showed higher attitude in the pretest than the high school experimental and combined school control conditions ($F(5, 164)=3.29$; $p=0.007$). Based on these results, school type, separated into academic, high-school and the third combined category for middle, general and combination schools, will be regarded as an additional exploratory independent variable in the following analyses.

Table 3 shows the average pre- and posttest values as well as the mean difference (post minus pretest value) and standard deviations for the six groups: academic track students in the experimental group (AE, $n=38$), academic track students in the control group (AC, $n=24$), high school students in the experimental group (HE, $n=36$), high school students in the control group (HC, $n=21$), combination students in the experimental condition (CE, $n=34$), and combination students in the control group (CC, $n=19$).

Table 2 Internal consistencies

	Internal consistency (Cronbach's α)	
	Pretest	Posttest
Interest	0.83	0.91
Attitude	0.86	0.88
Green scale	0.81	0.88
Environmental protection scale	0.80	0.83

Table 3 Average scores, differences between pre- and posttests, and standard deviations

		AE	AC	HE	HC	CE	CC
Self-assessed knowledge (1 – 5)	Pretest	3.11 (0.65)	2.96 (0.71)	2.94 (0.94)	3.14 (0.91)	3.24 (0.71)	2.42 (1.17)
	Posttest	3.50 (0.86)	3.70 (0.70)	3.37 (0.97)	3.33 (1.06)	3.30 (0.77)	2.74 (1.15)
	Difference	0.39 (0.86)	0.74 (0.86)	0.43 (1.01)	0.19 (1.21)	0.06 (0.79)	0.32 (0.95)
Interest (1 – 7)	Pretest	4.91 (1.25)	4.46 (1.09)	4.42 (1.22)	4.21 (1.06)	4.62 (1.44)	3.82 (1.89)
	Posttest	5.01 (1.42)	4.93 (1.00)	4.42 (1.42)	4.62 (1.65)	4.37 (1.49)	3.58 (1.84)
	Difference	0.11 (0.75)	0.48 (0.72)	0.00 (1.23)	0.40 (1.15)	− 0.25 (1.57)	− 0.24 (0.75)
Attitude (1 – 7)	Pretest	5.61 (1.05)	5.23 (0.73)	4.71 (1.18)	4.83 (1.41)	5.35 (1.21)	4.49 (1.95)
	Posttest	5.82 (1.02)	5.42 (0.95)	4.70 (1.34)	5.11 (1.39)	5.46 (1.44)	4.72 (1.93)
	Difference	0.21 (0.70)	0.20 (0.69)	− 0.01 (1.40)	0.29 (1.40)	0.10 (1.27)	0.23 (1.02)
Green Scale (1 – 5)	Pretest	3.43 (0.70)	3.21 (0.48)	3.07 (0.61)	3.11 (0.72)	3.38 (0.79)	3.05 (0.78)
	Posttest	3.55 (0.81)	3.42 (0.64)	3.12 (0.72)	3.35 (0.83)	3.27 (0.88)	3.03 (0.89)
	Difference	0.12 (0.45)	0.21 (0.53)	0.05 (0.67)	0.24 (0.60)	− 0.11 (0.54)	− 0.02 (0.52)
USS (1 – 5)	Pretest	3.85 (0.60)	3.64 (0.62)	3.49 (0.63)	3.39 (0.74)	3.66 (0.54)	3.42 (0.69)
	Posttest	3.97 (0.61)	3.62 (0.52)	3.38 (0.63)	3.41 (0.69)	3.51 (0.66)	3.22 (0.80)
	Difference	0.11 (0.28)	− 0.02 (0.50)	− 0.12 (0.51)	0.03 (0.41)	− 0.15 (0.45)	− 0.20 (0.43)

AE Academic track experimental group, *AC* Academic track control group, *HE* High school experimental group, *HC* High school control group, *CE* Combined school experimental group, *CC* Combined school control group. *USS* Environmental Protection Scale. A positive difference denotes an increase between pre- and post-test. Range of Likert scales are indicated under variable names

