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Increasing awareness of climate change with immersive virtual reality

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Previous research has shown that immersive virtual reality (VR) is a suitable tool for visualizing the consequences of climate change. The aim of the present study was to investigate whether visualization in VR has a stronger influence on climate change awareness and environmental attitudes compared to traditional media. Furthermore, it was examined how realistic a VR experience has to be in order to have an effect. The VR experience consisted of a model of the Aletsch glacier (Switzerland) melting over the course of 220 years. Explicit measurements (new environmental paradigm NEP, climate change scepticism, and nature relatedness) and an implicit measurement (implicit association test) were collected before and after the VR intervention and compared to three different non-VR control conditions (video, images with text, and plain text). In addition, the VR environment was varied in terms of degrees of realism and sophistication (3 conditions: abstract visualization, less sophisticated realistic visualization, more sophisticated realistic visualization). The six experimental conditions (3 VR conditions, three control conditions) were modeled as mixed effects, with VR versus control used as a fixed effect in a mixed effects modeling framework. Across all six conditions, environmental awareness (NEP) was higher after the participants (N = 142) had been confronted with the glacier melting, while no differences were found for nature relatedness and climate change scepticism before and after the interventions. There was no significant difference between VR and control conditions for any of the four measurements. Nevertheless, contrast analyses revealed that environmental awareness increased significantly only for the VR but not for the control conditions, suggesting that VR is more likely to lead to attitude change. Our results show that exposure to VR environments successfully increased environmental awareness independently of the design choices, suggesting that even abstract and less sophisticated VR environment designs may be sufficient to increase pro-environmental attitudes.

KEYWORDS

virtual reality, environmental attitude, changing attitude, climate change, realism, IAT, immersion, presence

1 Introduction

One of the greatest challenges faced by humanity is climate change, which has already led to dramatic consequences for the environment (e.g., sea ice and mountain glaciers are melting, wildlife populations and habitats are changing, extreme weather conditions are becoming more frequent). Climate change is caused by increased emissions of greenhouse gases (Pachauri et al., 2014). In order to counteract climate change it is therefore important to make people aware of the origins of climate change and to alter their attitudes and behavior. However, this endeavor has turned out to be challenging, and people's level of concern does not appropriately reflect the scope of the problem (Carmichael and Brulle, 2017).

One source of the problem is that climate change is a relatively abstract phenomenon, in the sense that the effects of greenhouse gas emissions are not immediately visible but take place over many years (temporal distance), and the consequences do not necessarily occur at the same place as the causing behavior (spatial distance). Temporal and spatial distance can - at least partially - explain why it is so hard to bring this issue into awareness to the extent that it changes behavior in a sustainable manner (Trope and Liberman, 2010). Using traditional media such as films or illustrated brochures can be used to explain the mechanisms of climate change and visualize its consequences. However, providing an immersive realistic experience of the consequences of climate change may have additional psychological effects that increase environmental awareness, as elaborated next.

Researchers and media developers are now able to create rich computer-generated 3D environments that enable participants to experience virtual environments as if they were real (Gonçalves et al., 2022). Immersive VR is typically experienced using a head-mounted display that digitally recreates user's movements in their physical space and creates depth perception by rendering a different image for each eye. Compared to conventional computer screens, head mounted displays shut out the outside world, and typically occupy a larger part of the field of view and have a larger field of regard, allowing users to experience an illusory sense of presence in the three-dimensional virtual world. Immersive VR thus enables a direct personal and embodied experience of climate change consequences that may bring participants psychologically closer to the issue when compared to simply watching a video (Markowitz et al., 2018; Markowitz and Bailenson, 2021). In particular, immersive VR can be used to visualize effects of climate change that can otherwise not be experienced directly due to large time spans (e.g., glacier melting) in a realistic way. Thus, the immersive experience can impact both the cognitive and affective processing of climate change. At the cognitive level, it might help users to establish a mental representation of the mechanisms that underlie climate change and its consequences. This, in turn, may raise the awareness of the risks associated with climate change (Ahn S. J. et al., 2014a; Kim, 2020). At the affective level, it can enhance the sense of being related and emotionally connected to the environment, thus making climate change a personally relevant matter (Akerlof et al., 2013; Ahn S. J. et al., 2014a).

While the potential of immersive VR as a persuasive tool (i.e., as means to change attitudes or behaviors; see Wienrich et al., 2021) has been recognized in other domains such as prejudice (Peck et al., 2013; Hasler et al., 2017), empathy (van Loon et al., 2018), or human rights (Bujić et al., 2020), its effect on environmental attitudes has not yet been extensively studied. Most previous studies using immersive VR in the context of climate change have focused on knowledge transfer (Markowitz and Bailenson, 2021). Nevertheless, there is some evidence that immersive VR can increase environmental awareness and pro-environmental behavior (Ahn S. J. et al., 2014a; Hsu et al., 2018; Markowitz et al., 2018; Fauville et al., 2020; Petersen et al., 2020; Chirico et al., 2021). For example, a visualization of the tree-cutting process had an impact on paper conservation (Ahn S. J. et al., 2014a), an underwater world helped to demonstrate the impact of rising seawater (Markowitz et al., 2018), or a landscape of Greenland served to illustrate the melting ice sheet (Petersen et al., 2020). Although these studies provide promising results, several crucial questions remain open. First, most of these results are based on a comparison of environmental awareness before and after exposure to immersive VR, without comparing the effects to a non-immersive control condition (Hsu et al., 2018; Markowitz et al., 2018; Petersen et al., 2020; Chirico et al., 2021). One of the studies that did make such a comparison found that watching a nature video through a head-mounted display (immersive technology) enhanced nature relatedness, but not to a higher extent than watching the same content on a conventional computer monitor (Soliman et al., 2017). Moreover, in the context of learning, it has been shown that high immersion does not always improve learning, and it has been suggested that there are also distracting effects of immersion on cognitive processing (e.g., attending to irrelevant information; Craig et al., 2002; Cummings and Bailenson, 2016; Makransky et al., 2019; Mania and Chalmers, 2001; Mayer, 2014; Pollard et al., 2020). Thus, it remains an open question to what extent immersive VR is more effective at increasing environmental awareness compared to traditional communication media (e.g., text, 2D desktop demonstration).

Furthermore, there is often no manipulation of design aspects within immersive VR. When setting up an immersive VR environment, VR designers are confronted with numerous decisions about the specific VR design, such as the degree of visual realism (i.e., how graphically realistic the virtual environment is), the level of interactivity with the virtual world, or the use of avatars. From the developers' perspective, it would be important to know which of the various aspects of a VR environment contribute most to the positive effects on attitude change. Previous studies have shown that visual realism is an important determinant of presence (IJsselsteijn et al., 2001; Schubert et al., 2001; Baños et al., 2004; Hvass et al., 2017; Weber et al., 2021). Presence refers to the subjective feeling of being in the virtual world (Slater and Wilbur, 1997). For example, in scenarios designed for participants with fear of height or other anxieties, more visual realism resulted in increased presence and affective responses (Hvass, 2018; Gromer et al., 2019). Increased presence is also associated with enhanced interest and personal involvement in immersive VR experiences (Makransky and Petersen, 2021). Based on these results, it can be hypothesized that immersive VR is most effective with high levels of visual realism. However, the role of visual realism in increasing environmental awareness is largely unexplored (Weber et al., 2021). There is some evidence in the context of learning that visual realism is not the most important factor: Rather, it seems more important that virtual representations are authentic, coherent, plausible, and functionally correspond to the applied context (Witmer and Singer, 1998; Hamstra et al., 2014; Jacobson, 2017).

