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Mastery experiences in immersive virtual reality promote pro-environmental waste-sorting behavior

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ABSTRACT

The rapid digitalization following COVID-19 necessitates best-practice knowledge on how to use educational technologies such as immersive virtual reality (IVR). At the same time, to deal with climate change, we require new ways to embed climate change education in formal education. The current study is one of the first to investigate the feasibility of an alternative educational approach to improving waste management in the classroom as part of formal education, utilizing mastery experiences in IVR. We explore the use of a novel IVR simulation on waste management, an example of pro-environmental behavior, for climate change education. A total of 173 high school students participated in a pre-registered intervention investigating the impact of IVR on knowledge and intentions to act pro-environmentally. A 2x2 design was used to compare different design approaches to the IVR simulation based on the instructional design elements of the instruction sequence (Direct Instruction vs. Productive Failure) and feedback (Corrective Feedback vs. Exaggerated Feedback). The results indicated that IVR was effective for increasing students' knowledge ($\eta^2 = 0.41$), intentions ($\eta^2 = 0.10$), self-efficacy ($\eta^2 = 0.4$), and response efficacy ($\eta^2 = 0.35$) and that students found the simulation interesting and enjoyable. Furthermore, self-efficacy was found to predict intentions ($B = 0.190$, $p = .015$), supporting the idea that cognitive and affective factors drive the effectiveness of IVR. No significant differences were found in the effectiveness of the instructional design elements. This suggests that IVR can be an effective educational technology for learning through mastery experiences, but that more research on the boundary conditions of how and when to apply different instructional design elements effectively is needed.

1. Introduction

The COVID-19 pandemic has led to rapid digitalization in education (Bygstad et al., 2022). This has resulted in an increased pedagogical focus on areas such as 21st-century skills (e.g., digitalization and digital competencies; Bygstad et al., 2022) and the reduction of digital inequality (González-Betancor et al., 2021). Additionally, climate change is becoming ever more evident (UNEP, 2021; UNESCO & UNFCCC, 2016). The prevalence of climate-related changes in our environment has increased the importance of climate change education (Janakiraman et al., 2021; Varela-Candamio et al., 2018). For instance, the United Nations Framework Convention on Climate Change's call for action (United Nations, 1992, article 6) has produced multiple areas in which to intervene to adapt to and mitigate climate change. Among these is the implementation of obligatory courses on climate understanding and

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individual behavior anchored in formal education (UNESCO & UNFCCC, 2016). We therefore need empirical knowledge about effective ways to teach individuals about the pro-environmental actions that are available to them (Martínez-Borreguere et al., 2019; Maurer & Bogner, 2020). This could for example be acquired through research investigating what educational technologies and instructional design elements to employ to succeed in this endeavor.

In the current paper, we present and discuss the design and evaluation of a novel immersive virtual reality (IVR) simulation, targeting climate change education through mastery experiences in a classroom setting. The specific behavior and knowledge domain targeted by the simulation was waste management, an operationalization of the construct of pro-environmental behavior. According to a recent report, waste management is a promising area for abating climate change (UNEP, 2021). The waste sector is responsible for 20% of anthropogenically-caused methane fluxes in the atmosphere, and the climate abatement potential from improving waste management is promising for 2030 (UNEP, 2021). Furthermore, this potential almost doubles when calculating for the projected effects in 2050 (UNEP, 2021).

Improved source separation of waste is important for the successful management of waste in an environmentally friendly way (Taufik et al., 2021; Ye et al., 2020). This requires improved citizen education on how to source-separate at home (Hole & Hole, 2020). An important target for climate change education in schools could then be teaching students how to handle their waste, as waste management can be both overwhelming and unintuitive (Ye et al., 2020). One central misconception such programs can target is the belief that separation of waste at home is not important, since it will be separated industrially regardless (Ritchie, 2018). While policymakers have begun to implement more comprehensive waste-sorting systems, these are only effective when used correctly, which is not always easy. For example, a recent report from the Danish municipality of Copenhagen found that more than half of citizens reported that sorting waste into 10 categories is too difficult and that they need more knowledge about how to sort their waste (Miljøstyrelsen, 2022). Additionally, citizens have primarily been informed about waste management through written material such as mail or brochures (Miljøstyrelsen, 2022), which has been found to have a limited effect on learning and behavior change (Nisa et al., 2019). The current study is one of the first to investigate the feasibility of an alternative educational approach to improving waste management in the classroom as part of formal education, utilizing mastery experiences in IVR.

To do this effectively, the employed simulation was designed based on up-to-date knowledge about effective instructional design in IVR. This is important, as instructional design is often overlooked in the development of IVR simulations (Radianti et al., 2020), but the underlying instructional design elements are important for IVR's effectiveness (Pellas et al., 2021). While meta-analyses have shown that IVR has a small effect size advantage over other media when it comes to learning (Wu et al., 2020), it is not a given that IVR will be effective (Pellas et al., 2021). This is also emphasized by the immersion principle of multimedia learning, which highlights that immersive lessons are only effective when they use appropriate instructional design elements (Makransky, 2021). Furthermore, a recent study highlighted how teachers select application-based learning content for their classroom primarily based on research-based educational benchmarks and evidence-based knowledge, showing that it is important to explicate the evidence that educational IVR simulations build on (Montazami et al., 2022). Many examples of studies finding inconclusive effects of IVR on learning exist (Pellas et al., 2021). Because of this, the current paper only investigates the use of IVR, and the first underlying research question of this paper concerns a manipulation check of whether the IVR simulation can be shown to be effective in general. This will be further operationalized in Section 2.

Research Question 1. Is IVR an effective educational technology for climate change education in a high school classroom setting?

A second and connected goal of the current research is increasing our understanding of the underlying, psychological mechanisms leading to the effectiveness of IVR for learning and behavior change. In the field of climate change education, discussion about how to combine cognitive and affective learning objectives is ongoing (Brundiers et al., 2021; Fischer et al., 2022). Immersive theories and principles of learning including the cognitive affective model of immersive learning (CAMIL; Makransky & Petersen, 2021), the extended model of immersive learning in VR (EMIL VR; Vogt, 2021), the emotional design principle of multimedia learning (Plass et al., 2022), and the immersion principle of multimedia learning (Makransky, 2021) describe the role of cognitive and affective processes in learning. In this paper, we build on these theories to explore the connection between psychological variables and outcome variables. The psychological variables were *interest* (a measure of how attentive and engaged a person is in something; Hidi & Renninger, 2006; Krapp, 2005), *enjoyment* (a measure of positive affect and a feeling of fun; Makransky et al., 2019b; Di Natale et al., 2020), *self-efficacy* (a person's belief in their ability to overcome challenges and complete tasks; Bandura, 1977), and *response efficacy* (the belief that actions make a difference; Plechatá et al., 2022a). The outcome variables were *knowledge about waste management* (measured as the number of items sorted correctly into waste management categories), *intentions to sort waste* (measured on a five-point Likert scale), and *transfer* (measured as the ability to sort novel waste items into correct categories). This leads to the second underlying research question of the current paper, which will be operationalized further in Section 2.1.

Research Question 2. What psychological mechanisms drive the effectiveness of IVR for climate change education?

The third research question furthers the agenda of understanding the differential effectiveness of IVR depending on design, using a 2x2 design. On the one axis, we manipulated the presentation of the *feedback* participants received (Corrective Feedback vs. Exaggerated Feedback). On the other axis, we investigated the *instruction sequence* (Productive Failure vs. Direct Instruction). This was done to learn more about *how* to design IVR simulations to be most effective for self-directed learning and problem-solving success. Mamun et al. (2022) emphasize the importance the underlying instructional design elements when engaging students in self-directed online learning, as self-directed learning is becoming ever more common with the current surge in digital and blended learning. However, while Mamun et al. (2022) studied how students' pedagogical approaches influenced their gains from self-directed online learning, we instead focus on how the underlying instructional design elements employed in designing IVR learning content influence students' learning gains. Based on this, Research Question 3 is as follows and will be operationalized further in Section 2.2 and 2.3.

Research Question 3. When designing IVR for climate change education, do different instructional design elements influence its effectiveness?