Table 4 Homogeneity of variances

	df	*F*	*p*
Self-assessed knowledge	1, 167	4.24	**0.041**
Interest	1, 168	2.16	0.144
Attitude	1, 167	0.06	0.814
Green scale	1, 170	0.17	0.681
USS	1, 168	0.264	0.608

USS Environmental Protection Scale. Significant results are marked in boldface

Table 5 Change in self-appraised knowledge between pre- and posttest

	df	*t*	*p*	*d*
AE	37	2.84	**0.036**	0.46
AC	22	4.10	**0.007**	0.86
HE	34	2.51	0.058	0.43
HC	20	0.72	0.449	0.16
CE	32	0.44	0.522	0.08
CC	18	1.46	0.222	0.33

AE Academic track experimental group, *AC* Academic track control group, *HE* High school experimental group, *HC* High school control group, *CE* Combined school experimental group, *CC* Combined school control group. Benjamini–Hochberg correction has been used to adjust *p*-values. Significant results are marked in boldface

Hypotheses testing

For hypotheses 1a, 2a, and 3a, directional t-tests for dependent samples were used to determine the magnitude of change from the pre to the post measurement point. For hypotheses 1b, 2b, and 3b, a multivariate analysis of variance (MANOVA) was utilized. Data was checked for multivariate normality using the Shapiro–Wilk test, indicating a violation of the multivariate normality assumption ($W = 0.23$; $p < 0.001$). Homogeneity of variances was assessed with Levene's test. Table 4 shows the results for each of the dependent variables, indicating homogenous variances for all variables except for self-assessed knowledge. With multivariate normality violated and variances largely homogenous, Pillai's trace was picked as a test statistic for the upcoming MANOVA, since it offers decent robustness even if these assumptions are not met (Ateş et al., 2019). For the initial t-tests within the two experimental conditions, a Holm-Bonferroni correction was administered to adjust for alpha error accumulation (Holm, 1979). Since the inclusion of school type required many more t-tests, but was of exploratory nature, Benjamini–Hochberg correction was used to adjust the p-values for those tests (Benjamini & Hochberg, 1995). All p-values reported are one-tailed.

Hypothesis 1a A t-test revealed that the VR application led to a higher self-appraisal of knowledge, $t(105) = 3.47$; $p = 0.004$; $d = 0.34$. This effect is considered small (Cohen, 1988) but supports hypothesis 1a. Self-assessed knowledge of participants in the control group increased as well, with another small effect, $t(62) = 3.31$; $p = 0.007$; $d = 0.42$. Table 5 shows test results and effect sizes under consideration of school type. These imply that students at an academic track school profit knowledge-wise from any intervention. For high school students, the VR application created a small effect in gain of self-appraised knowledge, while falling just short of statistical significance. Neither of the other groups showed a significant increase.

While a proper knowledge test was only implemented in the experimental condition for reasons laid out in the chapter describing our instruments, those four items should be analyzed for better interpretability of the self-assessed knowledge measure. Students in the experimental group scored an average of 4.61 out of 8 possible points ($Md=4.5$; $SD=2.43$). An ANOVA revealed differences in the knowledge score between school types, $F(2, 105)=28.84$; $p<0.001$; $\eta^2=0.355$. Students in the academic track high schools ($M=6.36$; $SD=1.70$) scored significantly higher on the knowledge test than students from the combined school group ($M=4.49$, $SD=2.43$; $p<0.001$) and the high school group ($M=2.88$, $SD=1.75$; $p<0.001$). In turn, the combined school group reached significantly higher scores than the high school group, $p=0.003$. For the total sample, scores on the knowledge test correlated significantly with the self-assessed knowledge item in both the pretest ($t(106)=2.52$; $p=0.013$; $r=0.238$) and the posttest ($t(104)=3.72$; $p<0.001$; $r=0.343$).

Hypothesis 2a The VR application did not influence interest ($t(107)=-0.36$; $p=1$; $d=0.03$), nor did the control group ($t(61)=1.97$; $p=0.187$; $d=0.25$). Table 6 shows a breakdown over the six subgroups. None of the VR groups showed a significant increase in interest. Interest significantly increased in the control group comprised of academic track students, to a medium effect. Overall, hypothesis 2a must be rejected.