Manipulating visual realism within immersive VR can serve as a more fine-tuned means of increasing (or reducing) the sense of presence. We therefore argue that such a manipulation helps to better understand the complex interrelationship between immersion, presence, and attitude change beyond simple comparisons between media (immersive VR vs. non-VR). In addition to these considerations, the focus on visual realism as a design aspect is also relevant from a practical perspective. Inspired by ever-improving technology, there is a tendency to strive for the highest possible degree of visual realism when developing immersive VR (Bowman and McMahan, 2007; Hvass et al., 2017; Erolin et al., 2019). Remarkably, this design choice significantly impacts development costs: To increase visual realism, 3D modellers and

FIGURE 1
Three views each taken from the three different VR environments.

developers may have to invest hundreds of working hours. Creating less realistic but visually coherent and authentic environments could emphasize the focus on educational practices, which in turn could achieve equal or even better effects. While the pursuit of photorealistic graphics may be the standard for most gaming applications, the role of visual realism for other immersive VR goals, such as increasing environmental awareness, will need to be thoroughly explored in order to create efficient immersive VR applications.

Another limitation of previous studies is that they have mostly relied on explicit measurements of environmental attitudes. In such measures, participants typically rate their agreement with certain environment-related statements on a predefined scale (e.g., likert scale ranging from 1–5; Ahn et al., 2014a; Ahn et al., 2014b; Markowitz et al., 2018; Petersen et al., 2020)[1]. In the indirect measurement, they counted how many napkins participants used to help clean up spilled water. Such an approach can be prone to social desirability or expectancy effects (Beattie and Sale, 2011). For example, people want to present themselves "greener" than they actually are (Beattie and McGuire, 2012), or they adapt their responses because they think that an increase in environmental awareness is expected from them after the virtual intervention. Such biases can lead to misleading results, especially when changes in questionnaire scores are not compared to a non-VR control condition. Moreover, attitudes have explicit and implicit components, both of which can influence behavior (Wilson et al., 2000; Evans, 2008). Thus, explicit measures alone may not be sufficient to assess the success of immersive VR in changing attitudes (Beattie and McGuire, 2012).

The aim of the present study is to explore the effectiveness of an immersive VR experience in increasing climate change awareness and environmental attitudes. In doing so, we aim to take into consideration some of the limitations of previous research outlined above, including (1) comparing immersive VR to non-VR interventions, (2) manipulating the design aspect of visual realism within the immersive VR experience, and (3) incorporating implicit measurements of environmental attitudes. To this end, we created different visualisations of the Aletsch glacier to represent the negative effect of climate change. The Aletsch glacier is the largest and best known glacier in Switzerland and is featured in many newspaper articles about climate change as the glacier is expected to shrink substantially within the next 80–100 years (Jouvet et al., 2011; Linsbauer et al., 2012). By demonstrating the effects of climate change *via* melting glaciers, and by simulating many years in a duration of only a few minutes, we aimed to make the invisible effects of climate change visible and directly tangible to the participants. Importantly, we created different virtual environments (VE), all showing the same narrated sequence of the Aletsch glacier melting but with different degrees of visual realism. Visual realism was varied by manipulating the parameters of texture resolution and repetition, glacier topography, atmospheric perspective and color adjustments (cf. methods). By manipulating these parameters, three conditions were created: a well-designed abstract condition, a well-designed realistic condition, and a less sophisticated realistic condition (see Figure 1).

Due to the reduced psychological distance (in space and time) to climate change consequences during the immersive VR experience (Trope and Liberman, 2010), we expected that the immersive VR experience would increase climate change awareness and environmental attitudes. Specifically, we expected these changes to be stronger in the immersive VR conditions compared to three non-VR control conditions (watching a video of the virtual application, reading a text with screenshots of the virtual application, or just reading a text). Within the immersive VR conditions, we expected that the well-designed realistic condition would lead to the highest levels of presence and therefore would have the strongest impact on climate

1 Note that Ahn S. J. et al. (2014a); Ahn S. J. G. et al. (2014b) also used an indirect measurement in addition to the explicit measurement.

change awareness and environmental attitudes. Finally, we supplemented well-established explicit measurements (new environmental paradigm, climate change scepticism, and nature relatedness) with a self-created version of an implicit association test (IAT; Greenwald et al., 1998) to measure environmental attitudes. The IAT uses response times in binary classification tasks to measure implicit attitudes toward concepts. The responses are facilitated when a target concept (e.g., "environmentally-friendly") and a matching affective concept (e.g., "pleasant") are allocated to the same response key (Schultz et al., 2004; Wang et al., 2019). IATs have been criticized (Mierke and Klauer, 2003; Rothermund and Wentura, 2004) but have nevertheless often been shown to be sensitive to cognitive interventions (Friese et al., 2006; Slabbinck et al., 2011; Rihs et al., 2022). For example, Beattie and McGuire (2012) found that the IAT measurement of implicit attitude toward low (vs. high) carbon footprint products, but not an explicit measurement of the same issue, was associated with an attentional focus toward negative images of climate change. We therefore expected to find effects of the immersive VR interventions on the implicit measure.

2 Material and methods

2.1 Participants

A total of 142 participants were recruited (age: $M = 27.21$, $SD = 9.47$) of which 82 were women and 60 were men. Most participants were students and received course credit in exchange for their participation. The remaining participants did not receive any compensation. Participants were treated in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and the study was approved by the local Ethics Committee.

2.2 Design

The study employed a between subjects design measuring all dependent variables both before and after the exposure to the condition. The three VR conditions were: Abstract and well designed (abstract, $n = 23$), realistic and well designed (real+, $n = 23$), or realistic with a less sophisticated design (real-, $n = 23$). The three control conditions were watching a screencast of the real + experience (video, $n = 24$), reading a text describing the process of the glacier melting (text, $n = 25$), and reading a shorter version of text but including some screenshots of real+ (text and picture, $n = 24$). While the three VR conditions varied in realism and in sophistication the three control conditions varied in the degree of visualisation, with video being the most visual and text the least visual control condition. The VR conditions were tested in a first step of data collection, followed by the control conditions. Thus, participants were not randomly assigned to VR or control, but they were randomly assigned to a specific condition within the VR or the control conditions. All interventions lasted approximately five and a half minutes.

2.3 Procedure

The experiment consisted of four stages.

TABLE 1 Correlation table of the four environmental attitudes measures. Computed on the untranformed CCS scale.

	IAT	CCS	NR	NEP
IAT	1			
CCS	−0.05	1		
NR	0.14	−0.2	1	
NEP	0.14	−0.38	0.36	1

1. Baseline a: All dependent variables except the IAT were first measured *via* online questionnaire between one and 2 weeks before the experiment in order to reduce reactive effects. The order of the three scales measuring explicit environmental awareness was randomized, as were the items within the scales.
2. Baseline b: At the beginning of the experiment the baseline IAT-measure was conducted.
3. VR or control intervention: Participants gave informed written consent and were reminded of their right to cancel the experiment without cause. VR: Participants were informed of possible dangers of the VR-experience, such as feeling dizzy or nauseous, and were given a bottle of water. Then, participants entered the VR environment. Control: Participants remained seated at the desk and were presented with one of the three control conditions.
4. Post intervention: After the VR-experience, participants first filled out a survey starting with a suspension of disbelief and a presence questionnaire and the evaluation of the stimuli-experience followed by the three scales measuring explicit environmental attitude. Then, the IAT was administered again followed by the debriefing of the participants.

