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Full length article

Troubled water: Enhancing flood preparedness with eXtended reality

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ABSTRACT

Effective mitigation of flood impacts depends not only on infrastructure but also on citizens' preparedness. Despite ongoing efforts in risk communication and disaster education, protective behaviors remain limited, leading to avoidable damage and losses. Immersive technologies may offer new ways to strengthen flood preparedness education. In our study, 'Troubled Water', we present two prototypes designed to engage users with flood-related risks and protective actions. A first element allows users to interact with virtual objects to learn their relevance for protective behavior; a second allows them to experience rising water levels in their physical environment. Both elements are delivered via tablet-based Augmented Reality, with the water-level simulation also available in head-mounted Mixed Reality. In a study of 160 participants across four groups, object interaction enhanced coping appraisals; water-level simulation increased threat appraisals; and all immersive experiences raised intentions to prepare for flood events. These findings suggest that immersive technology can play a valuable role in advancing flood preparedness education.

1. Introduction

Severe flooding threatens lives, compromises human health and food security, and damages property and infrastructure (IPCC, 2023). Reducing these impacts requires coordinated and often costly efforts from multiple actors, including politicians, planners, and scientists. Traditionally, such efforts have emphasized large-scale public initiatives. More recently, however, attention has also turned to individual preparedness. The United Nations' Sendai Framework for Disaster Risk Reduction (UNDRR, 2015), for example, highlights the central role of self-preparedness in effective risk management. It calls for citizens to assume responsibility for their own safety by taking measures such as developing household emergency plans, assembling and maintaining emergency kits, storing food and water supplies, and ensuring access to warning information (BBK, 2026).

The institutional emphasis on individual preparedness has found support in a number of recent studies—all of which confirm that individual preparedness reduces losses during severe flood events (Kreibich et al., 2021; Mohor et al., 2021). Although scholars widely agree on the value of emergency planning and numerous initiatives have sought to raise awareness and promote protective behaviors, most EU citizens nonetheless do not feel adequately prepared for disasters or emergencies (DG ECHO, 2024). This lack of preparedness can be attributed in part to limited personal experience with flooding (Bubeck et al., 2012).

One suggested solution to enhance the effectiveness of disaster preparedness education is to make use of technology (Fazeli et al., 2024; Guo et al., 2025; UNDRR, 2015). In the past decade, Extended Reality (XR) technologies have advanced rapidly and have become more accessible. By simulating experiences that cannot otherwise be created in real life, they have the potential to aid in risk communication (Tiede et al., 2026) and disaster preparedness education (Fazeli et al., 2024; Guo et al., 2025).

In this study, we introduced our prototypes 'Troubled Water', designed to demonstrate how immersive components may enhance flood preparedness education. We examined the influence of two XR-specific attributes, namely the ability to enable interaction with virtual objects and the capacity to elicit a sense of presence (Schubert, 2009; Slater, 2009), on individual flood protection. In particular, we investigated the short- and medium-term effects of our tablet-based Augmented Reality (AR) prototype and head-mounted Mixed Reality (MR) prototype on preparedness behaviors, protection intentions, and underlying cognitive processes, using a between-subjects study design.

2. Individual flood preparedness

When citizens are adequately prepared, the overall strain on public authorities and response organizations during severe floods is greatly

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reduced. Enabling individuals to prepare for and recover from flooding is thus a critical component of resilience strategies, which increasingly mandate that citizens in flood-prone areas take appropriate preparedness measures (UNDRR, 2015). To enact such strategies, however, public authorities must provide citizens with the knowledge and tools necessary for effective preparedness and response. In Germany, this is done mostly through brochures, warning apps, websites, or interactive hazard maps with safety guidelines (BBK, 2026).

Research has shown that there is a widespread tendency to underestimate the risk of severe floods and other natural hazards (Mol et al., 2020; Trumbo et al., 2014; Weinstein, 1989) and that in past flood events, citizens were often unprepared and unable to carry out measures to protect themselves and their property (Bubeck et al., 2012; Poussin et al., 2014). Considerable effort has thus been made to understand why and under what conditions individuals choose to prepare for natural hazards (Bubeck et al., 2012; Fazeli et al., 2024; Kohn et al., 2012; Paton, 2003; Wachinger et al., 2013). A comprehensive meta-analysis by Van Valkengoed and Steg (2019) summarizes the factors associated with adaptive behavior in the context of climate change, with much of the research focused on flood preparedness. Their findings underscore the importance of several motivational factors in shaping individual preparedness: *self-efficacy*, the belief in the own capacity to implement effective adaptive measures; *outcome efficacy*, the belief that these measures will successfully mitigate risk and confer protection; *negative affect*, an unpleasant emotional response to perceived threats; and *descriptive norms*, the individual's perception of whether others are engaging in adaptive behaviors. While findings regarding prior experience with natural hazards, risk perception, and domain-specific knowledge were heterogeneous across studies, the overall consensus points to a positive association with adaptive behavior. Van Valkengoed and Steg (2019) argue that since the key findings of their meta-analysis match with the main components of Protection Motivation Theory (PMT – Rogers, 1983), the model fits to explain protective behavior. Originating in health psychology, PMT has been widely applied in flood risk research (see meta analysis by Bamberg et al., 2017). It aims to capture the key cognitive processes that influence an individual's decision to engage in a protective or non-protective behavior. The framework consists of two appraisals. *Threat appraisal* concerns perceived vulnerability and severity of the threat, as well as the negative affect it elicits (i.e., fear). *Coping appraisal* reflects perceived response efficacy and the costs of protective measures, along with the individual's perceived self-efficacy in carrying them out. When high perceived risk (threat appraisal) is accompanied by strong coping appraisal, the intention to engage in protective behavior – including recommended actions – tends to increase (Bubeck et al., 2012). According to PMT, these cognitive processes are influenced by environmental and interpersonal sources of information. Environmental sources refer to factors like verbal persuasion and observational learning. Observational learning occurs when individuals observe the experiences and behavior consequences of others. Interpersonal determinants include personal characteristics such as personality traits and prior experiences with similar threats.