The structure of the paper is as follows. In Section 2, we describe existing empirical and theoretical literature on IVR, as well as previous findings regarding the psychological factors and the presented instructional design elements (Productive Failure, Direct Instruction, Exaggerated Feedback, and Corrective Feedback), to build our hypotheses. In Section 3, we present the methodological details of the study, including the data collection procedure, the analysis plan, the participants, and the materials used. In Section 4, our results are presented. In Section 5, we discuss the empirical contributions, practical implications, and limitations of our findings, as well as possible avenues for future research.

2. Theoretical and empirical background and hypotheses

In this paper, *IVR* is understood as life-like simulations delivered through head-mounted displays (HMDs), allowing the user to partake in meaningful actions in a virtual world (Slater, 2009; Slater & Sanchez-Vivez, 2016). IVR is a unique technology because it affords *presence*, the "feeling of being there," and *agency*, the ability to interact on one's own volition (Makransky & Petersen, 2021). Furthermore, IVR allows for learning through embodied experiences, such as using bodily movements to control and interact with the IVR environment (Johnson-Glenberg, 2019). Meta-analyses indicate that IVR-based lessons can be more effective for learning compared to traditional educational methods (Coban et al., 2022; Wu et al., 2020). IVR has also been shown to be effective in K–6 (Villena-Taranilla et al., 2022), K–12, and higher education settings (Pellas et al., 2021; Di Natale et al., 2020). The effectiveness of IVR has been found especially in connection to learning conceptual and procedural knowledge (Makransky et al., 2019a; Andreasen et al., 2019), in increasing transfer of knowledge to the real world (Araiza-Alba et al., 2021), and in allowing experiences that are impossible, dangerous, or too expensive to provide in the real world (Bailenson, 2018; Markowitz & Bailenson, 2021). One of the advantages of IVR is that it allows users to interact with 3D objects in a way that other media cannot (Pellas et al., 2021), which can be beneficial for learning complex knowledge (Azhar et al., 2018). This can also be an initial support for the generation of mental models (Vogt et al., 2021).

IVR is seeing increased use in the field of pro-environmental behavior change as a promising technology for educating people about pro-environmental behavior (Markowitz & Bailenson, 2021; Taufik et al., 2021). There has also been a rise in the literature on the effects of IVR for climate education (e.g., Scurati et al., 2021). Immersive experiences make it possible to move from information-based to experience-based learning (Plechatá et al., 2022c), making it possible to learn through mastery experiences. This allows learners to build mental models (networks of information that help us understand the world; Vogt, 2021; Vogt et al., 2021) that are based on experiences. IVR has been used as an alternative to existing interventions, such as public campaigns or information pamphlets (Nisa et al., 2019), as the technology has been shown to offer good transfer of behavior and knowledge from simulation settings to real-world settings (Araiza-Alba et al., 2021). For example, Ahn et al. (2014) and Markowitz and Bailenson (2021) emphasize its use in pro-environmental behavior, Taufik et al. (2021) emphasize its effectiveness in teaching consumers new behaviors, and Di Natale et al. (2020) emphasize its ability to contextualize school learning. Furthermore, people frequently report finding the technology more enjoyable to use than traditional teaching measures, and IVR has also been used with success to foster interest (Makransky & Mayer, 2022), self-efficacy, and response efficacy in students (Plechatá et al., 2022b; Markowitz & Bailenson, 2021). For example, Plechatá et al. (2022b) ran a field study on ninety 7th- or 8th-grade students as part of their education. They found that the simulation increased students' intentions to behave in a more pro-environmental way, as well as their knowledge and their ability to transfer their knowledge (Plechatá et al., 2022b). Furthermore, they found that students' self-efficacy was important for this increase (Plechatá et al., 2022b). Markowitz et al. (2018) ran four experiments, showing effectiveness for high school student, college student, and adult participants alike (Markowitz et al., 2018). The purpose of their investigation was to learn more about how IVR simulations can be used for environmental education (Markowitz et al., 2018). They found that their simulation increased not only knowledge about ocean acidification but also interest in the topic (Markowitz et al., 2018). Makransky and Mayer (2022) investigated how the level of immersion of a virtual field trip (comparing use of a desktop display to an HMD) might drive the effectiveness of the simulation in a classroom setting, using a climate-change-related field trip to Greenland. They found that the field trip experienced in an HMD led to higher presence, enjoyment, interest, and retention than the similar desktop experience (Makransky & Mayer, 2022). However, examples of studies with inconclusive or negative findings regarding the effectiveness of IVR for climate change education also exist. For example, Spangenberger et al. (2022) investigated whether experiencing the embodiment of a tree in IVR leads to higher nature connectedness. While they did find that increased immersion (regardless of media) raised nature connectedness in participants, they did not find any differences in the effectiveness of the two media (Spangenberger et al., 2022). Similarly, Soliman et al. (2017) investigated whether watching a video of nature in an HMD could increase nature relatedness and pro-environmental behaviors. They found that watching a nature video did increase nature relatedness but did not increase pro-environmental behaviors (Soliman et al., 2017). Furthermore, like Spangenberger et al. (2022), they did not find a difference in the effectiveness of an HMD compared to a desktop display (Soliman et al., 2017).

Previous research has thus suggested that IVR can be effectively used for climate change education, in part because of its ability to create the illusion of presence, the feeling of agency, and the experience of embodiment. The above literature then leads to our first preregistered hypothesis, related to Research Question 1, investigating whether the use of our educational IVR simulation on pro-environmental waste management behavior in a high school classroom setting can generally increase intentions and knowledge.

Hypothesis 1. The intervention will in general lead to a significant pre-to post-test increase in intentions (H1A) and knowledge (H1B).

2.1. Psychological processes behind climate change education

To design successful IVR simulations, we need to understand *how* our simulations produce changes in learners. In the literature, many educational and psychological factors have been implicated to understand the processes behind the acquisition of knowledge, behavioral intentions, and transfer. For example, Raghu and Rodrigues (2020) present different theories of behavior and behavior change, and Grilli and Curtis (2021) present different approaches to behavior change interventions. Some of these are interest, enjoyment, self-efficacy, and response efficacy (Di Natale et al., 2020; Raghu & Rodrigues, 2020). Interest has long been emphasized as important for education (Dewey, 1913). Theories such as Krapp's (2005) person-object theory of interest, Hidi and Renninger's (2006) four-phase model of interest development, the CAMIL (Makransky & Petersen, 2021), the emotional design principle of multimedia learning (Plass et al., 2022), and the immersion principle of multimedia learning (Makransky & Mayer, 2022) all recognize the importance of interest for educational outcomes. Similarly, Di Natale et al. (2020), in a review of the use of VR in K–12 and higher education, highlight how the interests of learners are central when facilitating learning. Lee et al. (2022) suggest that interest might be important because it increases the emotional engagement of people in their learning, while Tai et al. (2022) suggest that interest might increase participants' experience of flow, helping them learn. Similarly, Makransky and Mayer (2022) show how interest and time on task are related, suggesting that increased situational interest will also increase the amount of time students will be attentive towards the learning material. Interest can also be an important predictor of future learning (Makransky & Mayer, 2022). This follows the argument of Krapp's (2005) person-object theory of interest, which suggests that situational interest is necessary for the evolution of individual interests. Hidi and Renninger's four-phase model of interest development (2006) also suggests that the development of interest can be divided into multiple, sequential phases, going from something situationally bound to an underlying predisposition to engage with a specific type of material. This is also in accordance with the emotional design principle of multimedia learning, highlighting how affective factors foster cognitive processing (Plass et al., 2022). Further, IVR has been found to have a positive effect on students' enjoyment, which can increase effort and time on task (Di Natale et al., 2020).

