Promoting Eco-Friendly Behavior through Virtual Reality - Implementation and Evaluation of Immersive Feedback Conditions of a Virtual CO2 Calculator

Carolin Wienrich*
Psychology of Intelligent Interactive Systems
University of Würzburg
Würzburg, Germany

Stephanie Vogt†
Psychology of Intelligent Interactive Systems
University of Würzburg
Würzburg, Germany

Nina Döllinger*
Psychology of Intelligent Interactive Systems
University of Würzburg
Würzburg, Germany

David Obremski*
Psychology of Intelligent Interactive Systems
University of Würzburg
Würzburg, Germany

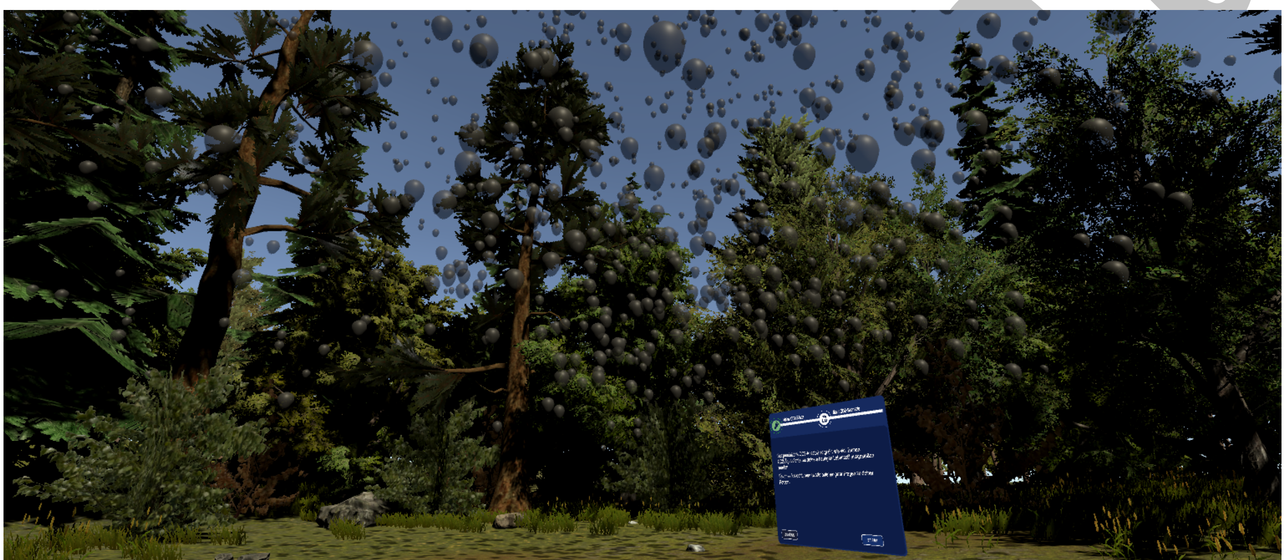

Figure 1: Balloon feedback representing CO_2 emissions.

ABSTRACT

Climate change is one of the most pressing global challenges in the 21st century. Urgent actions favoring the environment's well-being are essential to mitigate its potentially irreversible consequences. However, the delayed and often distant nature of the effects of sustainable behavior makes it challenging for individuals to connect with the issue personally. Immersive media are an opportunity to introduce innovative feedback mechanisms to highlight the urgency of behavior effects. We introduce a VR carbon calculator that visualizes users' annual carbon footprint as CO2-filled balloons over multiple periods. In a 2×2 design, participants calculated and visualized their carbon footprint numerically or as balloons over one or three years. We found no effect of our visualization but a significant impact of the visualized period on participants' environmental self-efficacy. These findings emphasize the importance of target-oriented design in VR behavior interventions.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Empirical studies in visualization**.

KEYWORDS

Virtual reality, intention-behavior gap, pro-environmental behavior.

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*firstname.lastname@uni-wuerzburg.de
†steffie.vogt@gmail.com

1 INTRODUCTION

For years, research groups worldwide have warned of the effects of anthropogenic climate change. With an assumed temperature increase of between $1.7°C$ and $4.4°C$ by the end of the 21st century, they predict heat waves, droughts, heavy precipitation, floods, and forest fires [5]. Despite the awareness of the topic and ongoing protests demanding robust measures for environmental protection, the climate goals set by policymakers may not be met [22]. One contributing factor to the challenge of achieving success in behavior change efforts is individual CO_2 consumption. The struggle to translate intentions into consistent actions, known as the "intention-behavior gap," is a common experience for many [2, 28, 29]. An obstacle to environmental behavior change is the lack of immediate, tangible consequences from our daily actions, making it difficult to link our behavior to environmental impacts [17]. Some interventions attempt to address this temporal barrier. For instance, CO_2 calculators provide information on how much CO_2 individual behavior generates, providing feedback on how one's consumption compares with others [16]. While informative, these approaches frequently fail to produce a revelation that would trigger genuine behavior change because the presented information is too abstract.