3. XR and flood preparedness

3.1. XR terminology

XR is an umbrella term for technologies that augment the physical world with spatial virtual content, spanning a continuum from Virtual Reality (VR) to MR and AR (Milgram et al., 1994). VR fully immerses users in synthetic environments. The boundary between AR and MR remains debated (Skarbez et al., 2021). Following Speicher et al. (2019), we distinguish them by degree of virtuality: AR provides minimal augmentation (e.g., tablet-based), whereas MR offers more immersive overlays and real-world interaction, typically via head-mounted displays.

3.2. XR attributes and behavior

Driven by the increasing availability of XR technologies, immersive applications to support behavior adaptation have been explored across various contexts, including pro-environmental action (Ahn et al., 2016; Chirico et al., 2021), phobia therapy (Morina et al., 2015), and physical rehabilitation (Howard, 2017). To understand how these applications differ from other learning environments, researchers have examined key attributes of immersive technology (Makransky & Petersen, 2021; Wienrich et al., 2021). In their Cognitive Affective Model of Immersive Learning (CAMIL) framework, Makransky and Petersen (2021) identify presence and agency as core psychological affordances that enhance learning in immersive environments. Additionally, Wienrich et al. (2021) propose four XR features that contribute to behavioral change: self-representation, context representation, representation of others, and virtual object use. In this study, we focus on interaction with virtual objects and (spatial) presence.

With XR, any object, its features, and its relations can be simulated, allowing users to see the consequences of their actions. Such hands-on *interactions with virtual objects* can closely mirror real-world interaction (Wienrich et al., 2021). Following Makransky and Petersen (2021), having the ability to exert control over parameters of the virtual environment is an important element of agency experience, i.e., the feeling of generating and controlling actions. For us, the key distinction of agency experience, while related to presence in a virtual environment, is the emphasis on user engagement enabled by the integration of object interactivity and gameful design principles (Deterding et al., 2011). Immersive simulations provide immediate feedback on users' actions and decisions, thereby presenting valuable opportunities for mastery experiences. According to Bandura (1977), they are a fundamental pathway to building self-efficacy (see also Makransky et al., 2020). These object-interaction environments offer strong support for experiential learning (Jantjies et al., 2018; Kolb, 1984; Kolb & Kolb, 2009; Kwon, 2019). Combining virtual with real objects in AR/MR may further enhance learning compared to fully virtual settings (Quarles et al., 2008).

The ability to foster *spatial presence* is a sub-element of presence as defined by Makransky and Petersen (2021), and is closely related to context representation as described by Wienrich et al. (2021). It describes the perception of being physically present in a virtual environment (Schubert, 2009; Slater, 2009) and the illusion that what is apparently happening is really happening (Slater, 2009). It has been shown that experiencing presence in a virtual environment can, at least to some extent, elicit feelings and emotions comparable to those evoked by real-world experiences (Chirico & Gaggioli, 2019). While well researched in VR, less is known about spatial presence in AR and MR.

3.3. Status quo: XR and flood preparedness

With a few studies evaluating multi-modal workshop formats (Bosschaart et al., 2016; Heidenreich et al., 2020; Terpstra et al., 2009) and recent work highlighting serious games for natural hazards as an important research area (Forrest et al., 2022; Solinska-Nowak et al., 2018), little research has addressed the development, implementation, and evaluation of concrete educational interventions to enhance citizens' preparedness. Very few studies focus specifically on the potential of immersive technology for enhancing protective behavior (Amberson et al., 2024; Fazeli et al., 2024; Verrucci et al., 2016).

Beyond academic work, reports on educational programs using immersive technology for disaster preparedness are equally rare. Although national and international organizations (e.g., BMI, 2022; UNDRR, 2015) and researchers (e.g., Fazeli et al., 2024) have called for more motivational, technology-supported preparedness education, only a few brief reports on such programs exist (e.g., The Tokyo Rinkai Disaster Prevention Park, 2022; UNDRR, 2021).

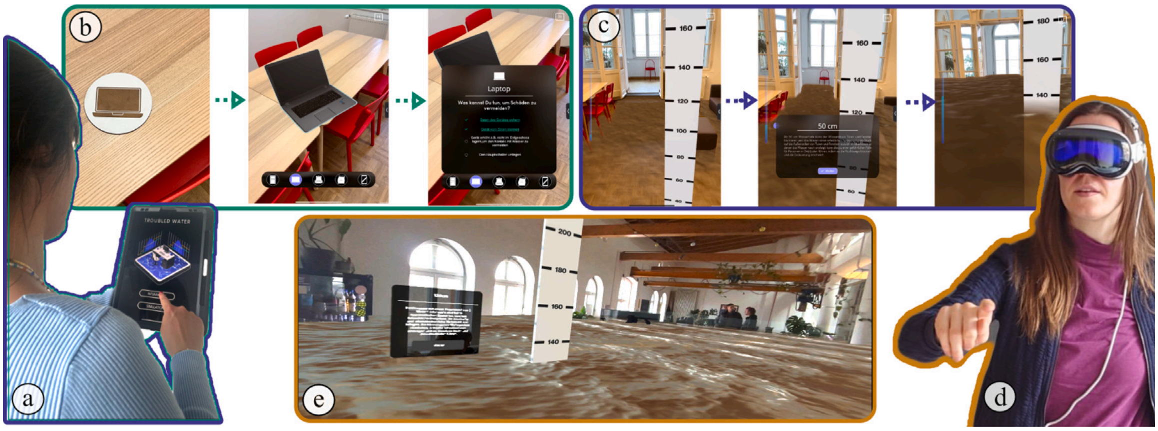

Fig. 1. (a) Outside view of the AR tablet-based prototype in the start screen. (b) screenshots of the AR objects element and (c) of the AR simulation element. (d) shows the outside view of the MR prototype, and (e) the inside view of the MR simulation element at 120 cm water level.