Hypothesis 3a When observing the test conditions alone, neither the VR application nor the traditional lesson showed a positive effect on any of the attitude measures we employed (Table 7). If school type is considered, the overall picture remains intact (Table 8). The academic track students in the experimental condition showed small effects regarding attitudes towards environmental protection, however not in a statistically significant manner. Furthermore, apart from students in the academic track experimental and high school control group, all other groups showed a trend towards a decrease in attitude towards

Table 6 Change in self-appraised interest between pre- and posttest

	df	*t*	*p*	*d*
AE	37	0.87	0.390	0.14
AC	21	3.13	**0.036**	0.67
HE	35	0.00	0.703	0.00
HC	20	1.62	0.182	0.35
CE	33	-0.93	0.970	0.16
CC	18	-1.37	0.970	0.31

AE Academic track experimental group, *AC* Academic track control group, *HE* High school experimental group, *HC* High school control group, *CE* Combined school experimental group, *CC* Combined school control group. Benjamini–Hochberg correction has been used to adjust *p*-values. Significant results are marked in boldface

Table 7 Change in self-appraised attitude between pre- and posttest

	df	*t*	*p*	*d*
VR Attitude	105	0.93	0.880	0.09
VR Green Scale	107	0.47	0.243	0.05
VR USS	105	– 1.09	1	0.11
Control Attitude	62	1.77	0.138	0.22
Control Green Scale	63	2.16	1	0.27
Control USS	63	– 0.99	1	0.12

USS Environmental Protection Scale. Holm-Bonferroni correction has been used to adjust *p*-values

Table 8 Change in self-appraised knowledge between pre- and posttest by test condition and school type

	df	*t*	*p*	*d*
AE Attitude	37	1.86	0.153	0.30
AE Green Scale	37	1.66	0.174	0.27
AE USS	36	2.45	0.058	0.40
AC Attitude	22	1.37	0.232	0.28
AC Green Scale	23	1.91	0.153	0.39
AC USS	23	– 0.19	0.712	0.03
HE Attitude	35	– 0.04	0.703	0.01
HE Green Scale	35	0.45	0.522	0.07
HE USS	35	– 1.35	0.970	0.23
HC Attitude	20	0.93	0.388	0.20
HC Green Scale	20	1.81	0.160	0.40
HC USS	20	0.32	0.567	0.07
CE Attitude	31	0.46	0.522	0.08
CE Green Scale	33	– 1.19	0.970	0.20
CE USS	32	– 1.89	0.970	0.33
CC Attitude	18	0.97	0.388	0.22
CC Green Scale	18	– 0.18	0.712	0.04
CC USS	18	– 2.01	0.970	0.46

AE Academic track experimental group, *AC* Academic track control group, *HE* High school experimental group, *HC* High school control group, *CE* Combined school experimental group, *CC* Combined school control group, *USS* Environmental Protection Scale. Benjamini–Hochberg correction has been used to adjust *p*-values

environmental protection as assessed by the USS. These results overall do not support hypothesis 3a, although the trend in the academic track experimental condition cautiously points towards attitudes being positively affected by some students.

Hypotheses 1b, 2b, and 3b

For group comparisons, a MANOVA was utilized. Our model examined the influence of test condition, school form and the interaction of those two variables on the pre-post-differences of self-appraised knowledge, interest, and three attitude scales. Test condition did not prove a significant factor in this model ($F(5, 153)=0.60$; $p=0.702$; $V=0.02$), neither did the interaction of condition and school type ($F(10, 308)=0.69$; $p=0.738$; $V=0.04$). School type was the only significant factor in this model ($F(10, 308)=1.93$; $p=0.041$; $V=0.12$). Therefore, hypotheses 1b, 2b, and 3b must be rejected. A correlation matrix of the dependent variables is provided in the appendix (see Appendix C).

Univariate comparisons revealed that school type was a significant predictor only for differences in attitude measured by the USS ($F(2, 157)=5.29$; $p=0.006$). Post-hoc Tukey-tests revealed that the academic track students specifically had a significantly higher change USS attitude ($p=0.016$) than students in the combined group. This fits the above result that USS attitude seemed to turn negative in the combined school group.