Raghu and Rodrigues (2020) highlight how self-efficacy is central in multiple theories as an important factor for influencing pro-environmental intentions and behavior such as waste management. Similarly, in a meta-analysis, Klöckner (2013) found self-efficacy to be an important factor in the success of pro-environmental behavior interventions. Furthermore, self-efficacy has been identified as the strongest predictor of future academic success (Richardson et al., 2012). Likewise, Plechatá et al. (2022a) indicate how self-efficacy is an important factor for developing pro-environmental intentions and behavior. The best way to improve self-efficacy is through mastery experience—that is, the experience of succeeding at something (Bandura, 1977, 1997). The protection motivation theory links the combination of self-efficacy and response efficacy to pro-environmental behavior (Plechatá et al., 2022c; Rogers, 1975). In accordance with this, response efficacy has been identified as important for pro-environmental behavior, as convincing people to change their behavior requires teaching them what behaviors can make a meaningful difference and why (Klöckner, 2013; Brügger et al., 2015).

The aforementioned research has highlighted the importance of self-efficacy, response efficacy, interest, and enjoyment and that IVR may be especially good at fostering these psychological factors. Because of this, in this study, we were interested in testing whether the simulation has an influence on measures of self-efficacy, response efficacy, interest, and enjoyment relating this to Research Question 2.

Exploratory Hypothesis 1. IVR has a positive effect on students' self-efficacy and response efficacy.

Exploratory Hypothesis 2. Students report high interest towards and enjoyment of the learning content in the IVR simulation.

As previously highlighted, the design of IVR simulations is important for their effectiveness (Pellas et al., 2021; Makransky, 2021), and one should consider both what underlying cognitive (Vogt, 2021) and affective (Plass et al., 2022) processes one seeks to activate. We expect that the effectiveness of the IVR simulation in terms of increasing students' knowledge, intentions, and transfer will depend on the simulation's ability to influence students' self-efficacy, interest, response efficacy, and enjoyment, under the assumption that these factors stimulate cognitive and affective processing in the students. To increase the likelihood of our simulation achieving this, we developed it based on up-to-date empirical findings regarding the design of IVR. These design decisions are highlighted briefly in Section 3.4. We thus wished to investigate whether our simulation would have an effect on students' interest, self-efficacy, response efficacy, and enjoyment, and whether this in turn would have an influence on their intention, knowledge, and transfer outcomes, as illustrated by Exploratory Hypothesis 3.

Exploratory Hypothesis 3. Students' intention, knowledge, and transfer outcomes will be influenced by their interest, self-efficacy, response efficacy, and enjoyment.

2.2. Exaggerated Feedback

One of the strengths of IVR compared to many existing educational technologies, as well as analog teaching methods, is its ability to make possible that which is not possible in the real world, while remaining believable. For example, Markowitz and Bailenson (2021) emphasize this potential in relation to pro-environmental behavior, Di Natale et al. (2020) emphasize it in relation to experiential learning, and Pellas et al. (2021) emphasize it in exploring hidden or scientific phenomena. One way this has been used is through the instructional design element of Exaggerated Feedback, in relation to participants' behavior in simulations (Hsu et al., 2018). This type of feedback makes the long-term consequences of behavior immediate, allowing people to see what the consequences of their actions would be in the far future (Hsu et al., 2018). Additionally, this feedback often has exaggerated consequences, showing the effects of repeated behavior or what would happen if many people performed the same action (Hsu et al., 2018). Hsu et al. (2018) used Exaggerated Feedback to influence 165 Taiwanese senior high school student's water conservation behavior, by having them flush a toilet and shower in IVR, while showing them the influence on a central water container as well as the environment. They found that the student's cognitions about, attitudes towards, and intentions for pro-environmental water conservation behavior increased through the experience and that the demonstrated changes in the environment had a significant influence on these outcomes (Hsu et al., 2018).

Similarly, Ahn et al. (2014) investigated how Exaggerated Feedback in IVR could be used to foster pro-environmental paper conservation behaviors. They compared the effectiveness of three different educational technologies: an IVR simulation, a print message, and a desktop condition (Ahn et al., 2014). Participants were first given information about paper conservation and then either experienced or read about cutting down a tree, while seeing the changes in a forest environment (Ahn et al., 2014). They found that Exaggerated Feedback in the IVR experience had a more positive effect on participants' behavior, compared to the other educational technologies (Ahn et al., 2014).

Investigating whether IVR can be used to reduce hot water consumption, Bailey et al. (2015) utilized Exaggerated Feedback related to participants' hot water use in a simulation. The more hot water a participant used in IVR, the more coal a virtual avatar would consume (Bailey et al., 2015). They found that participants subjected to the Exaggerated Feedback used colder water after their experience (Bailey et al., 2015).

We therefore hypothesize that adding Exaggerated Feedback to the simulation will increase students' intentions towards sorting their waste, by making the consequences of their actions more immediately visible. Based on the aforementioned research and Research Question 3, we thus pre-registered the hypotheses that the instructional design element of Exaggerated Feedback will have an influence on participants' intentions (H2), as well as their gameplay (H3).

Hypothesis 2. Students in the Exaggerated Feedback conditions will report significantly higher post-test intentions toward waste management than students in the Corrective Feedback conditions, controlling for pre-test scores.

Hypothesis 3. Students in the Exaggerated Feedback conditions will perform significantly better than those in the Corrective Feedback conditions in the in-game behavioral task.

2.3. Productive Failure

In addition to allowing users to experience things that would otherwise be difficult or impossible to experience, IVR allows users to do so in an environment that is safe (Di Natale et al., 2020; Markowitz & Bailenson, 2021). This creates opportunities for more learner-centered forms of education, which have been highlighted as an affordance of virtual reality (Makransky & Petersen, 2021). It can, for instance, allow users to openly explore the virtual environment without prior instruction or safety precautions, benefitting experiential learning strategies, where people learn by doing, rather than by instruction (Pellas et al., 2021).

One experiential learning strategy that can be used is Productive Failure (Kapur, 2008), which has shown how failure can be beneficial for learning. Kapur (2008) compared the learning outcomes of three-person student groups solving well-structured problems with groups solving ill-structured problems (Kapur, 2008). He found that the groups working with ill-structured problems not only showed more heterogenous solutions, but also a higher degree of failure; however, these groups outperformed their peers on later problem-solving, showing a delayed but increased effect of failure on learning (Kapur, 2008).

Productive Failure has also been investigated using IVR. For example, Lohre et al. (2021) report on a case of IVR being used for surgical training after a failed operation. After the failed operation, the surgeon was allowed to train and fail without consequence in IVR. The IVR environment helped the surgeon train, and the second operation was more successful (Lohre et al., 2021). Lohre et al. (2021) highlight how this use of the technology can be important, because failures during surgery can be fatal or at least increase post-surgery risks. Similarly, learning pro-environmental behavior in real life situations can be considered suboptimal, as failure will have real consequences.

Another strength of training in IVR is that transfer to real life scenarios can be stronger than when using other educational technologies, such as desktop simulations (Zhang et al., 2020). Zhang et al. (2020) studied the performance of 55 junior high school students using an IVR-assisted or a traditional class for learning about architecture and biology. They found that the traditional class and the IVR-assisted class had similar results concerning the dissemination of simple, well-structured material, but that IVR had an edge on the traditional class when disseminating ill-structured, complex content (Zhang et al., 2020).

We therefore hypothesize that because IVR allows users to learn through experiences and to fail without consequence, designing IVR learning experiences based on the principles of Productive Failure can increase learning. Based on this, our pre-registered hypothesis is that an IVR simulation about waste management utilizing Productive Failure could be beneficial for students' learning and transfer (H4) as well as increasing their performance in the gameplay scenario (H5). These hypotheses relate to Research Question 3.

Hypothesis 4. Students in the Productive Failure conditions will have a significantly higher post-test knowledge score (controlling for pre-test score) (H4A) and a significantly higher transfer score (H4B) than participants in the Direct Instruction conditions.

Hypothesis 5. Students in the Productive Failure conditions will perform significantly better than those in the Direct Instruction conditions in the in-game behavioral test.

3. Methods

3.1. Procedure

The study was pre-registered on osf.io (https://osf.io/fqebr). The study was an intervention study taking place in a natural setting, as a part of Danish high school students' education. We utilized a 2x2 design with four distinct IVR instructional design elements: instruction sequence (Productive Failure vs. Direct Instruction) x feedback (Corrective Feedback vs. Exaggerated Feedback). We collected data using a questionnaire before and after the IVR experience, as well as raw data from the simulation. The questionnaire was made using formr.org (Arslan et al., 2018). The entire experiment took on average 54 min to complete. This consisted of 15 min for the pre-test, 24 min for the simulation, and 15 min for the post-test. Test values were calculated by averaging items within each scale. When relevant, change scores were calculated by subtracting pre-test averages from post-test averages. Additional information on questionnaire items and the scales used can be found in the supplementary material.