2.4 Materials

Four measures aimed to capture the multidimensional construct *environmental attitudes*. The *New ecological paradigm* questionnaire (NEP) measured pro-environmental sentiment most generally (Dunlap et al., 2000). The *climate change scepticism* scale (CCS) measured the extent to which participants questioned the severity of climate change (Whitmarsh, 2013). An affective component of environmental attitude was captured by the *nature relatedness* (NR) questionnaire (Nisbet et al., 2008). To measure implicit attitudes towards the environment we created an *implicit association test* (IAT). Correlations of the measures are reported in Table 1.

For the VR and the video conditions secondary measures included the *Igroup Presence Questionnaire* (IPQ, Igroup, 2016), and the *suspension of disbelief* scale (SOD, Vorderer et al., 2004). With the exception of members of the plain text condition, participants were further asked two qualitative questions about the graphics (realism and graphical pleasantness). All participants were asked to rate the subjective experience of the stimuli with respect to excitement, pleasantness, and enjoyment (single item measures).

2.4.1 Stimuli

The three VR environments were all based on the same underlying 3D model of the Aletsch glacier melting created for a museum experience (Jouvet et al., 2011; Linsbauer et al., 2012). In both the virtual and the real environment, participants were standing on a

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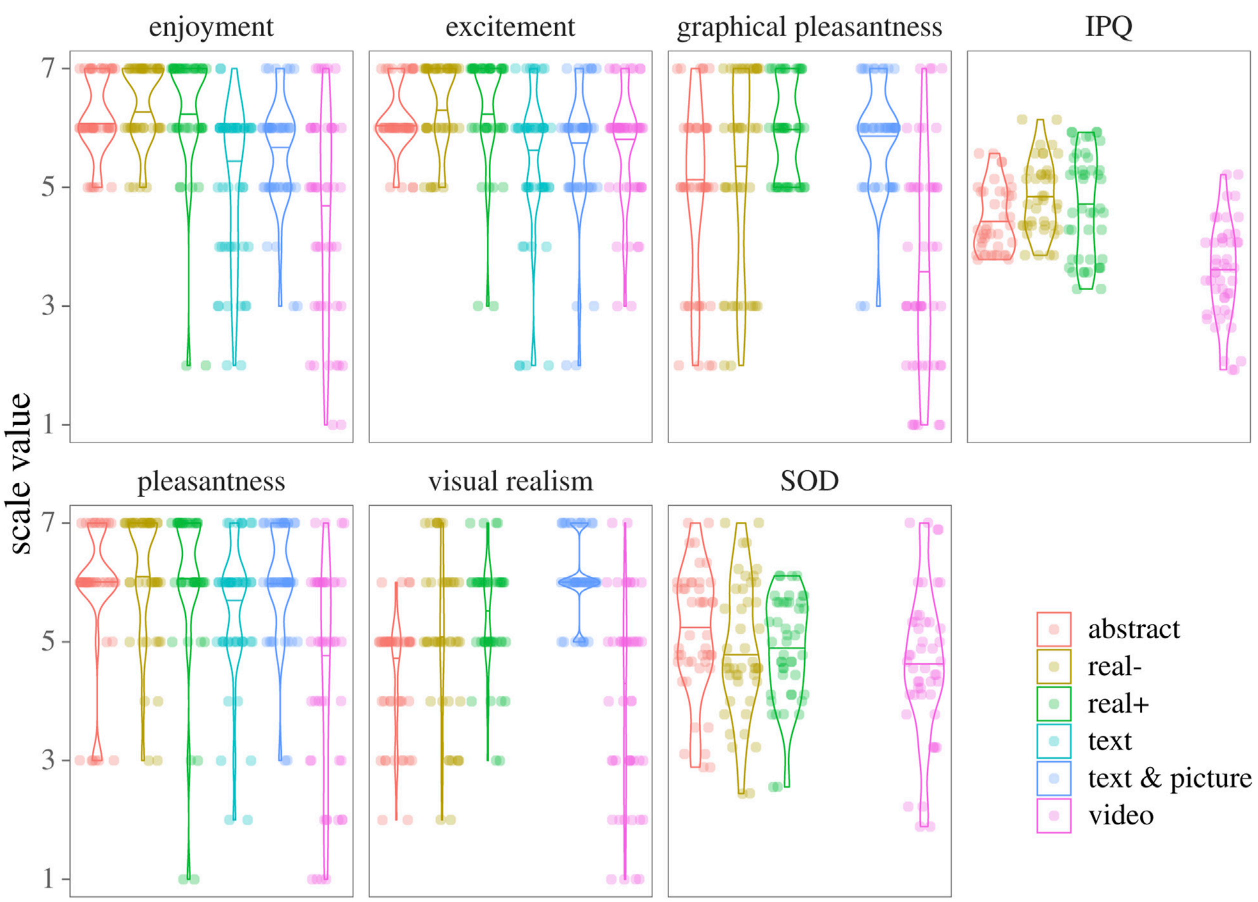

FIGURE 2
Manipulation check. Experience variables are based on one item each. IPQ and SOD represent average questionnaire scores.

platform surrounded by railing. This added a level of security to the experience and simultaneously limited the space participants could explore in a sensible way. Participants heard a narrator speaking German with a slight British accent who was introduced as John Tyndall, a British physicist who studied greenhouse gases and the Aletsch glacier in the 19th century. The narrator guided participants through 220 years, ending with how the glacier would look like in the year 2070 if global warming continues as it has. In the background, a realistic sound of the melting glacier (recorded with microphones in the actual glacier) set the mood and the sound stage.

The three different VR environments varied with respect to realism and visual coherence/sophistication. The conditions were: A well-designed abstract condition *abstract*, a well-designed realistic condition *text*, and a less sophisticated realistic condition *real-*. The VR environments were not designed to vary in image resolution, audio, or other factors affecting the quality of experience. In the video condition (*video*) participants watched a screencast of a typical experience in the well designed realistic VR condition. Participants in the text and picture condition (*text and picture*) read a text interlaced with pictures of the screencast describing the information content of the VR experience. The text was a slightly adapted transcript of the narrator's words. In the text condition (*text*) participants read a plain text version of the stimuli in the text and picture condition. The informational content and the duration of all six interventions were comparable.

2.4.2 New ecological paradigm (NEP)

The NEP scale is a widely used measure of pro-environmental orientation and environmental concern (Xiao et al., 2019). Its 15 items, some of which are reverse-coded, capture various aspects of environmental awareness. Even though some studies found two or more subscales, the NEP retains an internal consistency high enough to be used as a single measure of endorsement of an ecological worldview with a Cronbach's α = 0.83 (Dunlap et al., 2000). In our sample the Cronbach's Alpha estimated reliability of the NEP was α = 0.686, 95% CI [0.632, 0.739].

2.4.3 Climate change scepticism (CCS)

The CCS scale is a multidimensional measure of scepticism and uncertainty about climate change. Its high internal consistency (α = 0.92) enables the CCS to be used as a single measure of scepticism (Whitmarsh, 2013). The scale administered consisted of 12 items with five point Likert scale response options. CCS has been shown to be negatively predicted by NEP scores (Dunlap et al., 2000). The two scores were also substantially negatively correlated in our sample (see Table 1), $r = -0.38$. CCS was shown to be reliable in the current sample with Cronbach's α = 0.845, 95% CI [0.819, 0.871].