However, emerging technologies like Virtual Reality (VR) hold promise in bridging this gap by offering immersive experiences that can profoundly affect behavior change and effectively engage users on emotional and cognitive levels [7, 33]. VR offers the possibility of innovative feedback design through its technical properties, such as interactivity and realism, or to transcend the conventional notions of time and space [34]. For instance, abstract consequences of behavior such as values of CO_2 calculators can be visualized tangibly by allowing users to interact with objects that engagingly illustrate the abstract numbers. Far-future consequences can be conveyed by continuously modulating and illustrating the consequences of one's behavior depending on different time points [33].

Several studies have already demonstrated the potential of VR to contribute to environmental behavior changes [1, 7, 20]. However, these studies and the development of other assistive technology applications often overlook psychological insights [25, 31]. As such, Wienrich et al. [33] proposed a model (*BehaveFIT*) connecting the promising features of VR with barriers determining the so-called intention-behavior-gap. This interdisciplinary connection allows for systematically developing VR-based interventions to address individual environmental behavior. So far, little empirical work has systematically implemented and evaluated immersive feedback methods that address the temporal decoupling of actions and effects. Further, more research investigating immersive feedback engagingly conveying information is necessary. Thus, the following research question arises: *How do novel ways of immersive data visualization and the temporal decoupling of actions and effects impact the user's environmental self-efficacy and intention for pro-environmental behavior change?*

We aim to answer these research questions using a virtual CO_2 calculator. Through two immersive feedback methods, the application visualizes the users' CO_2 emissions. First, three-dimensional CO_2-filled balloons occur, illustrating the abstract amount of emission (see Figure 1). With an increased CO_2 footprint, the sky gets darker and darker. Participants can use a time-traveling machine exhibiting the consequences contingent upon one, two, and three years, thereby visualizing the temporal effects of their behavior. We measured two crucial predictors of behavior change: environmental self-efficacy and the intention to change behavior. The current work contributes to a theory-driven development and evaluation of two immersive feedback methods to set the base for changing individual environmental behavior.

2 RELATED WORK

Various theories and models attempt to illustrate or describe behavior change processes. Davis et al. [6] provide an overview of the existing research, present the most commonly cited theories established in research, and describe the process of behavior changes. One prominent example is the *Transtheoretical Model* [23]. It is a stage-based model including *Precontemplation*, *Contemplation*, *Preparation*, *Action*, *Maintenance*, and *Termination*. During behavior change, a person passes through all six phases. While the order of the stages is predetermined, the actual behavior represents merely one of the six stages, with preceding stages delineating initial motivation and intention. Thus, in scientific studies, intention is often measured and evaluated as a proxy for behavior.

The *Transtheoretical Model* highlights the importance of self-efficacy in behavior change. In the environmental context, self-efficacy is understood as the ability to behave in an environmentally protective manner and the perception of one's competence [11]. It thus majorly impacts behavior change. As early as 1986, Sia et al. [30] showed a relationship between the belief in influencing environmental problems and the political commitment to sustainability. Jody M. Hines and Tomera [14] described in a meta-analysis that the influence of self-efficacy on pro-environmental behavior is stronger than the subjects' environmental protection knowledge. Especially in the phase of preparation and action, an increase in self-efficacy is vital for implementing an action. In sum, behavior change is preceded by an intention and determined by self-efficacy.

2.1 Barriers to Environmentally Friendly Behavior Change

The six stages of the Transtheoretical Model are only sometimes fully completed. We have all experienced having good intentions and resolutions yet struggling to translate them sustainably into behavior, resulting in an *intention-behavior-gap* [2, 28, 29], otherwise referred to as value-behavior gap, attitude-behavior gap, or knowledge-behavior gap [4, 29]. Intentions may be the best predictor of behavior. However, they account only for 28% of the variance in future behavior, suggesting that other factors may predict successful behavior changes [28, 29]. Concerning the *Transtheoretical Model* [23], differentiation is made regarding the assumed initial stage, such as a person's intention or knowledge level.