3.1.1. Analyses

The analysis strategies for all hypotheses were pre-registered. They are briefly presented here. Hypothesis 1 was investigated using a repeated-measures ANOVA with the within-group independent variable of time and the dependent variables of knowledge (H1a) and intentions (H1b). Hypotheses 2 and 4a were investigated utilizing two ANCOVAs controlling for pre-test scores with the independent variable of Feedback (Exaggerated Feedback/Corrective Feedback) or Instructional Design (Productive Failure/Direct Instruction), and the dependent variable of post-test intentions or knowledge, respectively. Hypotheses 3 and 5 were investigated utilizing a Mann-Whitney *U* test, as the data was not normal distributed, with in-game behavioral task score (number of correctly sorted items) as the dependent variable and, respectively, feedback (Exaggerated Feedback/Corrective Feedback) or instruction sequence (Productive Failure/Direct Instruction) as the independent variable. Hypothesis 4b was investigated utilizing a one-way ANOVA with post-test transfer score as the dependent variable and instruction sequence (Productive Failure/Direct Instruction) as the independent variable. The results of these analyses are presented in Sections 4.1 and 4.3.

In addition, we investigated pre-registered exploratory analyses, which we present in the following section. Our pre-registration also included exploratory hypotheses about the influence of student demographics, as well as longitudinal effects. There were no major findings to report related to student demographics, and the response rate for the longitudinal measures was 7%, which was too low to perform meaningful statistical analyses. Exploratory Hypothesis 1 was investigated similarly to Hypothesis 1, using a repeated-measures ANOVA for the psychological variables self-efficacy and response-efficacy. Exploratory Hypothesis 2 was investigated by simple descriptive data, looking at the mean rating and standard deviation of interest and enjoyment items reported by participants after experiencing the simulation. Exploratory Hypothesis 3 was investigated using regression analyses with the change scores of the psychological variables (except for interest and enjoyment, which was only assessed in the post-test) to see whether they predicted the change scores of the measured dependent variables of knowledge and intentions, and the post-test score on transfer. The significant findings of these analyses are presented in Section 4.2.

3.1.2. Participants

Our a-priori power analysis, conducted using G*Power 3.1 (Faul et al., 2007), indicated that we needed a sample of 138 students to conduct our 2x2 ANOVA analyses, based on an expected effect size of $f = 0.31$ (taken from Ahn et al. (2014), who also studied behavior change using IVR) and a high power of 0.95 ($\alpha = 0.05$). Because we collaborated directly with schools, we pre-registered a conservative stopping rule of including a maximum of 200 students. This allowed us to include whole classes and accounted for potential drop-out. We collected data from 185 students but excluded 12 students from our analyses based on pre-registered rules (see Table 2). Our final sample thus consisted of 173 students (127 male, 43 female, 3 non-binary). The average age of the students was 17.68 ($SD = 1.78$). For more information on our sample, see Table 1. Furthermore, some analyses were conducted with a reduced sample because of pre-registered rules, as indicated by a superscripted "b" in Table 2. For instance, 12 participants scored perfectly on pre-test intentions, and 13 participants had no simulation data collected due to an internet malfunction, leading to a reduced sample in the intention and in-game behavior tests. Furthermore, one person did not respond to the enjoyment and interest questions. These cases of missing data were handled by conducting the related tests with a reduced sample.

Table 1
Expanded descriptive statistics ($N = 173$).

Grade	First year		Second year		Third year
	90 (52%)		53 (30.6%)		30 (17.3%)
Experience with IVR	0	1	2 to 10	11 to 50	51 +
	26 (15%)	27 (15.6%)	59 (34.1%)	25 (14.5%)	36 (20.8%)
English proficiency	Not at all	Not well	Well	Very well	Native speaker
	1 (0.6%)	2 (1.2%)	37 (21.4%)	123 (71.1%)	10 (5.8%)

Table 2
Participants excluded (total = 185, included = 173, excluded = 12).

Exclusion criteria	Number of participants	% (of 185)
High cybersickness[a]	11	5.9%
Did not understand instructions[a]	1	0.5%
Perfect behavior in pre-test[a], [b]	12	6.5%
Lacking simulation data[a], [b]	13	7%

[a] Pre-registered data exclusion criteria.
[b] Only excluded from specific analyses.

4. Material

The simulation used for this experiment was created using the Unity3D Game Engine. The simulation had five segments: tutorial, instruction, practice task, in-game behavioral test, and feedback (see Fig. 1). The instructions and practice task were reversed in the Productive Failure conditions. The individual segments will be described below.

4.1. *Segments of the Simulation*

In the following, the different segments of the simulation will be described. Screenshots from the simulation can be seen in Fig. 2.

4.1.1. *Tutorial*

Students started in a brief tutorial segment, where a virtual agent welcomed them and gave them information about the experiment and how to control their virtual avatar (see Fig. 2, Panel A). Tutorials have been shown to be important for IVR experiences, as the technology is still novel for many users, which can make it difficult for users to engage in the experience if no hands-on instructions are given on how to interact in the immersive virtual environment (Checa et al., 2021; Zaidi et al., 2019). This is also in accordance with the pre-training principle of multimedia learning (Meyer et al., 2019), instructing students on the central controls and the features of the immersive virtual environment before they explore it (Taçgın, 2020). The students then walked with the virtual agent into an apartment room (see Fig. 2, Panel B) with 12 waste bins matching the categories from the Copenhagen waste management system (Copenhagen Municipality, 2021; Copenhagen Municipality, N.D.). On the ground were 24 pieces of waste—two for each waste category (See Fig. 2, Panel E).

4.1.2. *Instruction*

The instruction segment took place through a PowerPoint presentation that appeared on one of the walls (see Fig. 2, Panel C). The virtual agent took the participant through this presentation, showing four prototypical examples of waste from every category. Furthermore, participants were told about the effects of incorrect waste-sorting on the environment. This was done because concrete information about how to act has been identified as important when fostering pro-environmental behavior (Klöckner, 2013) and because it has been found that climate change information should be communicated in a way that makes it clear that it is relevant to the individual (Brügger, 2020). Additionally, the instruction segment was designed following the modality principle, the voice principle, the personalization principle, and the redundancy principle of multimedia learning (Baceviciute et al., 2020; Mayer & Fiorella, 2021). The following is an example of instruction for bio waste: "The first category is bio waste. Bio waste is biodegradable waste. Here are some examples. [The examples were fish and meat, bread, eggs, and fruit; see Fig. 2, Panel C.] Outside, you can see the main effects of sorting bio waste incorrectly. See how the factory emits more greenhouse gases and how the trees are losing their leaves due to acid rain" (only for the Exaggerated Feedback conditions; see Fig. 2, Panel D).