2.4.4 Nature relatedness (NR)

The NR scale assesses different aspects of an individual's connectedness to nature–a relevant affective component of

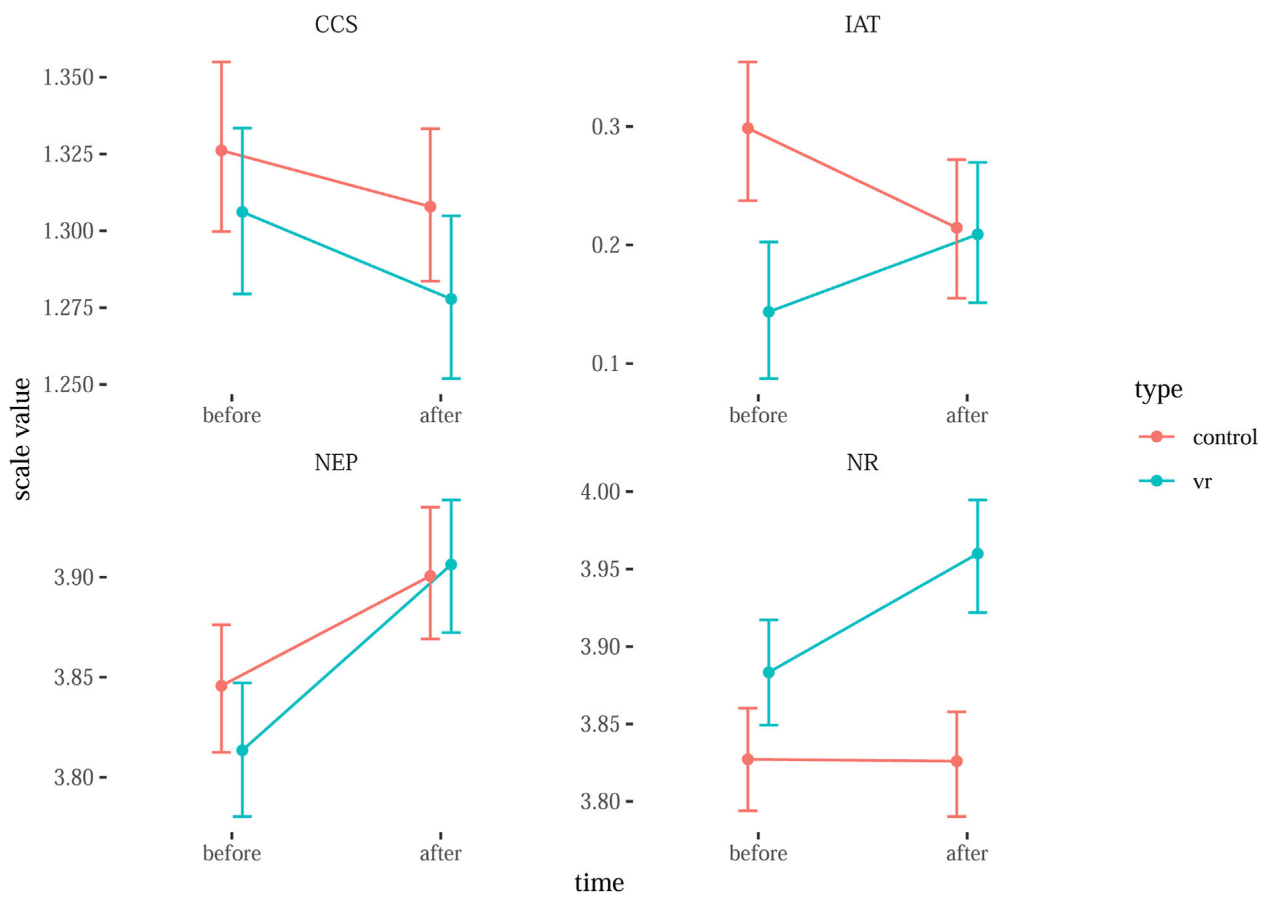

FIGURE 3
Conditional mean and CI of all four DV's for VR vs. control conditions. CCS has been transformed back to its original scale.

environmental awareness (Littledyke, 2008; Nisbet et al., 2008). It is comprised of 21 items with five point Likert scale response options, has good psychometric properties and is positively correlated with NEP scores (r = 0.54, Nisbet et al., 2008). In our sample NR and NEP correlated positively with r = 0.36. The measure showed a high internal consistency in our sample with Cronbach's α = 0.840, 95% CI [0.813, 0.866].

2.4.5 Implicit association test (IAT)

We included an IAT as a measure of implicit attitudes to capture an additional dimension of environmental awareness. The IAT is a standard paradigm used in various studies and is suitable for investigating the strength of associations (cf. Jost, 2019). One advantage of the IAT is its robustness to manipulation from explicit attitudes and social influences as it measures reaction time ratios between different categorisation tasks (Greenwald et al., 1998; Nosek et al., 2005). While IAT scores have been criticised in recent years–mostly for unverified psychometric properties–they remain useful as an additional measure to capture environmental awareness more thoroughly (Karpinski and Hilton, 2001; Fiedler et al., 2006; Wilson and Smith, 2017). We constructed the IAT in PsychoPy® analoguous to Wilson and Smith (2017) but using words only (Peirce et al., 2019).

The object-words included in the IAT were either man-made (DE: Gebäude, Stadt, Kleider, Computer, Lampe; EN: building, city, clothes, computer, lamp) or typically occurring in nature (DE: Baum, Wasser, Blume, Tier, Stein; EN: Tree, water, flower, animal, stone). The affective-words were either positive (DE: Ausgezeichnet, einwandfrei, hervorragend, positiv, gut; EN: Excellent, impeccable, outstanding, positive, good) or negative (DE: Schlimm, schlecht, negativ, schädlich, schwach; EN: Bad, poor (as in: poorly worded), harmful, weak). The PsychoPy script defining the IAT procedure can be found on the osf. io materials page (https://osf.io/n28cj/).

The raw data was adjusted according to the improved scoring algorithm and scores were computed so that higher scores represented higher implicit pro-environmental attitudes and *vice versa* (Greenwald et al., 2003).

2.4.6 Igroup presence questionnaire (IPQ)

The IPQ was designed to measure presence in virtual environments (including VR). Its validity, reliability and practicability have been confirmed in numerous studies (Schubert et al., 2001; Schuemie et al., 2002; Ling et al., 2014). The scale consists of 14 items with seven point Likert scale response options. Within our study, internal consistency was good with Cronbach's α = 0.826, 95% CI [0.785, 0.867].

2.4.7 Suspension of disbelief (SOD)

SOD describes a state of reduced scrutiny towards an artificial environment which mediates presence (Tussyadiah et al., 2018). The SOD scale was developed by Vorderer et al. (2004) as a subscale to the MEC Spacial Presence Questionnaire. The scale was chosen for its good psychometric properties (Vorderer et al., 2004). We used the full

TABLE 2 Models comparing VR to control conditions. Type is deviation coded, the coefficient type vr represents the difference between the VR condition compared to the average value at the first measurement.