The intention-behavior-gap has various reasons, depending on the context. Psychological studies highlight common barriers explaining the intention-behavior-gap [4, 9, 17]. Focusing on environmentally friendly behavior change, Kollmuss and Agyeman [17] identify influencing factors and barriers of pro-environmental behavior. They distinguish between demographic, external, and internal factors. Demographic factors include characteristics like education and gender. External factors are institutional, environmental, social, and cultural. Internal factors include motivation, values, knowledge, attitude, awareness, emotional involvement, perceived ability to influence behavior, responsibility, and priorities. Gifford et al. also examined barriers to pro-environmental behaviors [9]. They list what they call the *Dragons of Inactions*, which they divide into the following seven categories containing 36 subordinate barriers: Limited Cognition, Ideologies, Comparison With Others, Sunk Costs, Discredence, Perceived Risks, Limited Behavior. While demographic and external factors [17] are rather hard to manipulate to promote pro-environmental behaviors (e.g., too low an income to buy a photovoltaic system, poor availability of public transport), internal factors [17] and those described by Gifford [8] can be manipulated using the proper intervention.

2.2 BehaveFIT: A Framework Describing VR-Based Behavior Changes

One possibility for creating innovative interventions is the usage of VR technologies. VR offers technical properties, such as interactivity and realism, that allow us to transcend the conventional notions of time and space [34]. Wienrich et al. [33] merged the behavior change barriers proposed by different research groups and succinctly summarized and designated them into a framework for VR-based behavior change, *BehaveFIT*. In their framework, they differentiate between Temporal Distance, Spatial Distance, Distance to Effect, Distance to Control, Distance to Information, Distance to Benefits, and Distance to Persistence. With some of the subordinate barriers being less suitable for profiting from a VR-based intervention (e.g., relying on supra-human powers or technological solutions to solve climate change), this work focuses on two barriers that can benefit from the possibilities of immersive systems:

Temporal Distance: The Temporal Distance describes the barrier that risks are not perceived due to temporal discrepancies. The authors describe in their paper that our ancestors mainly dealt with immediate concerns and dangers. These here-and-now concerns are incompatible with the difficulty of solving climate and environmental problems, which often involve distant consequences and have delayed impacts.

Distance to Control: According to Gifford et al. [9], self-efficacy describes the feeling that climate change is a global problem, where many believe that there is nothing they as individuals can do about it. This, in turn, negatively impacts their motivation to act. Without experiencing self-efficacy, a critical motivation to act is missing.

Depending on the occurrence of one of the barriers and causes of behavior gaps listed above, different interventions can close an intention-behavior gap. VR offers many possibilities to support behavior change processes [20] and reduce the distances mentioned above. Fauville et al. [7] published a review of 13 papers that address the use of VR applications to promote environmental literacy. They explain the relationship between VR and pro-environmental behaviors and show how virtual applications can be engaging and effective for the user. They further identify helpful features of a VR application, such as the narration used, the degree of personalization, immersion, vividness, emotion, and negative affect. Additionally, the virtual environment, visual exploration, and the engaging nature of the applications impact environmental behavior.

BehaveFIT tied these features more directly to the psychological barriers mentioned above. It clusters the potentials of VR in *context representation*, *virtual objects*, *self-representation*, and *others representation* to contribute to the manipulation space in VR. Thus, effects that lie in the future can be elucidated, for example, by directly altering the virtual environment, or the sense of control can be enhanced by actively interacting with virtual objects.

2.3 Using VR For Eco-Friendly Behavior Change

One promising example of how VR can impact environmentally friendly behavior change is the study of Hsu et al. [13]. They designed an experimental learning game in which participants received exaggerated feedback on their water consumption. The immersive feedback displayed their water consumption not numerically but in 600ml water bottles. The authors found that subjects showed a significant change in cognition and behavioral intention through the VR application. However, they neither measured actual behavior nor self-efficacy. According to a study by Lee et al. [19], while immersive feedback was not required to foster understanding of the data presented, it helped elicit an emotional response in users as it gave more meaning to the data. Romat et al. [26] found that immersion in data visualization (2D vs. VR) positively impacts the users' enjoyment and engagement with the data. Further, Bailey et al. [3] showed that the vividness of a VR visualization of a person's energy consumption positively affected their pro-environmental behavior, namely their use of hot water in reality. While not all of these studies evaluated self-efficacy or behavior, they underline the potential of VR in behavior change processes.