In disaster management and training, XR technologies are gaining attention (see e.g., Khanal et al., 2022; Lovreglio, 2020; Scippo et al., 2024). Researchers have used VR to simulate natural hazards such as storm surges (Presa Reyes & Chen, 2017; Simpson et al., 2022), flash floods (Skinner, 2020), and hurricanes (Bernhardt et al., 2019). While some projects showcase technical possibilities (e.g., Presa Reyes & Chen, 2017; Sermet & Demir, 2019), others report educational benefits, including increased interest in flood-hazard learning (Skinner, 2020) and improved risk awareness (Mol et al., 2022; Simpson et al., 2022).

With AR, most research projects prioritized advancing technology for urban planning and flood-risk visualization over public preparedness education (e.g., Haynes et al., 2018; Lamrabet et al., 2024; Wursthorn et al., 2004). More toward preparedness education, Mirza et al. (2024) introduced a mobile AR game designed to help users identify objects essential for personal safety and well-being during an emergency. They found that the game influenced users' perceived behavioral control in simulated disaster scenarios. Their study did not directly assess protective behavior, focusing instead on evaluating the impact of time pressure. Rydvanskiy and Hedley (2021) carried out a MR project that considered disaster management, evaluating usability metrics. Their application integrated geospatial data and was designed for use with see-through MR glasses.

In sum, despite the fact that policymakers and researchers agree that VR shows great potential for enhancing disaster preparedness among the general public, few formal evaluations of its impact on protection behavior exist (Guo et al., 2025). Moreover, while AR and MR applications are increasingly used in disaster management, particularly in professional and operational settings, their use in promoting disaster preparedness has been underexplored.

4. Present research

The overarching goal of this work is to advance the development of effective flood preparedness interventions through immersive technology. Our focus is on AR and MR technology. Specifically, we aimed to design functional, engaging, and accessible prototypes that demonstrate how immersive components might be integrated into future educational programs to strengthen flood preparedness.

In this study, the prototypes were used to explore how immersive components could enhance flood preparedness. We combined insights on individual preparedness, particularly from the PMT framework, with XR-specific features shown to influence behavioral change, and proposed mechanisms linking these constructs. By grounding the study in human–computer interaction and risk education research, we aim to support theory-driven evaluations of technology-enhanced interventions in flood-risk contexts.

In particular, we addressed the following research questions:

RQ1: Is the ability to enable *interaction with virtual objects* an effective XR attribute to promote preparedness?

While many everyday items are relevant to protection behavior, we rarely consider their importance in the context of preparedness. AR and MR technologies allow users to interact with simulations of these objects integrated into a real-world environment, without requiring the physical items to be present. During these interactions, users can receive additional information and direct feedback. Such interactions may serve as 'mastery experiences' (Bandura, 1977; Makransky et al., 2020) for protective behavior, which we expected would increase participants' perceived ability to engage in adequate protective actions. This is in line with empirical evidence that highlights the importance of practical guidance on protective actions for self-efficacy and coping appraisals (Sutton et al., 2021; Wong-Parodi et al., 2018). Anticipating an increase in coping appraisals, we expected an increase in protection motivation, intention to prepare, and in actual protective behavior.

RQ2: Is the ability to foster *spatial presence* in a simulated flooding an effective XR attribute to promote preparedness?

By fostering spatial presence,VR technology allows individuals to experience, to some extent, what it feels like to be in a place affected by flooding. This approach allowed us to ethically examine the effects of a simulated but first-person flood experience, which can be an indicator for strong risk perception and protective behavior (Bubeck et al., 2012). Experiencing a strong sense of presence in virtual environments related to environmental threats has been shown to heighten risk perception and reinforce intentions to adopt protective behaviors (Breves, 2021; Fox et al., 2020). Proposed working mechanisms for these effects include reduced perceived temporal (Breves & Schramm, 2021) and spatial (Lee & Li, 2023; Touré-Tillery & Fishbach, 2017) distance to the simulated elements. Ommer et al. (2024) suggest that immersive visualization can make imagination of flooding easier. With AR and MR, spatial presence is focused on creating co-presence with elements in the direct physical environment of the user (Schubert, 2009; Stevens et al., 2002). In the context of simulating a flood, AR and MR thus might allow people to experience a flooding event in their immediate surroundings, i.e., to see flood water rising locally instead of in a simulated virtual world. Because locality, such as presenting photos of people's hometowns (Ommer et al., 2024), has been shown to be important in effective communication, the ability to maintain local surroundings in the virtual field might be beneficial to increase imagination and decrease perceived distance. We expected that the experience of simulated flooding would increase the perceived vulnerability as well as the perceived severity of the flood threat. Consequently, we anticipated both an increased intention to prepare and an increase in actual protective behavior.

Table 1
Text displayed in the AR objects prototype. Incorrect quiz options are marked with [x]. Text was originally displayed in German language.

Object	Description
Introduction	Here you can learn about the role of various objects relevant in flood protection behavior. Find the icons of the listed objects in the room and scan them to project the objects into your world. Then, tap the virtual objects to learn more about them.
Smartphone	It is important to stay informed and connected during a flood event. Stay updated via local radio, warning apps, and flood control center websites. Who would you contact first in the case of a flood event? Your family, your flatmates, neighbors or other people? Which of the following points would you discuss with your close circle in an acute flood situation? Options: pass on a warning, coordinate care for vulnerable individuals, share your thoughts about the annoying weather [x], share self-protection advice, plan who will secure pets, arrange a meeting point, other topics, that have been on the table for a long time [x]. Keep calls and messages clear and brief in emergency situations! Calls could spontaneously be interrupted.
Backpack	If you must evacuate your home, it is important to have an emergency kit ready. It should be stored easily accessible. What do you think should be in your emergency kit? Options: personal medications, good book [x], first aid kit, hygiene items, spare batteries/power bank, sledgehammer [x], important documents, flashlight, blanket/sleeping bag, clothing, toy animal [x], gaming console [x], radio. A backpack keeps your hands free!
Sandbag	In addition to structural elements, sandbags can help slow and direct water flow, preventing water from entering a building. If water has already entered the building, blocking entry points is no longer effective. However, strategically protecting critical infrastructure inside the building can still be beneficial. It is essential to keep emergency exits clear. How many sandbags do you need to secure a door? They are typically 50 cm long and weight 10–15 kilograms. Options: 5–10 sandbags [x], 20–30 sandbags [x], 50–60 sandbags. You need 50–60 sandbags to secure a door. Arrange them in a slight semicircle. Obtain sandbags early from local authorities or stores.
Laptop	Contact between electronic devices and water can be dangerous, potentially damaging the device and causing an electric shock. What precautions can you take? Options: back up data, unplug devices, store devices at an elevated location, turn off the main power switch. Try to avoid contact of electronic devices with water, but protect human life first; prioritize safety over electronic equipment!
Door	You have now interacted with all objects and learned a lot. Leaving a building during a flood can be life-threatening! Ensure that your escape route is safe and does not lead into greater danger. [If door was approached before other elements: Interact with the items listed to find out more about preparing for flood events! Come back to the door when you have discovered all the items.]