4.1.3. *Practice task*

The main activity of this simulation was the waste management task: to sort every piece of waste in the room into the 12 categories

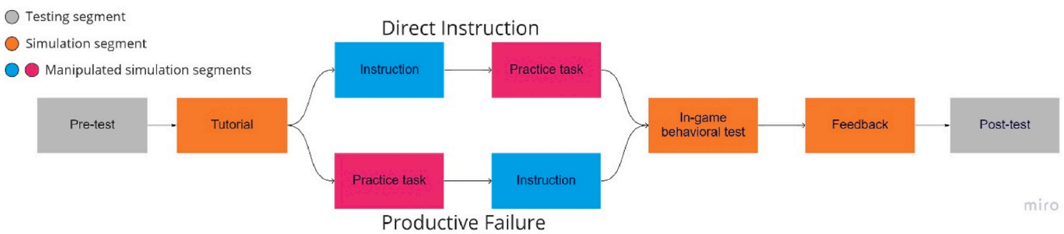

Fig. 1. Structure of the experiment, including each segment of the simulation. Grey segments were part of the data collection. The orange, blue, and red segments were part of the IVR experience. The blue and red boxes illustrate the order of the Productive Failure and Direct Instruction conditions. The color-blind friendly palette was taken from https://personal.sron.nl/~pault/. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

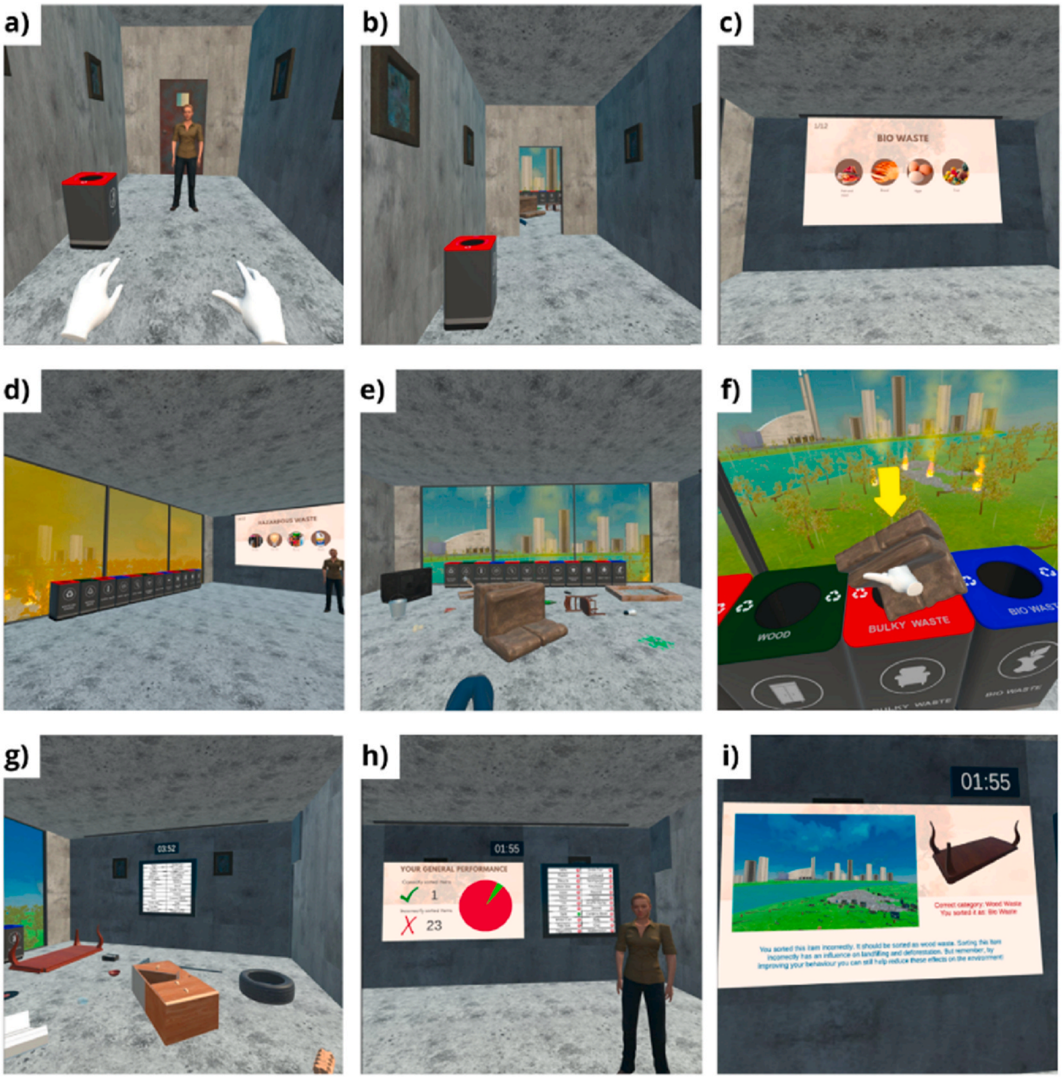

Fig. 2. Screenshots from the simulation: (a) the virtual avatar welcoming the participant to the simulation; (b) the tutorial just having finished, and the door to the first test room opening; (c) the informational slide about bio waste being shown; (d) the virtual avatar talking about the effects of a waste category; (e) the beginning of the first waste-sorting task with Exaggerated Feedbac; (f) a view of the participant sorting waste into a waste bin with Exaggerated Feedback; (g) the beginning of the waste management test; (h) the first part of the end-of-simulation feedback; and (i) the second part of the end-of-simulation feedback.

represented by the waste bins (See Fig. 2, Panels E and F). This was based on experiential learning, allowing people to learn by actively performing a relevant task (Pellas et al., 2021). This task was also central for allowing students to achieve mastery experience. The participant first meets this activity as a practice task, helping them get a feel for the game and allowing them to use their knowledge in a safe environment. The simulation was designed like this to create a lesson that would accommodate both Direct Instruction and Productive Failure, making it possible to practice either before receiving instruction or after receiving instruction. At the start of the task, the virtual agent tells the participant about why waste management is important for the environment and what they have to do (See Fig. 2, Panel D). A whiteboard is present in the room, with the name of every piece of waste written on it (See Fig. 2, Panel G). When the participant picks up a piece of waste, the corresponding name on the whiteboard is highlighted. This is done in accordance with the signaling principle of multimedia learning (Ibrahim et al., 2012), helping people easily decipher what piece of waste they were holding. Whenever the participant sorted a piece of waste, the corresponding name on the whiteboard was appended with either a checkmark or an X, depending on whether the participant sorted the waste correctly or incorrectly. The task ended once the participant sorted all 24 pieces of waste.

4.1.4. In-game behavioral test

The second waste management task was a timed test, in which participants had 4 min to sort 24 new pieces of waste in a room similar to the first task (See Fig. 2, Panel G). The timer was added to make the experience more challenging, building on the principles of gamification; it has been found that challenge positively influences student's learning when playing serious games (Hamari et al., 2016; Riopel et al., 2019). Participants were teleported to this room by pressing a button during their last segment, allowing them to start the timer themselves.

4.1.5. Feedback

The last segment consisted of performance feedback for the participant. This consisted of two elements: a slide showing their overall performance and 24 slides giving them feedback on each sorted piece of waste from the test. The slide showing overall performance was a simple count of correctly and incorrectly sorted items (see Fig. 2, Panel H). This was followed by 24 slides giving feedback on individual items: where the item belonged, whether it was sorted correctly, and the positive effects of the correct sorting of this item on the environment (see Fig. 2, Panel I). This segment was added because the feedback principle of multimedia learning dictates that explanatory feedback is beneficial for novice learners (Johnson & Priest, 2014).

5. Exaggerated Feedback

The participants in the Exaggerated Feedback condition experienced one key difference in the simulation: During their practice task, the environment would already be heavily marked by the effects of incorrect waste management. Furthermore, whenever these participants sorted a piece of waste, their choice would influence the effects on the environment, depending on which category of waste they sorted (see the supplementary material for more details). If they sorted the waste correctly, the corresponding effects would decrease, while they increased if they sorted the waste incorrectly. The changes in the environment were exaggerated in a manner that sorting one item was meant to reflect the effects of many people sorting this type of waste in this way for a long time, leading to severe effects on the environment (see comparison in Fig. 3).

6. Results

6.1. Effectiveness of the Simulation

An overview of the results can be seen in Table 3. When analyzing the general effectiveness of the simulation, we found a medium-to-large and significant increase in participants' ($N = 162$) intentions from before the intervention 3.96 ($SD = 0.75$) to 4.19 ($SD = 0.88$) after the VR intervention, $F = 18.43$, $p < .001$, $\eta^2 = 0.10$. Similarly, we found a significant, large increase in participants' (N = 173) knowledge about waste management from before the intervention ($M = 7.67$, $SD = 1.48$) to after the intervention ($M = 8.97$, $SD = 1.80$), $F = 121.47$, $p < .001$, $\eta^2 = 0.41$. In conclusion, participants both showed higher intentions to sort their waste and an ability to correctly sort waste into more categories than before the VR experience, showing support for hypotheses H1a and H1b (see Fig. 4) (see Table 3).