Regarding the barrier of Temporal Distance, Michel et al. [21] refer to a period of one month as short-term planning, between one and two years as medium-term planning, and three, five, or even ten years as a long-term planning horizon. Additionally, the CO_2 calculator of the Federal Environment Agency of Germany offers the possibility to display the consequences of actions over several years addressing the barrier temporal distance [16]. Users can calculate their balance for one year, five years, ten years, or 2050. However, no data is available about the impact of time manipulation on users and whether VR adds to the value of such data.

2.4 Summary and Present Study

Psychological barriers describe why behavior change is challenging. For successfully changing environmentally friendly behavior, overcoming *Temporal Distance* and the *Distance to Control* is essential. Further, intentions are a good but insufficient predictor. Other influencing variables like self-efficacy play a crucial role in actual behavior change. Recent examples already indicate promising results of VR interventions in environmental behavior. However, the potential to overcome the temporal barrier and feel the consequences of one's behavior regarding different periods (one or more years) has yet to be implemented and evaluated in VR. The present study combined the idea of a CO_2 calculator with immersive feedback methods and measured intention of behavior change and environmental self-efficacy regarding reducing the individual CO_2 emission.

Hypotheses. Based on the theoretical background presented, this work presents the implementation and subsequent evaluation of a VR-based CO_2 calculator to test for the following hypotheses:

H1: Showing a positive change in carbon footprint after behavior change for several years instead of one increases the self-efficacy for environmentally friendly behavior.

H2: Spatial visualization of subjects' carbon footprint increases self-efficacy for environmentally friendly behaviors compared to a numerical representation.

H3: Showing a positive change in carbon footprint after behavior change for several years instead of one increases the intention to change environmentally friendly behavior.

H4: Spatial visualization of the subjects' carbon footprint compared to a numerical representation increases their intention to change their environmentally friendly behavior.

3 IMPLEMENTATION

We developed the virtual CO_2 calculator application using the Unity game engine[1] version 2019.3.14f19. The application is displayed on the HTC-VIVE Pro Head-Mounted Display (HMD). The application requires one controller operated with the user's dominant hand.

3.1 The Virtual Environment

The scene of the virtual CO_2 calculator application consists of several trees, as well as guests and fields to resemble a rural, central European setting (see fig. 1). This environment aimed to provide users with a familiar backdrop (as similar settings could be found near to where the experiment was conducted), enhancing their ability to relate the experiences and planned behavioral changes within the VR environment to the real world [24]. However, it is not a photorealistic representation of a specific environment. We ensured that assets did not obstruct the menu and that the sky in the application was cloudless to ensure optimal visibility of the feedback condition represented by the balloons.

We implemented controller-based interactions to enable users to interact seamlessly with the menu on a virtual canvas (see Figure 2. The menu contains a tutorial for new CO_2 calculator users.

3.2 The CO2 Calculator

The CO_2 calculator within the virtual environment was implemented in C#. The user interface dynamically updated the content of text fields and images based on user input. The CO_2 calculator was based on an established carbon footprint calculator focused on the key sectors: personal data, heating, electricity, mobility, nutrition, and general consumption [16]. The heating and electricity sectors were not included in the individual calculation. Thus, 24 questions are decisive for the calculation: four on personal data, five on nutrition, ten on mobility, and five on consumption. In the mobility sector, for example, users are asked about the kilometers they have traveled by bicycle, car, ride-sharing, and plane. All questions were answered using selectable options and sliders in VR. The calculator stored user responses and calculated the corresponding CO_2 emissions. The result of the calculated CO_2 emissions is displayed to the user on the virtual canvas. The annual amount is displayed in t/year, rounded to the first decimal place (see Figure 2). This information represents the numerical representation.

[1]https://unity.com/de

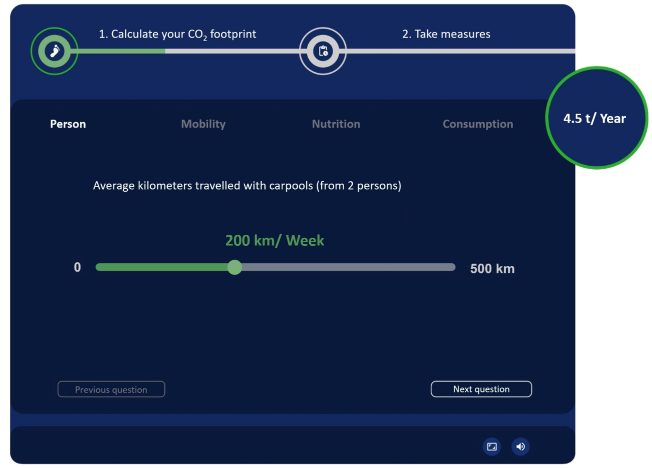

Figure 2: The virtual canvas used for calculating participants' CO_2 emissions

Additionally, the script stored the user's input parameters, enabling further statistical analysis and evaluation of the data.