DV	Coef	Estimate	CI	t value	df	*p*-value
IAT	(Intercept)	0.23	[0.106; 0.355]	3.63	225.16	0.00
	time	−0.01	[-0.085; 0.066]	−0.23	20.40	0.82
	type vr	−0.15	[-0.276; −0.028]	−2.39	225.16	0.02
	time:type1	0.07	[-0.001; 0.15]	1.83	20.40	0.08
CCS	(Intercept)	0.23	[0.199; 0.27]	12.84	278.36	0.00
	time	−0.01	[-0.029; 0.006]	−1.32	140.00	0.19
	type vr	−0.00	[-0.038; 0.034]	−0.12	278.36	0.91
	time:type1	−0.00	[-0.02; 0.015]	−0.32	140.00	0.75
NR	(Intercept)	3.82	[3.71; 3.925]	69.64	268.10	0.00
	time	0.04	[-0.009; 0.085]	1.51	9.57	0.16
	type vr	−0.01	[-0.118; 0.096]	−0.20	268.10	0.84
	time:type1	0.04	[-0.008; 0.086]	1.56	9.57	0.15
NEP	(Intercept)	3.76	[3.663; 3.849]	79.18	276.21	0.00
	time	0.07	[0.03; 0.117]	3.23	14.89	0.01
	type vr	−0.04	[-0.128; 0.058]	−0.74	276.21	0.46
	time:type1	0.02	[-0.025; 0.063]	0.83	14.89	0.42

(8-item) version of the scale, which showed an internal consistency of α = 0.805, 95% CI [0.759, 0.852].

2.4.8 Experience, enjoyment and demographics

As a manipulation check, participants rated the experienced stimuli with regard to their realism, design quality, excitement, pleasantness and overall enjoyment on a 7-point Likert scale from *do not agree at all* to *totally agree*. The items included statements such as "The VR experience was graphically pleasing", which were adjusted for the control conditions. Previous experience with VR was captured as well. Demographic information was collected with regard to age, gender, education, as well as a one-dimensional political orientation measure with seven options from *left* to *right*.

2.5 Equipment

The study used both the HTC Vive and the HTV Vive Pro (Wireless) in conjunction with a computer using an Intel® Core™ i7-7700K CPU at 4.20 GHz, 16.0 GB RAM, and an NVIDIA GeForce GTX 1080 Ti graphics processing unit.

2.6 Analysis

The analysis consisted of three steps: First, we used a manipulation check to confirm the intended perception of the stimuli in the different conditions, including the perceived level of realism. Then, the VR conditions were compared to the control conditions with a focus on differences in before-after changes in the different environmental awareness variables. Lastly, we took a closer look at the differences among the three VR conditions.

The manipulation checks relied on simple linear models using the dummy-coded *condition* (contrasting the three VR conditions) or *type* (contrasting VR and control conditions) as the relevant predictor, depending on the respective question/model. Setting real + as the reference condition for *condition* allowed for a direct comparison of real- and abstract to real+.

In a second step, we compared all VR conditions to all the control conditions using random effects both for the subjects and for the (six) conditions. Models with the predictors *time* (with levels *before* and *after*), *type*, and their interaction term were used to compare how VR and control conditions differ in their efficacy to increase pro environmental attitudes. The variable *type* was included with deviation-coded contrasts (UCLA: Statistical Consulting Group, 2022, see). This meant that the simple slope of *time* could be interpreted as the average increase over time across all (VR and control) conditions. To control the false discovery rate for multiple contrast analyses we used the Benjamini and Hochberg (1995) method implemented in the stats package in R (R Core Team, 2018). The interaction coefficient represents the difference in slope (before vs. after) of the VR group as compared to the average *time* slope. The *p*-value corresponding to the interaction term tests whether the *time* slopes differed between VR and control conditions.

A random intercept per participant accounted for the repeated measures structure. Additionally including a random *time* slope for the subject variable *participant* (nested in *condition*) would have lead to a saturated model and resulted in an identifiability error for all analyses. A random intercept and a random *time* slope for *condition* were introduced to allow for random variation due to the inherent randomness of our choice of VR and control conditions. Our analysis

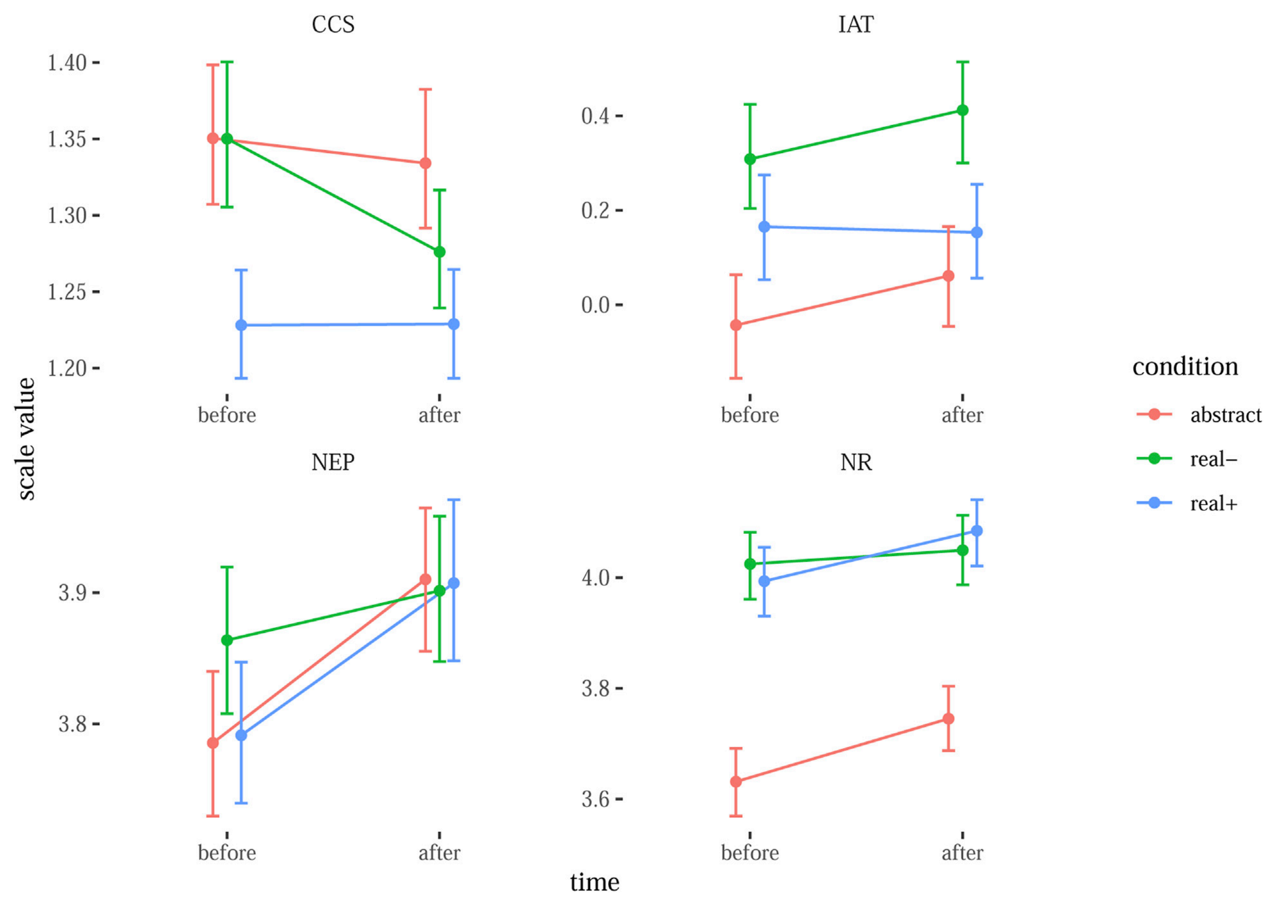

FIGURE 4
Conditional mean and CI of all four DV's comparing the three VR conditions. CCS has been transformed back to its original scale.

strategy was that a singular fit resulting from the model described would lead to first the removal of the random intercept per condition–this happened for IAT, NR and NEP–and if still singular to the removal of the random *time* slope for *condition*–this happened for CCS.