5. The 'Troubled Water' prototypes

We developed two prototypes that showcase potential immersive components for flood preparedness education: an AR and a MR prototype. The learning content is derived from disaster management guidelines (BBK, 2026) and insights provided by domain experts. The AR prototype is an iOS-based application that runs on iPad Pro models (Apple Inc., Cupertino, CA) released after 2020. It has two separate elements: *AR objects* and *AR simulation*. In the *AR objects* element (Fig. 1b), users explore their physical room and interact with virtual objects to learn about their relevance in protection behavior (see Table 1). The objects appear after users scan the icons placed in the room. They then learn about the object in a quiz-like information display. In the *AR simulation* element (Fig. 1c), a rising water level enhances the physical environment of users. The water level can be increased step by step and is accompanied by short informational texts on the dangers of flooding (see Table 2).

The MR prototype is a visionOS-based application that runs on the head-mounted on Apple Vision pro released in 2024 (Apple Inc., Cupertino, CA). The *MR simulation* element (Fig. 1e) is conceptually analogous to the *AR simulation* element. Head-mounted technology allowed us to we increase the field of view and to add the sound of water flows. Technological differences between AR and a MR required us to make minor changes in content (see Table 2 for details). At present, there is no available element that transfers the AR objects content to MR.

We selected technologies that incorporate advanced sensors, enabling accurate mapping of the surrounding environment. Development for both visionOS and iOS was carried out in Unity3D as the core engine (Unity Software Inc., San Francisco, CA), with Unity Pro required for visionOS compatibility. Using AR Foundation, we built the AR experience for iOS; while PolySpatial facilitated the seamless adaption of spatial computing features in visionOS. To create an immersive, interactive simulation, we integrated world-sensing and hand-tracking data. We used custom water shaders for realistic flood visualization.

6. Methods

6.1. Data collection

We collected data between May 2024 and January 2025 in a ground-level room close to the local river at TU Braunschweig. The first part of the data collection was conducted between 14 May 2024 and 15 November 2024. During this period, we used an iPad Pro (12.9 inches, 5th generation) for the two intervention groups *AR objects* and *AR simulation*. In an additional control group, participants interacted with an iOS-based commercial AR application that projects animals into their environment. The order of the experimental groups was counterbalanced; the long period of data collection was caused by recruiting issues during the summer break. Data collection for the third intervention group, using the head-mounted MR prototype, took place in December 2024 and January 2025. This unbalanced order was caused by the novelty of the Apple Vision pro (market launch in Germany in summer 2024) and the resulting time-consuming development. The Ethics Committee of the Institute of Psychology at TU Braunschweig has approved the study (identification number: FV-2024-07; 09.04.2024).

6.2. Study procedure

We used a pre-post-follow up design (see Fig. 2). After giving informed consent, participants started with the pre-questionnaire, administered on a laptop via the LimeSurvey platform (LimeSurvey GmbH, Hamburg, Germany). Next, they were provided with instructions for

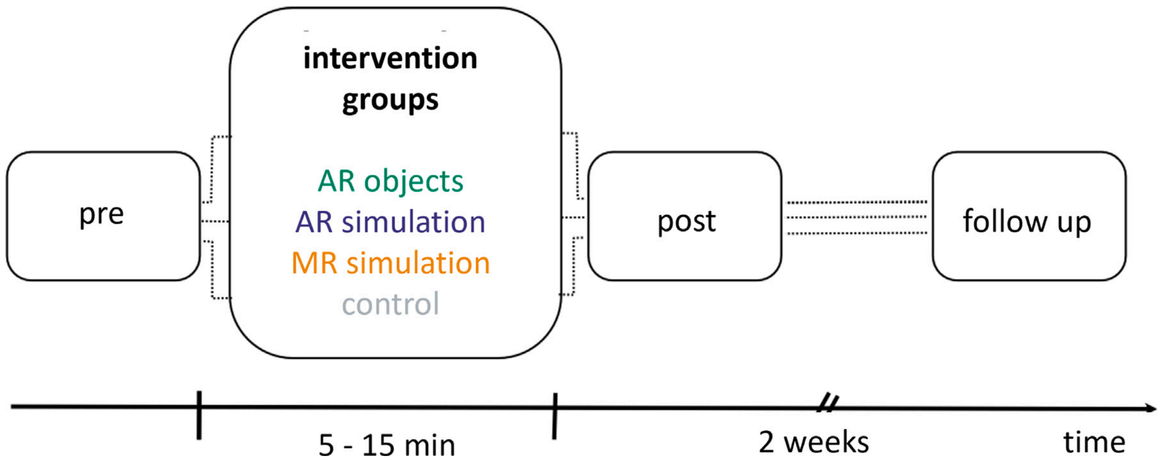

Fig. 2. Overview of study procedure with experimental groups.

engaging with the relevant prototype, which they then used for five to 15 min. Afterward, they completed a post-experiment questionnaire. Approximately 14 days after the in-person session (see Howe et al., 2019; Wallis et al., 2021), participants who consented to follow-up participation were emailed a link to the follow-up questionnaire. They were asked to complete it within 24 h; they received one email reminder.

6.3. Questionnaire

We created the questionnaire using established scales and adapting items from previous studies (see Table A.4 for an overview).