3.3 Balloon Visualization

To give users immersive feedback on their CO_2 consumption, virtual balloons filled with CO_2 were implemented (see fig. 1). The representation of CO_2 emissions as balloons is novel. No similar representation was found in previous literature reviews on CO_2 calculators. For this reason, the impact of the balloons was tested in a qualitative pilot study involving N=5 participants. These participants engaged with the application using the think-aloud method, where they were asked to vocalize their thoughts while being recorded [18]. The balloons were perceived as threatening, with the participants clearly associating them with exhaust fumes, reporting positive feelings as they disappeared. The balloons have a volume of 15 liters and are gray and transparent, as CO_2 is colorless to make the feedback more immersive. As the balloons have a capacity of 15 liters of CO_2, the consumed CO_2 emissions need to be rounded to 15 liters. Hence, rounding is applied to both the numeric and balloon visualizations, rendering the annual balance as balloons is more precise compared to the numeric presentation in t/year. The implementation involved individual objects representing balloons, each assigned a weight, and a realistic physics animation was applied to make the balloons descend realistically, as one liter of CO_2 weighs 1.96 grams. The balloons are randomly placed in the virtual environment. No balloons are situated in the immediate surroundings of the user. The added animation causes the balloons to move gently back and forth, although not in a way that allows the user to touch the balloons. Therefore, no interaction occurs between the user and the balloons.

3.4 Numeric Visualization

To investigate the effect of confronting the participants with their CO_2 consumption using CO_2-filled balloons, a less immersive numeric visualization was implemented for the control condition. In

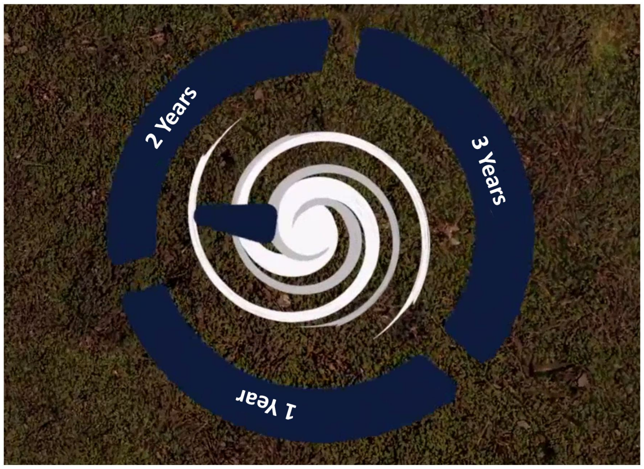

Figure 3: The interactive menu for selecting the period.

this condition, the same VR environment as in the balloon setting was used as a background, with the sole difference of a two-dimensional plane appearing in front of the participants showing the calculated amount of their CO_2 consumption instead of using balloons as a visualization technique.

3.5 Selection of Time Period

Additionally to the balloon or numeric visualization, the application provided users with the option to select a time dimension. This feature allowed users to evaluate their carbon emissions over different periods, such as one, two, and three years, via a canvas on the virtual ground. Depending on the direction in which users turn, they are presented with the extent of their total CO_2 consumption within the selected period. The script determines the user's direction via the HMD's orientation. Figure 3 illustrates the period selection menu. A maximum three-year time span is implemented due to performance issues, limiting the number of balloons on larger time spans. Apart from selecting the period in which the user rotates around his axis, there is no other teleportation method in the VE other than the physical space in the laboratory, which is approximately two square meters. The design of the feedback period menu aims to have high affordance, where the form and layout of the menu indicate a temporal component similar to a clock. The buttons are arranged circularly, following a clockwise direction. The survey of participants in the pilot study involving five respondents showed that the representation of the temporal dimension through the menu on the ground is intuitively usable. Participants drew an analogy to a "clock" or a "time vortex."

3.6 The Tutorial

The tutorial provided guidance and instruction to users without experience with VR. It consists of five explanatory texts accompanied by illustrations that explain how to use the controller, interact with the canvas, and change the selected period. Its primary goal is to familiarize users with the navigation controls, menu selection, data input methods, and overall user interface.

Table 1: The between-subjects design of the study

Time span of feedback	Visualization of CO_2 footprint	
	Numeric	Balloon
One year	Group 1 (control group)	Group 2
One, two or three years	Group 3	Group 4

4 USER STUDY

In a 2×2 design, we investigated the impact of feedback visualization (numerical vs. balloons) and period (one vs. one, two, and three years) of our CO_2 calculator on environmental self-efficacy and intention for behavior change. The participants were randomly assigned to one of these groups using a between-subject design (see Table 1).