Model diagnostics revealed substantive violations of model assumptions for CCS (heteroscedasticity and non-normality of residuals). A Box-Cox transformation of the CCS measure resulted in a much better model appropriateness/no violations of assumptions and did not change inference results. The Box-Cox transformation parameter ($\lambda = -1.596$) was estimated based on a linear model disregarding the repeated measure structure. All reported CCS results are therefore based on the transformed variable. All other scales did not reveal any violations of model assumptions or outliers and therefore did not require any transformations.

To compare the efficacy of the intervention between the three VR conditions, models with the predictors *time*, *condition* and their interaction term were used. In this model, a random intercept per participant accounted for the repeated measures structure. Further including a random *time* slope for each participant resulted in an identifiability error due to the fact that there was only one observation per time point (saturated model) and was thus not included in the final model.

Similarly to the variable *type* in the above analysis, *condition* was deviation contrast coded. This meant that the simple slope of *time* represented the average increase over time across all three VR conditions. Interaction coefficients now represent the difference in slope of a particular condition compared to the average *time* slope. We conducted contrast analyses–again controlling the false discovery rate–to detect whether a dependent variable increased over time in any condition. The interaction coefficient indicated whether the increase over time differed between the respective condition and the average increase across all three conditions. Comparing to a model with only main effects (and no interaction effect) provided a statistical test of the interaction effect.

The analysis was conducted in the open-source statistical software program R (R Core Team, 2018). All mixed effects models were fit using the *lme4* and the *lmerTest* packages (Bates et al., 2015; Kuznetsova et al., 2017).

3 Results

3.1 Manipulation check

Suspension of Disbelief and presence were measured in all but the two text conditions. Participants of the plain text condition (text) did not rate the experience on graphical pleasantness or visual realism either (see Figure 2) The comparison between the three VR conditions and the three control conditions showed that the VR conditions were

TABLE 3 Models comparing the three VR conditions. Condition is deviation coded, i.e. the coefficient condition_real + represents the difference between the realistic VR condition compared to the average value over all three conditions at the first measurement.

DV	Coef	Estimate	CI	t value	df	*p*-value
IAT	(Intercept)	0.08	[-0.109; 0.266]	0.81	106.86	0.42
	condition_real+	0.10	[-0.166; 0.364]	0.72	106.86	0.47
	condition_abstract	−0.23	[-0.491; 0.039]	−1.65	106.86	0.10
	time	0.07	[-0.043; 0.173]	1.17	66.00	0.24
	condition_real+:time	−0.08	[-0.23; 0.076]	−0.98	66.00	0.33
	condition_abstract:time	0.04	[-0.114; 0.192]	0.50	66.00	0.62
CCS	(Intercept)	0.23	[0.181; 0.283]	8.84	131.56	0.00
	condition_real+	−0.06	[-0.129; 0.014]	−1.54	131.56	0.12
	condition_abstract	0.01	[-0.057; 0.086]	0.38	131.56	0.70
	time	−0.01	[-0.038; 0.009]	−1.21	66.00	0.23
	condition_real+:time	0.01	[-0.018; 0.048]	0.88	66.00	0.38
	condition_abstract:time	0.01	[-0.026; 0.04]	0.41	66.00	0.68
NR	(Intercept)	3.81	[3.674; 3.939]	55.49	129.34	0.00
	condition_real+	0.10	[-0.091; 0.283]	0.99	129.34	0.33
	condition_abstract	−0.29	[-0.476; −0.102]	−2.98	129.34	0.00
	time	0.08	[0.009; 0.144]	2.21	66.00	0.03
	condition_real+:time	0.01	[-0.081; 0.11]	0.30	66.00	0.77
	condition_abstract:time	0.04	[-0.058; 0.132]	0.76	66.00	0.45
NEP	(Intercept)	3.72	[3.591; 3.85]	55.49	132.00	0.00
	condition_real+	−0.04	[-0.228; 0.138]	−0.48	132.00	0.63
	condition_abstract	−0.06	[-0.243; 0.123]	−0.63	132.00	0.53
	time	0.09	[0.031; 0.154]	2.94	66.00	0.01
	condition_real+:time	0.02	[-0.064; 0.11]	0.52	66.00	0.60
	condition_abstract:time	0.03	[-0.055; 0.119]	0.71	66.00	0.48

rated as more exciting (M_{type} = 6.38, $M_{control}$ = 5.53) and more enjoyable (M_{type} = 6.38, $M_{control}$ = 6.45) than the control conditions, *excitement*: $F = 21.22$, $p < 0.001$; *enjoyment*: $F = 17.37$, $p = 0.013$. *Pleasantness* of the experience was not affected, neither was *realism* nor *graphical pleasantness* when comparing the VR conditions to the video condition. While presence (IPQ) was significantly higher in the VR conditions compared to the video condition, suspension of disbelief (SOD) was not; IPQ: $\beta_{type} = 1.085$, $F = 37.323$, $p < 0.001$; SOD: $\beta_{type} = 0.354$, $F = 1.886$, $p = 0.173$. As intended, perceived realism of the environment differed between the three VR conditions with the real + environment being most and the abstract environment being the least realistic, $F_{condition} = 4.49$, $p = 0.0148$; $M_{real+} = 5.43$, $M_{real-} = 5.087$, $M_{abstract} = 4.43$. We designed the VR environments to differ in graphical pleasantness, with *real+* and *abstract* aiming to be the more pleasant environments. Yet, graphical pleasantness was higher in both realistic conditions compared to the abstract condition, $F_{condition} = 3.21$, $p = 0.047$, $M_{real+} = 5.96$, $M_{real-} = 5.35$, $M_{abstract} = 4.91$. The different VR conditions had no significant influence on enjoyment, pleasantness, and excitement. Neither presence (*IPQ*) nor suspension of disbelief (*SOD*) varied significantly between the three VR conditions, SOD: $F_{condition} = 0.58$, $p = 0.562$; IPQ: $F_{condition} = 1.63$, $p = 0.204$.

To summarize, the three VR environments varied in realism and to some degree in graphical pleasantness while the overall experience (IPQ, SOD) remained unchanged (as visualized in Figure 2). Overall, participants found the VR experience more exciting and enjoyable than the control conditions, and presence was higher when comparing the VR conditions to the video condition. We therefore conclude that the manipulation of the VR environments was successful.

3.2 VR vs. control

In Figure 3 we display the estimated means of each dependent variable including bootstrapped confidence intervals for participants in the VR conditions and the participants in the control conditions over both time points. Estimated model parameters can be found in Table 2.

NEP increased significantly across all groups (VR and control), β_{time} = 0.074, 95% CI [0.030, 0.117], p = 0.005. When looking at the individual slopes per group (i.e. VR or control) a (simple slope) contrast analysis revealed that while the *time* slope of the VR group was significant, the slope of the control group was not, VR: β = 0.046, t (14.4) = 2.83, p = 0.013; control: β = 0.027, t (13) = 1.72, p = 0.109. However, the interaction term was not significant, so the *time* slopes did not significantly differ between the two groups, $\beta_{time:type}$ = 0.002, 95% CI [−0.025, 0.063], p = 0.152.

Overall, CCS did not decrease significantly over time, β_{time} = −0.012, 95% CI [−0.029, 0.006], p = 0.189 and VR and control groups did also not differ in this regard as revealed in the non-significant interaction effect, $\beta_{time:type}$ = 0.003, 95% CI [−0.02, 0.015], p = 0.753.