We measured the system usability of our prototypes using a German translation of the System Usability Scale (Brooke, 1996; Rummel, 2016). We assessed the perceived realism of the flood simulations and perceived physical presence (see Multimodal Presence Scale, Makransky et al., 2017; Volkmann et al., 2018) with one item each. These items were only presented to the participants of the simulation groups.

We focused on changes in threat appraisals, using nine items, and coping appraisals, using eight items. Flood-specific items were primarily based on Zabini et al. (2021) and Heidenreich et al. (2020). We used a single item for protection motivation (Heidenreich & Thieken, 2024). The items related to PMT were included in the pre-, post-, and follow-up questionnaires.

To assess protection intention, we used five items asking participants about their intention to implement specific protective measures within the next two weeks. The selection of the protective measures was based mainly on recommendations from the German Federal Office of Civil Protection and Disaster Assistance (BBK, 2026). However, we excluded an item on structural building measures from the analysis, as it did not show any variance in our student sample. Protection intention items were presented solely in the post-questionnaire. To assess performed protection behavior, we presented an adapted version of the protection intention items in the follow-up questionnaire, asking the participants about implementation of the same protective measures within the previous two weeks. We addressed general demographics, personal experience and living situation in the post questionnaire. Collected but not reported in this work were items on general fear (Grühn & Röcke, 2003; Watson & Clark, 1994), ownership appraisal (see Heidenreich & Thieken, 2024), emotion-focused coping (Loch et al., 2011), resilience (Sarubin et al., 2015), technology affinity (Wessel et al., 2019) and open-ended questions about participants' explicit knowledge of protection measures.

Table 2
Text elements displayed in AR simulation and MR simulation. Phases are identical in AR and MR, apart from an additional stop at 120 m in the MR prototype. Text was originally displayed in German language.

Phase	Description
Introduction	Here you experience a virtual flood event. Scan the symbol on the floor to start the simulation. Additional disclaimer in MR: The water will rise above your head by the end of the simulation. Although it is only a projection, this may cause discomfort. If you feel uncomfortable, you can remove the headset at any time. You can move around the room, but keep in mind that the projected water may obscure obstacles. Make sure your surroundings are safe, or stay at the starting point.
0 cm	Flooding often brings contamination, especially when sewage systems overflow and pollutants from industry and agriculture are released. Contact can cause skin irritation and infections. It is important to avoid direct contact!
15 cm	Even at a water depth of just 15 cm, flooding can become dangerous, as it is strong enough to knock people over. The underestimated current and objects floating in the water increase the risk.
20 cm	At a water level of 20 cm, many buildings have electrical outlets positioned at this height. Electrical currents in water are dangerous and can cause paralysis. Avoid water near electrical sources and turn off electricity.
30 cm	At a water depth of 30 cm, the risk of injury from hidden objects like branches, glass and metal increases. These can be hard to detect under the water surface and cause cuts or more severe injuries.
50 cm	From 50 cm, water pressure can block doors and windows, creating dangerous traps for people inside buildings and making evacuation difficult.
120 cm	Additional stop in MR without further information to allow exiting the simulation before it rises over head level.
200 cm	Floods with water levels of 2 meters or more are serious and life-threatening. Entire residential areas can be submerged, critical infrastructure disabled, and massive property damage caused.

6.4. Participants

We recruited 160 participants through a emailing list of the department. Psychology students were compensated with course credit. The participants were on average 22.6 years old ($SD = 4.0$, range: 18–34 years), 71.8% identified as women. The participants who knowingly lived in a flood-prone area constituted 18.1% and those who had personally experienced one or more floods made up 33.8% of participants. Of those who had experienced flooding, 6.9% reported that they personally had suffered material loss or health impacts; an additional 5.0% stated that friends or family members had suffered material loss or health impacts. Only 3.8% of the participants reported using immersive technology on a regular basis. No participant indicated experiencing motion sickness or related discomfort. The participants were evenly distributed across the intervention groups (n = 40 each) at pre- and post-measurement stages. As participation in the follow-up was voluntary, only 130 participants took part: *AR objects* (n = 34), *AR simulation* (n = 32), *MR simulation* (n = 35), and *control* (n = 29).

6.5. Data analysis

While our research questions were structured by XR attributes, namely virtual object interaction and sense of presence, we separately conducted statistical analysis for between-group differences for each preparedness measure. This approach enabled us to identify how specific preparedness outcomes were influenced by the different attributes operationalized in our prototypes.

6.5.1. Threat appraisals, coping appraisals, and protection motivation

To examine changes in threat and coping appraisals as well as protection motivation, we performed linear mixed model analysis with intervention group (with the levels AR objects, AR simulation, MR simulation, and control) and time point (with the levels post- and follow-up) as fixed effects. Pre-measure data were included as a fixed effect to control for confounding factors (similar to analysis of covariance). We assessed the stability of intervention effects over time by including an intervention × time interaction term. The participant intercepts were modeled as random effects: This resulted in the following model equation:

$$value \sim pre + intervention + time$$
$$+ intervention : time + pre : time + (1 \mid participant)$$

The models were fit using maximum likelihood estimation (ML); t-tests were performed using Satterthwaite's method using lmerTest extension of the lme4 R package (Bates et al., 2025). We focused on the main effects of the interventions. Significances indicated relevant differences between the intervention group and the control group, averaged over the post- and follow-up measures. We also examined the interactions between the interventions and time. Significant interactions indicated that the change of the main intervention effect was not stable over time, i.e., the effect either increased or decreased between the post- and follow-up measures. We reported Benjamini–Hochberg adjusted p-values to control the False Discovery Rate (FDR = 0.05) and 95% confidence intervals (CI).