4.1 Participants

Sixty-three students ($M_{age} = 21.75, SD_{age} = 2.90$) participated in the study, recruited via the online recruitment platform of the local university. Of the 63 participants, 15 were male, and 48 were female. The samples in our four experimental groups were similar in structure, and there was no difference in the distribution of age or gender.

4.2 Experimental Setup

We used the HTC-VIVE Pro as the HMD to conduct the VR experience. Participants used VIVE controllers to interact with the virtual canvas. We assessed behavior change intention data in VR. The other data was collected through an online questionnaire using LimeSurvey2[2] on a Windows 10 computer.

4.3 Measures

Environmental Self-Efficacy. We assessed environmental self-efficacy using a questionnaire derived from Tabernero and Hernández [32]. It includes nine items assessed on a five-point Likert scale.

Intention for Behavior Change. We assessed behavior change intention via the VR application. Participants indicated their planned behavior in the second step of the virtual CO_2 calculator, "my CO_2 scenario". They answered all questions a second time, focusing on their future behavior. The collected data provided information on participants' intention to change their CO_2 emissions compared to their current behavior and in which categories they aim for change.

Cybersickness. To control for potential negative effects of our VR system, we assessed cybersickness using the Simulator Sickness Questionnaire (SSQ) [15]. Using a five-point Likert scale, it assesses the three dimensions of nausea, oculomotor disturbances, and disorientation on 16 items. The SSQ is assessed before and after a VR interaction to determine if the interaction significantly impacts the participants' well-being.

4.4 Experimental Procedure

At the beginning of the experiment, participants read and signed an informed consent form and data protection statement. They were

[2]https://www.limesurvey.org

Table 2: Descriptive results of the post- and pre-intervention difference of self-efficacy.

Time span of feedback	Visualization of CO_2 footprint	
	Numeric M(SD)	Balloon M(SD)
One year	$-.44(4.75)$	$-1.83(3.73)$
One, two or three years	$2.43(3.30)$	$1.80(4.49)$

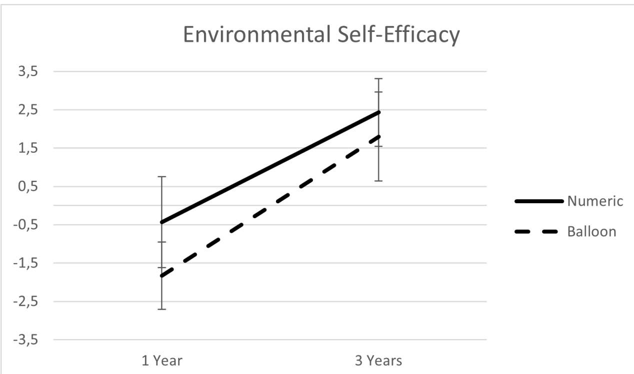

Figure 4: Results of the environmental self-efficacy pre-post difference in the four conditions. Positive values indicate increased environmental self-efficacy after the intervention.

informed about their right to terminate the experiment without any disadvantage. Next, participants completed the pre-questionnaires, including demographic information, Environmental Self-Efficacy, and the SSQ. After completing the pre-questionnaires, participants performed the system's tutorial (see Section 3.6),familiarizing them with the virtual environment. After the tutorial, the virtual CO_2 calculator was opened to test the study's hypotheses. The CO_2 calculator had two steps: "Your CO_2 Footprint" and "Your CO_2 Scenario"(see Figure 2).In the first step, participants provided information about their current behavior in mobility, diet, and consumption categories and received feedback on their current CO_2 footprint. In the second step, "Your CO_2 Scenario", participants could indicate their intended behavior for the future and receive feedback on their planned behavior's potential impact. Figure 1 shows the feedback displayed with balloons. After completing, participants removed the HMD and answered the post-questionnaire, including environmental self-efficacy assessments and the SSQ. The study duration was 45 minutes, including about 20 minutes in VR.

5 RESULTS

For all analyses, we used the statistics software R. To control for α-cumulation, we lowered the significance level to .01. To compare the effect of the intervention on the dependent variables between the four conditions, we calculated the difference between the post- and pre-measure for each variable. Positive values indicate an increase, and negative values indicate a decrease in the respective variable.

Table 3: Descriptive results of the post- and pre-intervention difference of intention for behavior change.