Discussion

Summary

Regarding hypothesis 1a, our results indicate that knowledge was gained in both conditions, at least according to students' self-assessment. However, since we found a significant correlation between our knowledge test and self-appraised knowledge, we can assume somewhat valid self-assessments by the students. It is noteworthy that the increase in knowledge was particularly high among students from the academic track school in both conditions.

It is also noticeable that students from the academic track school perform best in the knowledge test, and there is generally a large variation in the knowledge test results between different types of schools which possibly confirms the different performance levels at the different types of German school.

Concerning hypothesis 2a, our results illustrate that, except for one instance (academic track school in the control group), no increase in interest was observed in either condition.

Regarding hypothesis 3a, it should be noted that no significant increase in pro-environmental attitudes could be found. Only for one measurement method a non-statistically significant increase in the VR condition was found.

Hypotheses 1b, 2b and 3b all had to be rejected. Thus, differences between the conditions (VR vs traditional lesson) could not be uncovered, but differences between the types of schools were identified through an exploratory analysis. Interestingly, the type of school is relevant when interpreting our results. For example, students from the academic track school showed more of an increase in pro-environmental attitudes, while the effect is somewhat opposite for students from the combined school group, indicating a decrease in pro-environmental attitudes.

Implications

Both the VR application and the traditional lesson using conventional teaching methods were effective regarding the increase of self-assessed knowledge, meaning that the VR application can convey information comparably to methods that have probably been used by teachers for decades. The magnitude of effectiveness seems to be largely dependent on school type. Academic track students seemed to be able to work with any method equally well, whereas high school students seemed to have an easier time with the VR application. These findings are similar to those of Šikl et al. (2024) in which a significant influence of school type on learning was also observed. In their study, students with an academic background performed consistently better in the pretest than pupils at “lower” secondary schools and showed greater learning results on the topic of topography, regardless of the learning technology (VR vs PowerPoint slideshow). At the same time, students in the combined group of our study seemed to struggle with the VR application, possibly because the lack of prior knowledge in combination with the unfamiliarity of the new technology creates too steep of a learning curve (Hamilton et al., 2021). Indeed, some findings indicate that an optimization of cognitive load might be required to make VR-based applications more viable, for example by implementing instructional design principles like signaling (Albus et al., 2021) and pre-training (Pflieger et al., 2024). However, the traditional approach did not create a significant increase in self-appraised knowledge either.

The VR application was unable to create a change in interest, while the traditional lesson could only achieve an increase with academic track students. Focus group interviews with the students were conducted one to two weeks after they explored the application. Results of the focus group interviews were published in another paper (Mulders et al., 2023) and shall therefore only be mentioned in passing. Nevertheless, those study results indicated that many of the students were already interested in environmentalism prior to the lesson, implying that an improvement in interest would have been difficult to achieve. These qualitative results are supported the somewhat high pre-test values of interest (see Table 3).

For academic track students, the VR application showed only a slight but not significant ability to improve attitude as measured by the USS, while the traditional lesson could not achieve this. Some studies have suggested that academic track students are generally more likely to gather a quick understanding of topics presented to them (Guill et al., 2017). This means that they might have had a chance to reflect on the new information provided and change their attitude by the end of the lesson. Many of the students in our focus group interviews mentioned that they talked about the contents of the VR application with their classmates or family after the lesson had ended (Mulders et al., 2023). The fact that many students needed this time to reflect might explain the lack of improvement immediately after the lesson for most school types.

Overall, we did not find a difference between the two experimental conditions. This could be due to a methodological issue. Our study involves a comparison of media, where students either explored the Amazon rainforest in VR or they were taught the same topic through a teacher-centered lesson using printed materials. Consequently, these lessons do not only differ in the type of media presentation but also in other parameters (e.g. social form, instructions). Therefore, conducting a manipulation check is challenging. Possible differences in learning outcomes cannot be unequivocally attributed to the experimental manipulation. Thus, the results of such studies are biased (Buchner, 2023; Mulders, 2023a) and caution should be exercised when interpreting our study results. Future studies should aim to make the experimental conditions more comparable.