6.5.2. Protection intention and behavior

We analyzed both protection intention and behavior in two ways. First, we looked at overall scales that integrate the different protection behaviors and evaluated scale differences between intervention groups using analysis of variance (ANOVA). For ease of interpretation, we also used a single behavior-based analysis of behaviors, recoding the intention responses into a dichotomous variable with two options. For intentions, we divided the protection behavior data into two categories into: *plan to perform* and *do not plan to perform* the protection behavior. Participants who reported that they were *neither planning nor intending to perform* the protection behavior were grouped together into the category *do not plan to participate*. For protection behavior, only the answer *done* was rated as performing in the activity. For intention and behavior, we excluded the participants that reported to have already performed the behavior before the study. To account for differences in the number of responses, we reported the percentage of individuals who plan to perform or have performed in the protection behavior. We used χ^2 and Fisher's exact tests to check for differences between groups.

7. Results

On account of the extended duration of our data collection period and the inability to fully counterbalance group order due to technical delays, we conducted tests for group differences before interventions. χ^2 - tests did not indicate significant differences in reported experiences with floodings. However, participants in the MR simulation group, which was recorded later, reported a significantly lower perceived vulnerability to flooding compared to all other groups, $F(3, 156) = 5.64$, $p = 0.001$, $\eta^2 = 0.10$.

7.1. System usability, realism and presence

The system usability of our prototypes was rated good to excellent (AR objects: M = 82.38, SD = 10.53, AR simulation: M = 82.81, SD = 9.46, MR simulation: M = 84.13, SD = 9.89) (see Bangor et al., 2008). The virtual flooding was perceived partly real in the AR (M = 2.82, SD = 1.06) and MR (M = 3.52, SD = 1.09) simulations, with significantly higher values in the MR simulation, $F(1, 66) = 7.07$, $p = 0.010$, $\eta_p^2 = 0.11$. In both simulation groups, participants reported feeling somewhat as if they were actually experiencing a flood (spatial presence AR simulation: M = 2.96, SD = 1.00, MR simulation: M = 3.60, SD = 0.98), with significantly higher values for MR simulation, $F(1, 66) = 6.80$, $p = 0.011$, $\eta_p^2 = 0.10$.

7.2. Coping and threat appraisals

For coping appraisals (see Fig. 3a), we found significant effects for the AR objects group only. Participants reported self-efficacy increased by 1.14 units, CI: 0.88 – 1.40, $t(234.80) = 8.73$, *adj* $p < .001$, $\beta_{std} = 1.17$. The perceived response efficacy increased by 0.29 units, CI: 0.06 – 0.52, $t(284.26) = 2.44$, *adj* $p = 0.033$, $\beta_{std} = 0.45$.

Regarding threat appraisals (see Fig. 3a), only participants in the AR simulation group reported increased vulnerability, $\beta = 0.39$, CI: 0.16 – 0.62, $t(268.46) = 3.28$, *adj* $p = 0.004$, $\beta_{std} = 0.48$. Perceived severity increased in both simulation groups. For participants in the AR simulation group, severity increased by 0.59 units, CI: 0.28 – 0.90, $t(256.46) = 3.74$, *adj* $p = 0.001$, $\beta_{std} = 0.66$. For the MR simulation group, severity increased by 0.49 units, CI: 0.18 – 0.80, $t(256.46) = 3.09$, *adj* $p = 0.007$, $\beta_{std} = 0.55$. Similarly, participants in both simulation groups reported increased fear. Participants fear increased by 0.49 units in the AR simulation group, CI: 0.17 – 0.80, $t(243.74) = 3.05$, $p = 0.03$, *adj* $p = 0.007$, $\beta_{std} = 0.46$, and by 0.53 units in the MR simulation group, CI: 0.22 – 0.85, $t(243.74) = 3.34$, *adj* $p = 0.004$, $\beta_{std} = 0.50$. In the MR simulation group fear significantly decreased between post- and follow-up measure, $\beta = -0.44$, CI: −0.80 – −0.09, $t(146.02) = 2.46$, *adj* $p = 0.033$, $\beta_{std} = -0.41$.

The reported protection motivation increased by 0.68 units in the AR objects group (CI: 0.38 – 0.97, $t(281.35) = 4.46$, *adj* $p = 0.001$, $\beta_{std} = 0.69$). Participants in the MR simulation group reported increased protection motivation by 0.43 units, CI: 0.13 – 0.72, $t(281.35) = 2.83$, *adj* $p = 0.013$, $\beta_{std} = 0.43$.

7.3. Effects on protection intention and protection behavior

The overall intention to participate in protection behaviors after interventions differed significantly between groups, Cronbachs α = 0.66, $F(3156) = 5.46$, $p = 0.001$, $\eta_p^2 = 0.10$ (see Fig. 4a). Regression coefficients showed that all three intervention groups scored significantly higher on the scale than the control group (AR objects: $\beta = 0.73$, CI = 0.30 – 1.17, $p = 0.006$, AR simulation: $\beta = 0.71$, CI = 0.28 – 1.14, $p = 0.008$, MR simulation: $\beta = 0.73$, CI = 0.30–1.10, $p = 0.006$). There were no significant differences between the three intervention groups. Analysis of single protective behaviors (see Fig. 4b) revealed significant between group differences solely in the intention to think about packing an emergency kit, $\chi^2(3) = 17.05$, $p = 0.001$, $V = 0.34$. Participants