There was no overall NR increase over time, β_{time} = 0.038, 95% CI [−0.009, 0.085], p = 0.164. Further contrast analyses revealed that while the *time* slope was essentially horizontal in the control group there was a trend towards significance for the *time* slope in the VR group, VR: β = 0.038, t(10.66) = 2.142, p = 0.056; control: β = −0.001, t (9.67) = .035, p = 0.973. However, the difference in slopes between the control group and the VR group was not significant, $\beta_{time:type}$ = 0.08, 95% CI [−0.017, 0.172], p = 0.152.

Across all conditions, IAT scores did not change over time, β_{time} = 0.009, 95% CI [−0.085, 0.066], p = 0.822, but there was a trend for an interaction between time and condition, $\beta_{time:type}$ = 0.075, 95% CI [−0.001, 0.150], p = 0.0824: IAT scores decreased in the control conditions but increased in the VR conditions, as depicted in Figure 3. However, further contrast analyses showed that the *time* slope was also non-significant for both groups separately, VR: β = 0.032, t(23) = 1.118, p = 0.275; control: β = −0.042, t(21.2) = −1.47, p = 0.156.

In summary, the directions of all estimates were coherent with our hypothesis. NEP increased significantly across all groups. However, even though interaction did not turn out to be significant, the contrast analysis show that the difference is significant in the VR conditions but not in the control conditions. There was a trend for an increase of NR across the VR groups, but not in the control groups. However, none of the results showed any significant difference between the *time* slopes in the VR groups versus the control groups.

3.3 Comparing VR conditions

The estimated means of the four environmental attitude measures by condition are visualised in Figure 4. The parameters of the models used can be found in Table 3. Whether the *time* slope differed significantly between conditions was tested by comparing the full model to a model without the *time:condition* interaction term. Contrast analyses were used to get further insight into the *time* slopes of each condition. Care must be taken not to overinterpret contrast results when the interaction effect is not significant.

NEP increased significantly over time across all VR conditions, β_{time} = 0.093 95% CI [0.031, 0.154], p = 0.005. The assigned VR environment had no significant impact on the *time* slope as the model comparison testing the *time:condition* interaction was non-significant, $\chi^2(df = 2)$ = 1.586, p = 0.452. Contrast analysis further showed that NEP increased significantly in both real+ and abstract (β_{time} = 0.058, t (66) = 2.121, p = 0.038 and β_{time} = 0.062, t(66) = 2.280, p = 0.026, respectively), but not in real- (β_{time} = 0.019, t(66) = 0.689, p = 0.493).

Overall, CCS scores did not decrease significantly over time, β_{time} = −0.015 95% CI [−0.038, 0.009], p = 0.229. However, this effect did not differ between the conditions, $\chi^2(df = 2)$ = 1.806, p = 0.4052. Contrast analysis provided some further insight: The CCS score did not decrease significantly in any of the conditions. Contrast analysis revealed a trend for decrease of CCS over time in real-only, real-: β_{time} = −0.018, t(66) = −1.758, p = 0.083; real+:β_{time} = 0.000, t (66) = 0.021, p = 0.983; abstract: β_{time} = −0.003, t(66) = −0.365, p = 0.716.

NR increased significantly over time across all VR conditions, β_{time} = 0.077, 95% CI [0.009, 0.144], p = 0.030. The effect did not differ between the conditions, though, $\chi^2(df = 2)$ = 1.236, p = 0.539. When looking at the *time* effect within each condition separately none of the slopes remained significant – likely due to a reduction of power and multiple testing adjustment. Only in the abstract condition the *time* effect bordered on significance, abstract: β_{time} = 0.0569, t(66) = 1.901, p = 0.0616; real+ and real-: p > 0.1. On a further note, it was evident that - across both time points - participants in the abstract condition scored much lower in NR compared to the average score, $\beta_{condition-abstract}$ = −0.289, 95% CI [−0.476, −0.102], p = 0.003.

IAT scores did not increase significantly over time across all conditions, β_{time} = 0.065, 95% CI [−0.043; 0.173], p = 0.245. The *time* slopes did not differ between the conditions either, $\chi^2(df = 2)$ = 1.000, p = 0.606. Furthermore, contrast analyses also did not reveal a significant increase of IAT scores over time in any of the three conditions, all effects p > 0.1.

Taken together, our results show that real, real+, and abstract interventions did have a similar effects on changes (or no changes) of environmental awareness over time. Specifically, while the VR environments increased NEP and NR there was no evidence that this effect varied between the VR conditions.

4 Discussion

The aim of this study was to examine whether an immersive experience of climate change consequences in VR increases climate change awareness. The visualization showed in time lapse how the Swiss Aletsch glacier melts over a period of 220 years. Thus, by providing an embodied experience that overcomes the temporal distance of climate change consequences, we expected a stronger impact of the immersive VR experience when compared to less immersive 2D control conditions. Indeed, participants experienced the VR conditions as being more exciting and enjoyable, and they had a higher sense of presence when compared to the control conditions. This confirms the general usefulness of VR interventions to convey pro-environmental messages. Across all conditions, environmental awareness (as measured by NEP) increased after the intervention. This indicates that glacier melting is well suited to illustrate climate change and that it affects peoples' attitudes towards it. Not only is glacier melting compelling evidence of global warming, it can also serve as a symbol of climate change showing how dramatic changes of climate are affecting our environment. Our results show that confronting people with this phenomenon can positively influence environmental awareness. Although the change in NEP did not differ between immersive VR and the control conditions (non-significant *time:type* interaction), the increase in environmental awareness was only significant for the VR conditions, while there was no change for the control conditions. While a straight-forward interpretation is not possible, we think that this result is of interest in light of a number of previous studies that have shown that virtual realities have persuasive potential because they are immersive and thus enable a presence experience (e.g., Weibel et al., 2011; Weibel and Wissmath, 2011; Makransky and Petersen, 2021). Because presence was higher in the VR conditions when compared to the control conditions (i.e. the video condition), it may be that presence accounts for at least part of the increased environmental awareness. We therefore interpret these results in favour of the potential of immersive VR in increasing climate change awareness (Ahn S. J. et al., 2014a; Hsu et al., 2018; Markowitz et al., 2018; Fauville et al., 2020; Petersen et al., 2020; Chirico et al., 2021).

Since presence can contribute to something not only being comprehended but actually experienced (cf. Weber et al., 2021, or Tussyadiah et al., 2018, in the field of tourism), it can be assumed that this very fact provides a benefit in the VR conditions and distinguishes VR from the other conditions. In this sense, Wirth et al. (2007), for example, assumes that presence is an "amplifier of media effects" (p. 519).

We also expected a stronger increase in nature relatedness for immersive VR (vs. control). There was no overall increase in nature relatedness across all conditions, although there was a trend for an increase exclusively in the VR conditions. The absence of a clear effect of VR on nature relatedness is in line with other recent studies (Soliman et al., 2017; Spangenberger et al., 2022). For example, Spangenberger et al. used VR to "embody" participants with a tree (participants could do small branch movements with their arms). They found that the increased level of immersion in VR, when compared to a video watching control condition, did not translate into stronger effects on nature relatedness. These and our own results suggest that nature relatedness may be difficult to modulate with short-time interventions, particularly when using traditional media. As pointed out by others, interactivity with the environment and movements of the person's own body resembling the virtual body when interacting with the environment may be important factors in increasing nature relatedness, which was not the case in the present study (Ahn et al., 2016; Spangenberger et al., 2022).