When investigating Exploratory Hypotheses 1 and 2, we found the following: the pre-post variables all showed a significant increase over time. Self-efficacy had a positive, large increase, from 3.59 ($SD = 0.74$) before the intervention to 4.15 ($SD = 0.61$) after the intervention, $F = 110.91$, $p < .001$, $\eta^2 = 0.4$. Response efficacy showed a medium-to-large positive increase, from 4 ($SD = 0.68$) to 4.45 ($SD = 0.67$), $F = 91.56$, $p < .001$, $\eta^2 = 0.35$ (see Fig. 4) (see Table 3). Finally, participants, on average, reported an interest in learning

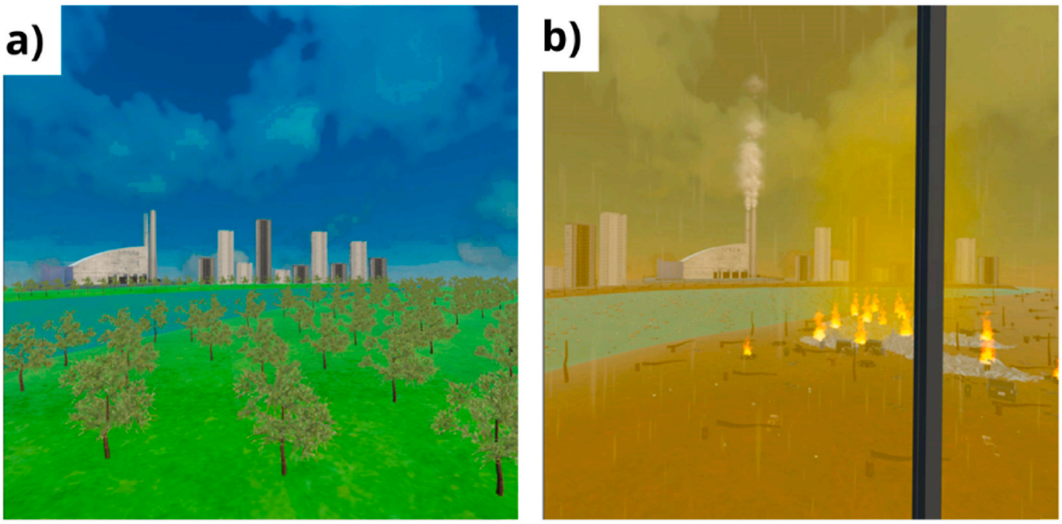

Fig. 3. Screenshots from the simulation, showing the environment (a) without Exaggerated Feedback and (b) with high levels of Exaggerated Feedback.

Table 3
Overview of results for change over time hypotheses.

Hypothesis		Before	After			
Hypothesis 1	*N*	*M* (*SD*)	*M* (*SD*)	*F*	*p*	η^2
H1a: Intentions	162	3.96 (0.75)	4.19 (0.88)	18.43	<.001	0.10
H1b: Knowledge	173	7.67 (1.48)	8.97 (1.80)	121.47	<.001	0.41
Exploratory Hypothesis 1		Before	After			
	N	*M* (*SD*)	*M* (*SD*)	*F*	*p*	η^2
Self-efficacy	173	3.59 (0.74)	4.15 (0.61)	110.91	>.001	0.4
Response efficacy	173	4 (0.68)	4.45 (0.67)	91.56	>.001	0.35

Table 4
Overview of results for instructional design element comparisons.

Hypothesis	Exaggerated Feedback		Corrective Feedback			
H2: Intentions	*M* (*SD*)	*N*	*M* (*SD*)	*N*	*F*	*p*
	4.08 (0.97)	86	4.32 (0.75)	76	1.37	.244
H3: In-game performance	Mean rank	*N*	Mean rank	*N*	*p*	
	79.15	86	84.16	76	.494	
H4a: Knowledge	Productive Failure		Direct Instruction			
	M (*SD*)	*N*	*M* (*SD*)	*N*	*F*	*p*
	9.10 (1.86)	88	8.84 (1.74)	85	0.29	.588
H4b: Transfer	4.98 (1.45)	88	4.93 (1.53)	85	0.04	.833
	Mean rank	*N*	*M* (*SD*)	*N*	*p*	
H5: In-game performance	84.55	83	78.3	79	.394	

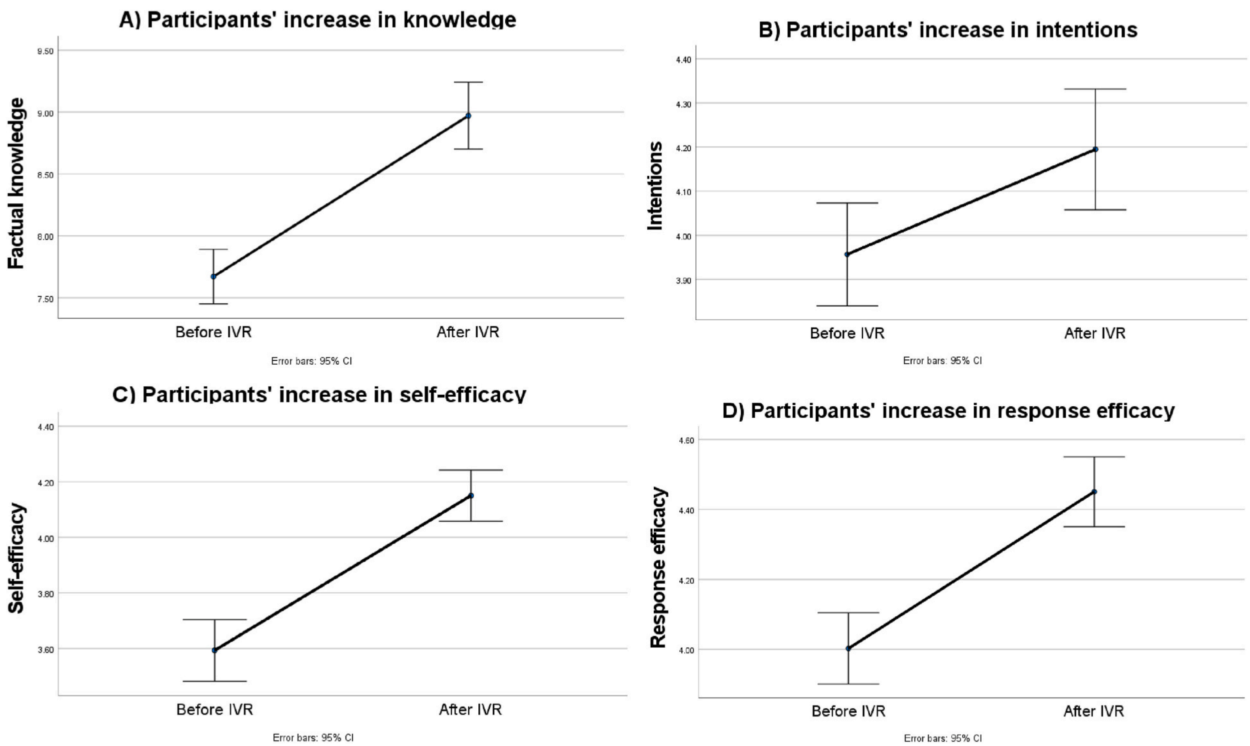

Fig. 4. Pre-to-post-score changes in participants' (a) knowledge, (b) intentions, (c) self-efficacy, and (d) response efficacy. Error bars represent the 95% confidence interval.

through the simulation of 3.81 (*SD* = 0.74) and an average enjoyment of the experience of 4.45 (*SD* = 0.7), on a five-point Likert scale.

6.2. Psychological processes behind learning, intentions, and transfer

We conducted regression analyses to gain an understanding of the mechanisms behind changes in participants' knowledge, intentions, and transfer (see Fig. 5 for a model of the results). We found borderline evidence that interest predicted participants' knowledge increase, $B = 0.313$, $p = .050$, $CI_{.95} = [0.000, 0.626]$. Furthermore, we found that the change in self-efficacy significantly predicted changes in intentions, $B = 0.190$, $p = .015$, $CI_{.95} = [0.037, 0.342]$. No significant results were found regarding response efficacy and enjoyment. In conclusion, the results indicate that students' self-efficacy predicts their behavior intentions, and there is marginal evidence related to students' level of interest predicting their learning.