Time span of feedback	Visualization of CO_2 footprint	
	Numeric M(SD)	Balloon M(SD)
One year	$-.52(5.37)$	$-.38(2.67)$
One, two or three years	$-1.21(2.14)$	$-2.14(1.90)$

Figure 5: Results of the intention of behavior change pre-post difference in the four conditions. Positive values indicate an increase after the intervention.

Environmental Self-Efficacy. Table 2 and Figure 4 show the descriptive differences between the participants' measures of environmental self-efficacy post- and pre-intervention. To investigate the impact of the feedback period and the visualization on environmental self-efficacy, we calculated a two-factorial ANOVA. The assumptions of the ANOVA were met in that the residuals are normally distributed ($W = 0.98, p = 0.537$) and have homogeneity of variance ($F(3) = 0.42, p = 0.738$). The ANOVA revealed a significant main effect of the factor period of the feedback on the participants' environmental self-efficacy, $F(1, 59) = 9.95$, $p = .003$, $\eta^2 = .90$. Participants in the groups with the extended feedback period showed significantly higher values in environmental self-efficacy after the intervention. There was no significant main effect of the factor visualization of the participants' CO_2 footprint ($F(1, 59) = 1.01$, $p = .319$, $\eta^2 = .09$) and no significant interaction of the two factors ($F(1, 59) = .14$, $p = .714$, $\eta^2 = .01$) on the participants' environmental self-efficacy.

Intention for Behavior Change. The descriptive results of the differences between post- and pre-intervention measures of intention for behavior change are shown in Table 3 and Figure 5. To investigate the impact of the feedback period and the visualization on intention for behavior change a two-factorial ANOVA was calculated. The assumptions of the ANOVA were not met entirely. The residuals had homogeneity of variance ($F(3) = 1.01, p = 0.393$), but were not distributed normally ($W = 0.89, p = 3.11e^{-08}$). Due to the robustness of the ANOVA [12, 27] and the conservative significance level of $\alpha = .01$ to mitigate the risk for α-errors, the ANOVA was still calculated. The ANOVA revealed no significant main effect of the factor period of the feedback ($F(1, 59) = 2.18$, $p = .145$, $\eta^2 = .79$), the factor visualization of the participants' CO_2 footprint ($F(1, 59) = .18$, $p = .677$, $\eta^2 = .06$), and no significant interaction effect of the two factors ($F(1, 59) = .40$, $p = .530$, $\eta^2 = .15$) on the participants' intention for behavior change.

Simulator Sickness. A paired-sample t-test was calculated for the control variable of Simulator Sickness. The assumptions of the t-test were not met entirely. The data were not normally distributed ($W = 0.78, p = 1.826e^{-12}$), but have homogeneity of variance ($t(1) = 1.33, p = .251$). Thus, we calculated a non-parametric Wilcoxon signed rank test. The test revealed that there was no significant difference in the participants' SSQ pre ($M = 11.10, SD = 13.06$) and post ($M = 13.54, SD = 15.92$) intervention ($W = 2119, p = .508$).

6 DISCUSSION

The extendable period of one, two, and three years for the participants' feedback on their CO_2 footprint significantly increased their environmental self-efficacy compared to the feedback for one year. Hence, we accepted H1. However, the spatial visualization of the participants' carbon footprint using CO_2-filled balloons did not lead to the expected change in their environmental self-efficacy. Thus, we could not accept H2.

In terms of the participants' intention to change their environmentally friendly behaviors, neither the increased period of the feedback of their CO_2 footprint nor the spatial visualization thereof using CO_2-filled balloons led to a significant increase. Hence, we could not accept H3 and H4. Participants who observed the consequences of behavior change over two and three years exhibited greater environmental self-efficacy than those exposed to one-year outcomes. This finding aligns with Gifford et al.'s [9] assertion that the challenge in promoting eco-friendly behaviors lies in the delayed and inconspicuous nature of the consequences, a gap that VR can potentially bridge effectively [33]. Furthermore, we can initially only postulate an effect of the representation of the time span; we cannot specify when the effect occurs (after 1 year, 2 years, etc.).

In the application proposed in this paper, the temporal dimension extends over three years, which is a small period compared to other CO_2 calculators. Michel et al. [21] refer to one month as short-term planning, up to two years as medium-term planning, and three to ten years as long-term planning. By definition, the Federal Environment Agency of Germany [16] allows users of its CO_2 calculator to plan for the medium and long term. The periods were shortened in the virtual CO_2 calculator as perceiving noticeable differences above a certain number of balloons was challenging. Since the environmental self-efficacy of the participants already changed significantly at only three years, we assume that showing the estimated CO_2 footprint for an even more extended period could lead to even more potent effects. While showing the consequences over several years affected the participants' environmental self-efficacy significantly, it did not affect their intention to change their environmentally friendly behavior.