In a similar vein, there was no change in climate change scepticism (CCS). The absence of an effect on this measure might not be surprising because of a floor effect: Values were already very low for the vast majority of participants before the interventions (M = 1.5 on a scale from 1–5), leaving less room for changes to even lower scores after the respective intervention. Moreover, people who are sceptic about climate change may not be prone to changing their minds as a result of interventions since their firm opinion may be related to stable traits and political/ideological orientations (McCright et al., 2016; Trémolière and Djeriouat, 2021). In addition to these established measurements, we introduced an implicit measurement of pro-environmental attitudes (Implicit Association Test - IAT) in this study. There was no effect across all conditions and within each condition separately (VR vs. control) on the IAT score. Noteworthy, in a previous study, it has been found that the IAT score decreased in both an active and passive control condition from the first to the second measurement, suggesting that there might be an intervention-independent decrease in IAT effects due to practice (Rihs et al., 2022). In this regard, not the absolute change but rather the relative change between conditions might be relevant, and there was indeed a trend for a differential change in the IAT score in this study (increase for VR vs. decrease for control). This pattern of results may indicate that the VR, but not the control conditions, counteracted the decrease in the IAT score due to repeated measurement. Thus, although the present results do not allow to draw any firm conclusions, they nevertheless point to a possible value of using implicit measurements for the evaluation of the effectiveness of VR interventions on attitude change.

Another aim of the present study was to explore whether specific VR design choices with regard to visual realism would affect climate change awareness. Therefore, we varied the degree of visual realism and sophistication of the VR environment and compared an abstract and two realistic depictions of the Aletsch glacier melting. The results show that our manipulations did work in the intended way: The sophisticated realistic environment was perceived as the most realistic, the abstract environment was perceived as least realistic. Crucially, we found no evidence that realism in VR depictions favours presence or any of the environmental measurements. The only hint that we found was that environmental awareness (NEP) only increased for the well-designed abstract and realistic condition, but not for the less sophisticated realistic conditions. This result should be taken with caution, however, because baseline values before VR exposure in the real-condition were higher than in the other two conditions, whereas values after the intervention were similar. Our results suggest that visual realism *per se* does not necessarily foster changes in attitudes. This has important implications. New consumers of VR experiences base their expectations regarding visual fidelity on high-end graphics in the gaming industry. However, it is expensive and time-intensive to create high visual realism and budgets for non-profit and educational applications are usually multiple orders of magnitude smaller when compared to the gaming industry. We show that a less sophisticated and less realistic, but visually coherent and authentic environment (the abstract condition) exerts the same positive impact on climate change awareness as the realistic environments (real- and real +). This is consistent with previous studies that indicate, on the one hand, that authenticity, coherence, and functionality of virtual environments are as important or even more important than realism in achieving the desired effect (Witmer and Singer, 1998; Hamstra et al., 2014; Jacobson, 2017) and that, on the other hand, cartoon-like visualizations can have the same effect as realistic ones (Huang, 2021). Our findings provide practitioners in the field of environmental VR with an argument to shift scarce resources from the realistic visual reconstruction to other aspects of production like coherence, both in regards to look and content. Which of the various other aspects of VR design ultimately influence attitude changes needs to be investigated in future studies.

A few limitations should be considered. First of all, various subjective decisions were made in the design of the VR environments. We therefore cannot conclusively state that visual realism plays no role in terms of presence or attitude change. It is possible that our *well designed and realistic* condition was not realistic enough or that the design of the *less realistic* condition (real-) was still too well designed to induce differences in experiential effects between the environments. Furthermore, we explored the effect of visual realism in a specific context (glacier melting, attitude change), which limits the generalizability of our results to other contexts (e.g., *learning* about climate change). Moreover, the implicit measurement that we developed in this study (IAT) can be regarded as a promising starting point, but more effort is required to develop and validate such implicit measurements.

Further, our sample size was not representative of the general population. Consequently, there was limited variance in some of our measurements, which might have reduced the probability of finding a change due to the VR interventions (see discussion above). In a similar vein, our sample size was rather small, so that possible moderating variables for the effect of the VR intervention on environmental awareness could not be assessed. For example, Sajjadi et al. (2022) found that serious games about system thinking had the strongest effects on pro-environmental attitudes for those participants with less past science education. Future studies should take such variables into account.

The measurements that were used in this study were limited to attitudes toward climate change and towards the environment. When using VR as a persuasive tool to counteract climate change, it would be promising for future research to also measure real (or at least hypothetical) pro-environmental behaviour (Deringer and Hanley, 2021). Moreover, future VR experiences could be more interactive and may for example allow participants to learn more about actions they can take to reduce greenhouse gas emissions and other pro-environmental behaviour. This concurs with recent claims that effective climate change interventions should also focus on solutions rather than solely highlight impacts (Markowitz et al., 2014). In addition, future studies could include other indirect methods of measuring environmental attitudes besides the IAT, which might have a more direct behavioral link. One possibility would be to incorporate the concept of System Thinking. According to Arnold and Wade (2015) systems thinking involves synergistic and analytical skills to identify and understand different components of a system as well as their causal relationships. Lezak and Thibodeau (2016) were able to show that systems thinkers tend to support policies on climate change. Sajjadi et al. (2022) could show that a learning experience can increase systems thinking and that systems thinking in turn leads to policy support regarding measures concerning food-energy-water nexus. The authors have developed an interesting method to indirectly measure system thinking by assessing different scenarios and their impacts. We consider it promising to use this method in future studies similar to ours.

It should be clear that interventions such as the one assessed in this study cannot solve current climate change problems. Exploring means to increase environmental awareness is a step into the right direction, but an urgent change in societal attitudes and behavioural adaptations at the institutional and personal levels are required. In the future, immersive VR applications might not only be used to visualize climate change consequences, but maybe also to increase the awareness of planetary limits, energy limits, and other contents that fosters the critical reflection of consumption behaviour and economic growth (Nardi et al., 2018).

According to various experts, glacier melt is the most tangible manifestation of climate change, as it can impressively demonstrate its effects (e.g., Price, 2009; Carey, 2010; Jackson, 2015). In our study, we were able to show that the visualization of glacier melt can have an influence on our attitude. However, it should be mentioned that melting glaciers do not have a direct impact on our personal lives unlike, for example, heat waves or floods. Accordingly, Whitmarsh (2008) was able to show that personal experience of air pollution influences perceptions and behaviors related to climate change. Future studies could therefore draw on visualizations that show more drastic consequences of climate change. It is possible that these would have an even stronger impact on attitudes.

To conclude, this study shows that climate change consequences can successfully be visualized in immersive VR, and that such visualizations have the potential to change climate change awareness, although the results need to be replicated and extended with a larger and more diverse sample and validated implicit measurements. The comparisons between immersive VR and the control conditions showed a nuanced picture, with more similarities than differences, highlighting that media comparison is an important step for a critical assessment of the effectiveness of immersive VR interventions.

Data availability statement

The analyzed data sets, the analysis script, and additional materials for this study (e.g. stimuli) can be found on the Open Science Framework repository: https://osf.io/y7nz5/.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of the Faculty of Human Sciences, University of Bern. The patients/participants provided their written informed consent to participate in this study.

Author contributions

DW and JC developed the idea for the study. The study was designed by DW, JC, and ST with inputs regarding implementation and experimental design from FM. JC created the three virtual environments while DW created the stimuli of the three control conditions. BM and ST were responsible for the data analysis and inference. MH and ST wrote the manuscript with support from DW, FM, JC, and BM.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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