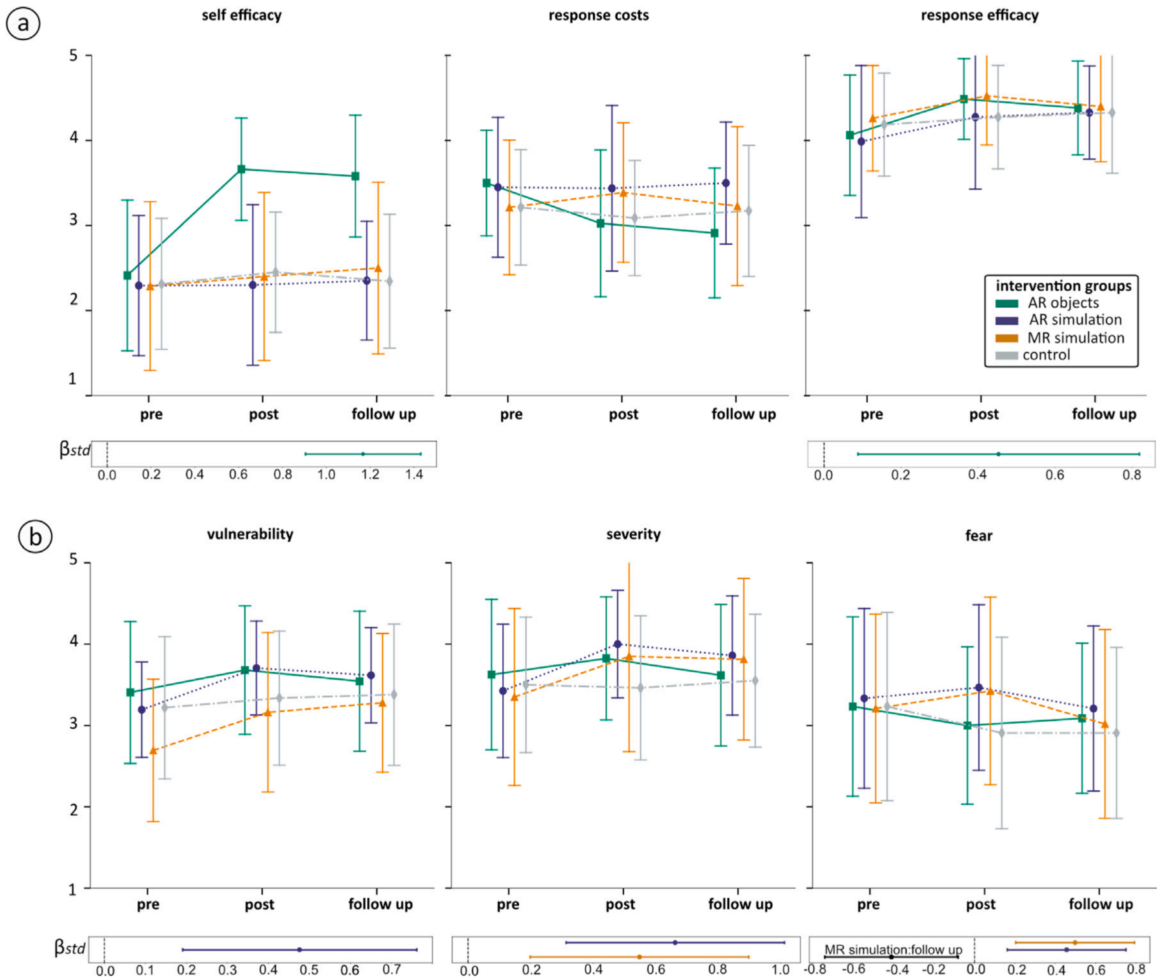

Fig. 3. (top) Descriptive plots illustrating changes in outcomes across pre-, post-, and follow-up assessments. (bottom) Standardized coefficients (β_{std}) with 95% confidence intervals for all significant effects identified in the linear mixed-model analysis. (a) Coping appraisals and (b) threat appraisals. Black (β_{std} line in fear plot indicates the significant interaction term.

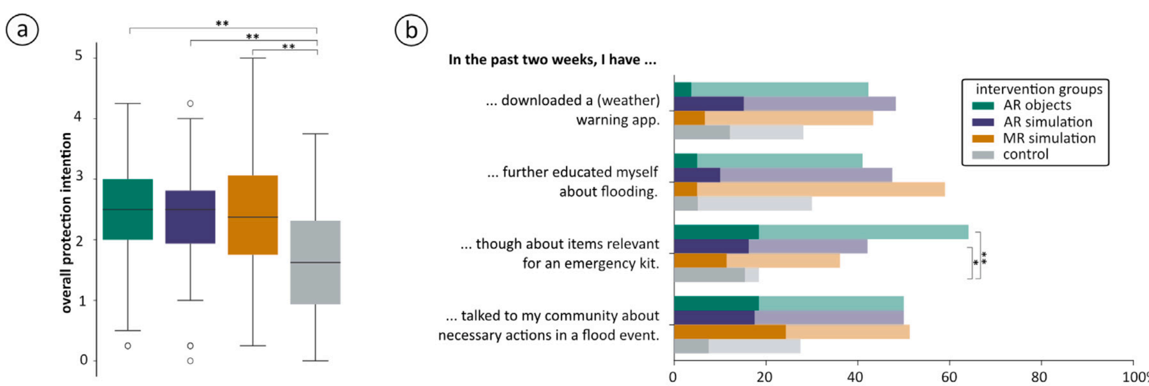

Fig. 4. (a) Box plots showing group differences in overall intention to participate in protection activities. (b) Bar charts showing the percentage of participants who reported performing the protection behavior within two weeks after the intervention. The shaded bars indicate the percentage of participants who reported intending to perform the protection behavior immediately after the intervention. * indicate a significant difference at p <.05, ** p <.01.

in the AR objects group showed the largest increase compared to the control group, $\chi^2 = 14.71$, $p = .001$, $V = 0.46$; the participants of the AR simulation group also reported significantly increased intention $\chi^2 = 9.39$, $p = 0.046$, $V = 0.36$. In the post-intervention follow up two weeks later, none of the intervention groups differed significantly from the control group in either overall protective behavior (Cronbachs α = 0.47) or at the level of single behaviors.

8. Discussion

In this work, we presented our 'Troubled Water' prototypes, developed in response to calls for integrating technology into educational programs for enhancing individual flood protection behavior (Fazeli et al., 2024; Guo et al., 2025; UNDRR, 2015). We showcase potential immersive components for flood preparedness education. Specifically, we employ XR technologies to allow interaction with virtual objects relevant to flood protection behavior and enable users to experience to sense presence in a virtual flood. Our study suggests that both attributes are effective in enhancing specific elements of preparedness.