6.3. Comparisons of instructional design elements

The last step in our analyses was to investigate whether the underlying instructional design elements of the simulation (Exaggerated Feedback vs. Corrective Feedback; Direct Instruction vs. Productive Failure) made a difference in the main outcomes of intentions, knowledge, and transfer (see Table 4). When comparing the post-test intentions, controlling for pre-test scores, of the Exaggerated Feedback ($N = 86$, $M = 4.08$, $SD = 0.97$) and Corrective Feedback ($N = 76$, $M = 4.32$, $SD = 0.75$) groups, we found no significant differences, $F = 1.37$, $p = .244$. When comparing the performance of the Exaggerated Feedback ($N = 86$, mean rank = 79.15) and Corrective Feedback ($N = 76$, mean rank = 84.16) groups on the in-game sorting test, we did not find any significant differences, $p = .494$. In conclusion, H2 and H3 were not supported. That is, experiencing Exaggerated Feedback in the environment did not seem to have any influence on participants' changes in intentions to perform pro-environmental waste management behavior or on their performance in the simulation itself.

Similarly, Productive Failure ($N = 88$, $M = 9.1$, $SD = 1.86$) did not lead to higher post-test knowledge scores than Direct Instruction ($N = 85$, $M = 8.84$, $SD = 1.74$) when controlling for their pre-score knowledge, $F = 0.29$, $p = .588$. There were also no significant differences between the Productive Failure ($M = 4.98$, $SD = 1.45$) and Direct Instruction ($M = 4.93$, $SD = 1.53$) groups on post-test transfer scores, $F = 0.04$, $p = .833$. Furthermore, when comparing the performance of participants experiencing Productive Failure ($N = 83$, mean rank = 84.55) with those experiencing Direct Instruction ($N = 79$, mean rank = 78.3) using a Mann-Whitney U test, we did not find any significant differences in participants' ability to sort waste into the correct waste bins during the test segment, $p = .394$. In conclusion, H4a, H4b, and H5 were not supported: we found no group differences between Productive Failure and Direct Instruction on central learning outcomes from the experiment.

7. Discussion

7.1. Empirical contributions

The current study contributes important empirical knowledge showing that IVR designed for mastery experiences can be a useful educational technology for teaching high school students how to perform pro-environmental behaviors such as waste management, while also improving their intentions to apply this knowledge in the real world. The simulation showed a large effect ($\eta^2 = 0.41$) on students' knowledge of waste management and a medium-to-large effect ($\eta^2 = 0.10$) on their intentions to sort their waste. There are mixed findings regarding the effectiveness of IVR simulations for learning (Pellas et al., 2021), nature connectedness (e.g., Spangenberger et al., 2022), and pro-environmental behavior (Soliman et al., 2017). Because of this, multiple reviews call for an increased focus on what design decisions are important for the effectiveness of IVR (Pellas et al., 2021; Radianti et al., 2020). The current paper contributes importantly to this goal. The simulation was designed based on best-practice empirical and theoretical literature, as presented in Section 3.4, which can be identified as one possible reason for the effectiveness of this simulation. Furthermore, as will be discussed later in this section, we did not find any differences in the effectiveness of the IVR simulation when manipulating the instructional design elements of instruction sequence and feedback. While some previous research has shown how IVR can be used for improving pro-environmental behavior intentions and knowledge (as presented in Section 2), this is one of the first studies seeking to expand these findings to the effectiveness of teaching waste management, in an ecologically valid classroom setting.

When investigating the psychological processes behind our findings, our analyses suggested that self-efficacy was a significant predictor of intentions, and marginal evidence suggested that interest is a predictor of learning. Self-efficacy has been generally highlighted as an important factor in behavior change, ensuring that people have the confidence and belief in themselves to learn new behaviors and execute pro-environmental behavior (as presented in Section 2). Multiple meta-analyses have found that self-efficacy and intentions are linked. For example, Klöckner (2013) investigated this link in environmental behavior; Sheeran et al. (2016)

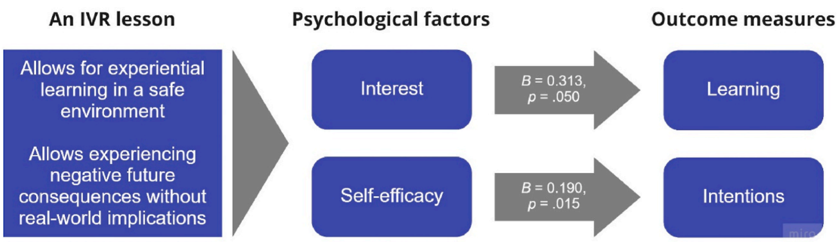

Fig. 5. A model of the results from the regression analyses. From left to right: The expected mechanisms of an IVR learning environment allowing for the changes. The expected psychological variables that are influenced. Their predictive power of the outcome variables measured in this study.

investigated this link in health-related behavior; and Floyd et al. (2000) investigated the protection motivation theory, which predicts that participants' intentions to act are influenced by their belief that they can act in the first place. According to Bandura (1977; 1997), the strongest way to influence a person's self-efficacy is through mastery experience. IVR is uniquely equipped to allow for learning through experience rather than through receiving information (Plechatá et al., 2022c). Therefore, learning in IVR builds self-efficacy through mastery experience, rather than vicarious experience (Makransky & Petersen, 2021). For instance, the simulation in this paper builds on mastery experience, as its primary task is for students to experience sorting waste while receiving feedback, giving them the experience of their performance improving. The findings of the current study thus build on previous research, while expanding it to the behavior of waste management. We showed that as students' belief in their own ability to sort waste increased, so did their intentions towards applying their knowledge to the real world. As the findings on interest and knowledge were only marginally significant, further research is needed to investigate this connection.

Surprisingly, this study did not find any differences in the outcomes regarding the manipulations of instruction sequence and feedback. The effects of both Exaggerated Feedback and Productive Failure have been well-established in the literature. The findings therefore could represent boundary conditions for each of the instructional design elements. Regarding Exaggerated Feedback, it could be that the manipulation of the outside environment in the simulation was not strong enough to make a difference, compared with a generally evidence-based intervention. The design of the Exaggerated Feedback in the simulation may have been too far removed from the participant as it was only visible through the windows of the apartment. This could make it feel less personal and less dangerous, reducing its influence on participants' intentions (Brügger et al., 2015; Brügger, 2020). Hoffmann et al. (2022) emphasize how experiencing real climate change is important for changes in pro-environmental behavior. An alternative approach could be placing participants outside, in the middle of the environmental effects, increasing the threat. This would also make the environment a clearer part of the learning task, reducing the possibility that participants did not notice the environmental changes because they were too focused on the task itself. Therefore, future research should investigate ways of increasing risk perception while also building self-efficacy and response efficacy in IVR (Brügger, 2020; Plechatá et al., 2022c). To further increase our understanding of the effectiveness of Exaggerated Feedback, items could also have been added to the questionnaire to investigate what, if any, changes participants noticed in the environment.

Regarding the inconclusive results related to the instruction sequence, a possible explanation could be related to cognitive load (Ahn et al., 2022; Makransky et al., 2021). Cognitive load has been identified as an important variable in understanding IVR-based learning (Ahn et al., 2022; Makransky et al., 2021; Parong & Mayer, 2018). In the current simulation, because of the complexity of the task, it could be that Direct Instruction assisted students in making sense of the IVR environment before starting the simulation by preparing them for the many waste bins, reducing the extraneous load of processing the IVR environment. This could be a form of pre-training which has repeatedly been shown to be beneficial in IVR learning (Meyer et al., 2019; Petersen et al., 2020). This is consistent with Taçgın's (2020) findings that increased student experience with IVR, as well as increased structuring and guiding of the IVR content, improves students' evaluation of IVR as a beneficial learning tool. Furthermore, the lack of formal instructions to a complex task increases the amounts of information students must handle at once, possibly counteracting some of the positive effects of Productive Failure. This might also make it more difficult for students to start building a mental model, as they are given less information and instead must rely on their existing knowledge (Sinha & Kapur, 2021; Vogt, 2021). Consistent with these findings, Kapur (2008) found that the positive effects of Productive Failure only became apparent in delayed tests.