However, different from the experimental conditions, school type seems to play a big role in how effective the VR application is in its ability to foster knowledge, interest, and attitude. This might serve as a pointer for developers. Future applications should be fitted to a more specific target audience. Another possibility would be making applications more accessible to groups with little to no prior knowledge.

Limitations

This paper is subject to a few limitations. As implied above, the timing of the posttest questionnaire immediately after the lesson concluded might not have given students enough time to reflect on their experience with the VR application or traditional lesson. The teachers also added that the information density in the VR application was too high for many students, leading to cognitive overload (Buchner et al., 2022; Leahy & Sweller, 2011). Perhaps VR applications should be tested in shorter time frames than the 90-min lessons of this paper. Alternatively, more supporting materials could be provided to the teachers to better aid the students while they learn with the application.

Both teachers and students pointed out the length and high register of the questionnaires, making them exhausting and difficult to follow for many of the students. In the combined schools, instructions in the questionnaire were often misunderstood and hence not followed, leading to high dropout and few usable data entries. Future endeavors should more thoroughly test their material for inclusive language. Questionnaire length could have been accommodated by restricting the number of items to the bare minimum. While mainly established and validated scales were used, some self-conceived measures (i.e. for interest) were added. These often showed no effect, making it difficult to interpret them or assess their validity compared to other measures.

In our study, students in the experimental condition used their own mobile devices, mostly tablets. Among others, Wu et al. (2020) emphasized that learning with HMD-based VR, compared to desktop-based VR, is more beneficial to learning for K-12 students. Hence, it is possible and worth investigating in future scenarios whether the same app, when made available for HMDs, could have generated more measurable effects on knowledge, interest, and attitude.

The lack of supervision during the lessons poses another problem. This way, it remains unclear whether students in the experimental condition correctly used the application, or missed out on content that might have influenced their knowledge, interest, or attitude, which may in turn lead to higher variance within the sample. The procedure in the control group is even more so a black box, since teachers were given instructions to design their lessons in the way they traditionally would, not in a standardized way designed by the researchers. While we had hoped that comparing the regular classroom setting students were used to with a setting based on VR would increase the external validity of the experiment, it seemed to only further exacerbate the conceptual problems that lie within media comparison studies in general (Buchner, 2023; Mulders, 2023a). Additionally, because the greenpeace VR application is designed to retrieve as little personal data as possible, there is also no log data that could be investigated.

There are further methodological limitations that should be addressed: After concerns were raised by the teachers involved in this study, knowledge items were only included in the experimental condition, with one item measuring self-appraised knowledge in both conditions. On one hand, self-appraisal of knowledge is not always accurate, as the oft-cited *Dunning-Kruger effect* shows (Dunning, 2011). It is therefore entirely possible that students overestimated their knowledge in the pretest, leading to a smaller measured change in knowledge than actually took place. Also, removing the proper knowledge items from the control group posttest also hindered an adequate comparison between the two groups. On the other hand, there is a significant correlation between the four knowledge items in the experimental condition and the self-appraised knowledge item, indicating that the assessment of students of their own knowledge is at least somewhat accurate. Next, the 40% dropout rate due to straight-lining may have biased our data by selectively removing less engaged participants. This exclusion could result in a sample skewed toward more motivated students, potentially leading to unreliable data and affecting the generalizability of our findings. Future studies should consider incorporating attention checks or more engaging assessments to reduce straight-lining and mitigate this potential bias. Another potential limitation of our study is the variance introduced by class assignment, which was not accounted for in the analysis. Differences between classes, such as teaching style or classroom dynamics, could have influenced the outcomes independently of the experimental condition. Future studies should use multilevel modeling to control for class-level variance of potentially nested data.