8.1. Effects of virtual object interaction

Our study demonstrated that *interaction with relevant virtual objects* can enhance individuals' perceived ability to effectively perform protection behavior and strengthen their overall intention to engage in them. It can specifically motivate people to plan to think about their individual emergency preparation. The interactions appeared to encourage participants to consider preparing a personal emergency kit. We suggest that these effects may have been facilitated by the mastering of interactions with realistic, relevant objects, and the reception of receiving direct feedback (Bandura, 1977; Kolb, 1984; Kolb & Kolb, 2009). However, the AR objects group also received the greatest amount of additional information on flood preparedness, limiting the interpretative value of this finding and preventing us from attributing the effect solely to XR attributes. Moreover, we found no evidence that these positive effects transferred to self-reported behaviors two weeks after the intervention. Future work will compare our XR interventions with content-matched analog or 2D-based interventions to isolate the unique contribution of XR.

8.2. Effects of sense of presence

We demonstrated that *experiencing presence in simulated flooding* can increase the participant's perceived likelihood of being personally affected by a flooding; the perceived negative impact of such an event on oneself; and the overall intention to engage in protective behaviors. This increase might be explained through a relationship between spatial presence in XR environments and psychological distance (Liberman & Trope, 1998; Trope & Liberman, 2010). That is, participants could feel that flooding was temporally (Breves & Schramm, 2021) or spatially less distant (Lee & Li, 2023; Touré-Tillery & Fishbach, 2017) from their own person after the flood experience; and therefore perceive higher risk. Strong reports of spatial presence in both AR and MR further support this conclusion. While participants reported greater perceived realism and spatial presence in MR compared to AR, the only notable difference in the preparedness measures was that the MR intervention led to a significant increase in protection motivation, whereas the AR intervention did not. No substantial differences were observed in threat appraisals, intentions, or behaviors. The limited impact of the higher-virtuality flooding experience could suggest a ceiling effect, with tablet-based simulation already evoking the strongest possible response to a virtual flood scenario. Alternatively, although user experience measures did not indicate issues in the MR condition, the novelty and complexity of MR might have diverted attention from the flood scenario itself. Given that tablet-based AR is more accessible compared to head-mounted MR, choosing MR would only be justified once more evidence is available to support its advantages.

8.3. Limitations and open challenges

As discussed above, we were unable to demonstrate a positive effect on overall preparedness behavior for any of the interventions two weeks after implementation. This suggests that neither the increase in coping appraisal following the virtual object interaction, nor the rise in threat appraisal after experiencing a flood simulation, were alone sufficient to effectively increase protection behavior. This finding aligns with previous research that argues that disaster preparedness is a dynamic behavioral process. Individuals with preparedness intentions do not necessarily progress to actual behavioral changes; moreover, threat and coping appraisals have varying impacts throughout this process (Ma et al., 2024). The lack of transition from increased intentions to behavior could be due to absence of social environmental elements in our interventions. Factors such as social norms (Van Valkengoed & Steg, 2019), network behaviors (Bubeck et al., 2018), and sense of community (Paton & Johnston, 2001) have consistently shown to play a crucial role in promoting preparedness behaviors. Additionally, it is important to consider the relatively short interaction time, only five to 15 min, that participants spent engaging with the intervention technology, which may have limited the interventions' overall effectiveness.

By itself, this study does not enable us to draw independently valid conclusions about the benefits of XR technology for disaster preparedness. It was not designed to compare the effectiveness of AR and MR content with traditional approaches nor with VR-based approaches in flood preparedness education. Hence, future studies should aim to distinguish between the benefits derived from XR as a delivery medium and those resulting from the content of the intervention itself, regardless of the medium used.

Lastly, it is necessary to extend the exploration beyond our current sample to achieve better generalizability of the results. Our young and predominantly female student sample likely differs from a cross-section of society in aspects such as prior flood experience and vulnerability, which may influence the effects of our prototypes. When using highly immersive virtual applications, especially with vulnerable groups such as children or individuals with previous traumatic experiences, potential negative effects of perceived presence in distressing situations must be carefully considered (Slater et al., 2020).

9. Implications and outlook

In this study, we demonstrated that immersive elements in flood preparedness interventions can positively influence the cognitive processes underlying protection behavior and an individual's overall intentions to prepare for flood events. Based on these results, we argue that future programs for enhancing flood preparedness should make use of the potential of XR technology, namely the ability to enable interaction with flood-relevant items and foster spatial presence in a simulated flood situation. With virtual object interaction strongly increasing coping appraisals, and spatial presence showing medium–large effects on threat appraisals, we recommend employing both attributes in XR supported disaster preparedness programs. We do not, however, propose XR as a standalone solution. Instead, we suggest that specific XR attributes be employed as tools embedded within holistic educational frameworks. To further expand the educational potential of XR, we aim to explore additional XR attributes in future work, including integrating avatars into users' immediate environments that communicate first-person flood-experiences and demonstrate protective behaviors. Such features may support observational learning (Bandura, 1977) and enhance users' sense of agency (Makransky & Petersen, 2021).

Additionally, we intend to investigate XR supported disaster preparedness education with a focus on primary and secondary school students. Disaster education programs targeting children have been found to enhance community resilience, as they act as agents of change by spreading knowledge and behaviors within their communities. This demographic would also benefit, as they often have limited prior experience with disasters and have been shown to respond particularly well to XR-based learning formats (Midtbust et al., 2018; Mutch, 2014; Sakurai et al., 2020; Simon-Liedtke & Baraas, 2022).

Lastly, we see great potential for integrating geospatial and meteorological data into XR simulations. Our current study demonstrates that experiencing a XR flood simulation can enhance the perception of threat. Enabling simulations of past or hypothetical events tailored to the user's specific location could improve literacy around warning information and deepen understanding of uncertainty in risk communication.

CRediT authorship contribution statement

Leonie Terfurth: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anna Heidenreich:** Writing – review & editing, Methodology, Conceptualization. **Elisabeth Glunz:** Writing – review & editing, Methodology, Conceptualization. **Thomas Kox:** Writing – review & editing, Supervision. **Lars Gerhold:** Writing – review & editing, Conceptualization, Supervision.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI Inc., San Francisco, USA) in order to improve the language in selected paragraphs. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.chbr.2026.101004.

Data availability

Data and analysis scripts are available at OSF (osf.io/rhq73). Both prototypes are available for download in the App Store upon request.

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