7.2. Practical implications

Since 1992, the United Nations has stressed the importance of education in dealing with human-caused climate change (UnitedNations, 1992). Multiple national and international meetings and legislations have sought to make this possible (UNESCO & UNFCCC, 2016; UNEP, 2021). Research has also contributed with knowledge on how to realize this goal, focusing on improving methods for behavior change. For example, Hole and Hole (2020) call for increased education, Harker-Schuch et al. (2020) emphasize that it is important to teach students how *and* why to engage in environmental behavior, and Ye et al. (2020) call for more citizen-centric approaches to improving waste management. The current study suggests that IVR can successfully be implemented in high school classrooms, helping future adults adopt pro-environmental intentions and the necessary knowledge to back them up. Additionally, students reported enjoying this learning content. This approach might be a meaningful addition to high school climate change education. This is especially important considering the expected arrival of the metaverse, suggesting that IVR might become a bigger part of our everyday lives, including our education (Pimentel et al., 2022). The success of this experiment in a classroom setting suggests that it is feasible to use IVR in high school education. We managed to use IVR in multiple classrooms, in separate high schools. Although 13 (7%) of the students in our study experienced minor technical problems, such as small glitches in the simulation or uncertainty about how to maneuver the technology, they still managed to finish the simulation successfully. One concern that could be raised is the physical space requirements of IVR: in the current study, we had to use multiple classrooms to easily set up the HMDs required for making the experiment a success.

7.3. Limitations and future research

One limitation of this study is the lack of longitudinal data, exploring whether participants' improved intentions and knowledge led to continued behavioral and educational improvements. Generally, learning new behaviors has two phases: the immediate behavior, practiced while learning; and the continuous behavior, which is sustained through habit (Grilli & Curtis, 2021). This study focused on the first phase, with little insights into the second phase. In the current study, we operationalized pro-environmental behavior in terms of students' intentions. However, intentions are not always predictive of actual greenhouse gas emissions (e.g., Nielsen et al., 2022). Future research could seek to implement more ecologically valid behavior measures, such as recording actual sorting behaviors. The lack of longitudinal data is also relevant when it comes to our knowledge measures. While the students show an increase in knowledge from before to after the experience in this study, it is important to investigate whether this knowledge is retained over time.

A further consideration is that we employed a pre-to post-test design for assessing learning outcomes. A limitation with this design is the possibility that students' knowledge may increase through the testing effect (Schneider et al., 2019). An alternative design that has been used in the literature is the use of a domain-specific prior knowledge test (e.g., Richter et al., 2018). In the current study, we chose to use a pre-to post-test design because the calculation of change scores was necessary to investigate the hypotheses.

It is also important to note that this was not a media study, and previous findings regarding desktop simulations with similar goals have also shown positive effects (Gaggi et al., 2020; Hirose et al., 2004). Previous research has documented the positive effects of IVR compared to other media regarding self-efficacy (Makransky et al., 2019a), interest (Makransky & Mayer, 2022), and learning (Wu et al., 2020). Therefore, the goal of this study was to understand the effect of the underlying psychological mechanisms and the influence of different instructional design elements in developing IVR-based climate change lessons, rather than comparing IVR to other media.

A general limitation to using IVR is cybersickness. A total of 6% of the participants in our study experienced high levels of cybersickness. Previous research has reported that some levels of cybersickness is normal when using IVR, with up to 12.9% of users feeling the need to prematurely end their IVR experience (Caserman et al., 2021). Although the level of cybersickness in our sample was lower, it still means that some participants were excluded from our data analyses, which could be of concern in a classroom setting. In a recent study on the relation between demographics, user experience, and cybersickness, Luong et al. (2022) found that experience with IVR and the distance travelled in IVR, among other things, predicted levels of cybersickness. In the current study, 64.7% of participants had tried IVR fewer than 11 times, with 11 of these people never having used an IVR device at all. Further, while participants in our simulation had to move around a great deal to pick up and sort waste, we implemented teleportation to reduce the influence of movement on cybersickness (Caserman et al., 2021). This likely limited cybersickness to some extent. However, more research is needed to investigate the influence of cybersickness in classroom settings.

This study focused on the education and training aspect of applying IVR in the classroom. However, this kind of pro-environmental behavior intervention could also be considered outreach and relationship-building (Grilli & Curtis, 2021) through integrating climate change education in local communities. Generally, pro-environmental behavior interventions that seek to involve entire communities show the highest effect (Grilli & Curtis, 2021). This is an increasingly important direction for research and practice, as the waste management categories used in this study are currently being implemented in Denmark. Because of this, it will be important to produce easy-to-understand materials to assist people in learning how to sort according to these categories. This can be done as a classroom intervention, as in this study, or as a part of a bigger outreach and relationship-building intervention, targeting entire communities.

Another limitation in this study was that we did not collect data about embedding IVR in the classroom from the teachers' perspective. Southgate et al. (2019) investigated the embedding of IVR in the classroom with teachers as co-researchers, thereby investigating the classroom itself, the teachers, and the students. This enabled them to learn more about the ethical, organizational, and educational issues and possibilities related to embedding IVR in the classroom. Future field studies could also collect information about the integration of IVR experiences into the curriculum more systematically. Previous studies suggest that teachers' self-efficacy is important for their willingness to adopt novel approaches to teaching (e.g., Orona et al., 2022). Bower et al. (2020) and Cooper et al. (2019) confirm this in relation to teachers using IVR in the classroom. Improved knowledge-sharing between teachers can similarly increase their opportunities for learning about new educational resources (Wang et al., 2021). An additional focus of new research could then be improving teacher's self-efficacy towards using IVR as an educational resource (Lee & Lee, 2014), and how to promote knowledge-sharing about the technology (Wang et al., 2021).

8. Conclusion

The current paper has sought to investigate the use of IVR in high school classrooms as an educational technology for climate change education, seeking to increase pro-environmental intentions, knowledge, and transfer regarding waste management behavior. Regarding Research Question 1, the results extend important knowledge about the feasibility of using IVR for climate change education: the study highlighted how IVR can be a useful educational technology for waste management education in a high school classroom setting, with a medium-to-large effect on intentions ($p < .001$, $\eta^2 = 0.10$) and a large effect on knowledge ($p < .001$, $\eta^2 = 0.41$). These results have empirical implications, as the current study is one of the first investigating IVR for teaching complex pro-environmental behaviors such as waste management, and as the current study was conducted as part of high school student's education, showing that the technology is practically useful in a high school setting. Research Question 2 was focused on the mechanisms of learning in IVR. The results indicated that self-efficacy ($B = 0.190$, $p = .015$) may be especially important when seeking to increase intentions and interest ($B = 0.313$, $p = .05$) could be potentially important when seeking to foster learning in IVR-based pro-environmental behavior interventions. This is in line with current research evidence, suggesting that cognitive and affective factors influence the effectiveness of IVR. With Research Question 3, we investigated how different underlying instructional design elements may influence the effectiveness of IVR simulations. The study did not find any differences caused by the manipulated instructional design elements, suggesting that while the evidence-based intervention was effective, the included manipulations of feedback (Exaggerated Feedback vs. Corrective Feedback) and instruction sequence (Productive Failure vs. Direct Instruction) did not improve the effectiveness of the simulation. This suggests potential boundary conditions to the effectiveness of these instructional design elements. Future research investigating *when* and *why* these instructional design elements work in IVR is needed. Other potential avenues for future research involve exploring whether the effectiveness of IVR simulations generalize to longitudinal studies, including real-life measures of behavior, and seeking to learn more about what it takes for teachers to use the technology in the classroom.

Credit author statement

Valdemar Aksel Stenberdt: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Original draft, Guido Makransky: Conceptualization; Data curation; Investigation; Methodology; Supervision; Review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is available through our pre-regitration on https://osf.io/fqebr/files/osfstorage.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compedu.2023.104760.

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