Conclusion

There is no stopping the digitization trend in German classrooms. With the ubiquity of cell phones and approaches like the flipped classroom (Akçayır & Akçayır, 2018), learning behavior might increasingly shift away from dedicated time slots and towards a perpetual process embedded into the daily lives of students. Holding a functioning, effective, and efficient application that can foster this kind of learning in our literal hands may prove valuable. For the most part, we failed to find attitude-level changes immediately following the VR application experience. However, the follow-up focus group interviews indicate that such attitudinal changes can be generated in students after reflecting on the experience (Mulders & Träg, 2023). It can be concluded that the virtual world generated by greenpeace offers a different approach to the Amazon rainforest topic. In contrast to traditional teaching methods that focus on the acquisition of knowledge, the focus of the greenpeace VR application is more on the affective experience and emotional engagement of the students. Accordingly, in another study, we were able to uncover that learning outcomes significantly relate to affective learning processes such as experiencing presence and flow, indicating that learning with VR is qualitatively different (Mulders & Träg, 2023). In principle, the greenpeace VR experience draws upon the attitudes of students. And while an immediate change in attitude or behavior after a single lesson is utopian, the initiated change in attitude may well guide future sustainable behavior (Ajzen & Fishbein, 2000). Overall, teaching SDGs and turning students into responsible adults has never seemed to be more achievable than now. If VR and other digital media are made available, individuals would be given the opportunity to engage in immersive experiences regarding issues of sustainability, while decreasing the chance of physical harm (Singer-Brodowski et al., 2022). However, a short intervention like ours may not have been sufficient to induce significant changes in students' environmental attitudes or to translate these attitudes into long-term behavioral intentions. To address this, future studies should consider longer intervention durations or multiple sessions to better gauge the impact on environmental attitudes and behavior.

Furthermore, our results suggest that weaker learners may require additional guidance when using the VR application, as their limited prior knowledge might hinder their ability to focus on relevant content. This aligns with the *expertise reversal effect* (Kalyuga, 2007), where instructional supports benefit novice learners but can overload the working memory of more experienced learners. For stronger learners, such aids may become redundant or even counterproductive. Future VR designs should consider adaptive guidance, providing support tailored to the learner's expertise level to optimize cognitive load and learning outcomes. Regarding future research, it would be interesting to explore the expertise reversal effect using Artificial Intelligence techniques. Avatars, as a form of conversational agent (Khosrawi-Rad et al., 2022), could possibly adapt to the learners prior knowledge. For a VR application to be conducive to learning for students of different school types and thus with varying levels of prior knowledge, it should be adaptable. For example, for students with weaker learning abilities, (1) pre-training could be incorporated, (2) an avatar could offer additional background knowledge as needed, or (3) the learning pathway could be segmented. In contrast, for academically strong students, these aids could be omitted as they may further burden working memory (Kalyuga, 2007). Building on this, future studies could also examine cognitive load induced by missing prior knowledge, due to the addition and removal of additional guidance within a VR application. Hence, the VR application developed by greenpeace seems to need revision to be conducive to learning for students in all types of schools. Nevertheless, in this study, we did not examine the students' prior knowledge in detail, nor did we verify whether they had already gained experience with VR technologies. In order to assist students according to their prerequisites, this should be appropriately assessed in the future.

Additionally, pedagogical guidelines for teachers could be developed to help create a smoother experience (Fischer et al., 2021). For example, recommendations on how teachers should approach implementation before, during and after the VR experience might be helpful.

As indicated by the results of the questionnaires presented in this article as well as the focus group interviews (Mulders & Träg, 2023), future endeavors should examine the implementation of the greenpeace VR application not only in singular lessons. Instead, voluntary classes or more project-oriented learning environments that enable more degrees of freedom and therefore allow for more elaborate preparation, supervision, and contiguous and socially embedded reflection should be considered. This type of controlled environment would also facilitate the investigation of possible mediators and moderators related to VR, like flow or presence (Csikszentmihalyi, 1997; Makransky & Mayer, 2022; Mulders & Träg, 2023).

In summary, this study was able to provide initial insights into the extent to which an VR learning application can contribute to the teaching of the 17 SDGs in schools. A revision of the previous VR application and the exploration of its effectiveness considering different learning objectives (e.g. cognitive, affective) and student-specific learning abilities seems indicated.

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Declarations

Conflict of interest There is no conflict of interest. The evaluation study was commissioned by greenpeace, but then conducted and analyzed independently by scientists of the University of Duisburg-Essen. Greenpeace covered the costs of one student assistant for the duration of the evaluation.

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