Using three-dimensional balloons as feedback had no effect on self-efficacy nor the intention to change environmentally friendly behavior, compared to numeric feedback in VR. Whether the feedback of the three-dimensional balloons is a suitable form of visualization has to be answered ambivalently. There are still some variables that can be investigated in more detail in future studies. The arrangement of the balloons and interactivity are some examples. Besides the balloons, the whole virtual space affects the users' perception. Since we did not control the users' field of vision, it is not guaranteed that all changes in the virtual environment were perceived. Here, an opposite effect could have occurred: Subjects might have the impression that their behavioral change has little effect on the number of balloons. The sky is littered with CO_2-filled balloons in their current and future behavior. In the balloon visualization, changes may be more challenging to detect compared to the numeric feedback, where the value is presented as double or triple in magnitude.

There are possible solutions to this problem: First, the feedback could be limited to the individual categories. A separate presentation of the CO_2 balance for mobility, nutrition, and consumption provides for small numerical values and, thus, for better differentiation of the number of balloons. Similar effects could be achieved with different colors if the coloring of the balloons differs depending on the category to which they belong. This suggestion came from a test person interested in their CO_2 emissions in the respective categories. A second approach is to rearrange the balloons. For example, the balloons could be placed closer to the user as CO_2 levels increase. Possibly even so close that individual balloons enter the personal space of the test subjects. Hall describes personal space as the realm surrounding a person and which they psychologically consider to be their property [10]. This phenomenon can also be transferred to the medium of VR [35].

A similar approach is used by Hsu et al. [13], who use exaggerated feedback to educate subjects about their water consumption. It is possible to amplify the feedback of the balloons. Thus, an exaggerated presentation method may enhance the desired effect of an environmentally friendly behavior change, but the information content of the application would be distorted. The exact calculation of the CO_2-values, which are based on the data of the Federal Environment Agency of Germany, serves the clarification and the comprehensibility of the virtual CO_2 calculator [16]. The study cannot confirm the assumptions that showing the consequences over two and three years and the three-dimensional feedback of the balloons increase the intention of an environmentally friendly change of behavior. However, there is a general high intention to change behavior in all four groups. This suggests a positive effect of confronting the participants with their CO_2 footprint in VR in general, independent of the manipulations in this study. However, these assumptions should be verified by comparing the VR-based CO_2 calculator results with a regular browser-based CO_2 calculator.

7 CONCLUSION AND FUTURE WORK

This paper presented the implementation of a VR-based CO_2 calculator to make the abstract topic of climate change more tangible and, by bridging the temporal gap between environmentally damaging behavior and impact, setting the basis for behavioral change among users. The implemented CO_2 calculator uses two different periods of providing feedback about the participants' future calculated CO_2

footprint (one year vs. one, two, and three years) and using two different techniques to visualize their CO_2 footprint (numeric, vs. spatial, using virtual balloons). In the subsequent user study, we investigated whether the implemented features of extended periods for feedback and the visualization of the participants' CO_2 footprint using virtual balloons positively impacted the participants' prerequisites for environmentally friendly behavior change.

Based on related work, we expected that the participants' environmental self-efficacy and their intention to change environmentally friendly behavior would increase with an extended period of feedback on their CO_2 footprint, as well the spatial visualization thereof using virtual CO_2-filled balloons. The results revealed that the extended period of feedback on the participants' CO_2 significantly impacted their self-efficacy. Innovative methods for visualizing consequences that lie far in the future, thus becoming tangible for people, positively affect environmental self-efficacy. VR can, in principle, convey these effects well [33]. A media comparison was not the aim of our study, so we did not test visualizations with other media against the VR visualizations. Therefore, whether VR was necessary to trigger the effect must remain open here. Future studies could test the temporal representation again with different media visualizations against VR.

Future work should consider novel ways to visually represent the participants' CO_2 footprint in VR since the implemented visualization using virtual balloons did not significantly affect the dependent variables. Furthermore, the assessment of actual change in environmentally friendly behavior change should be considered to see whether using a VR-based CO_2 calculator can lead to short- and long-term behavior change. Additionally, a diverse sample could yield diverse results, for example by including older participants in future studies. Overall, the study shows that psychological distances can be overcome through innovative virtual feedback methods and thus provide a good basis for behavioral change.

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