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Public engagement by strategic science communication: an evaluation study on the impact of an interactive science exhibition on the German energy transition

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Introduction: Science exhibitions are a promising instrument to uniquely encourage public engagement with scientific issues. However, knowledge about the actual effectiveness of science communication activities is mostly lacking. Therefore, this study examined the impact of a science exhibition on the German energy transition on visitors' cognitive, affective, and behavioral public engagement. Additionally, we extend knowledge on the role of gamification by examining whether an integrated game can further enhance engagement, either directly or indirectly, through positive exhibition experiences.
Methods: We used a pretest-posttest survey (N = 767 visitors at seven museum locations) to evaluate the impact of the science exhibition and the game.
Results: The results show that the exhibition had a positive effect on cognitive and partly affective as well as behavioral engagement. For gamification, we found no positive direct effects of using the game. However, analyses revealed indirect effects on cognition and affect mediated by positive exhibition experiences.
Discussion: The findings of our study demonstrate the potential of science exhibitions as valuable tools for promoting public engagement with complex issues. Moreover, they show that future research is needed to explore how exhibitions and gamification elements can foster behavioral engagement effectively.

KEYWORDS
public engagement, evaluation, science exhibition, gamification, energy transition, climate change

1 Introduction

Many countries today are undergoing large-scale societal transformations, several of which involve complex scientific challenges. Among the most critical are climate change mitigation strategies, such as energy transitions. Energy transitions refer to the replacement of fossil fuels with renewable energies and are considered a key component in reducing greenhouse gas emissions. They entail a fundamental technological restructuring of entire energy systems and industrial processes (BMBF, 2024). At the same time, energy transitions profoundly affect daily life and influence societal values (Milchram et al., 2019). As a result, their success depends not only on scientific and technological progress but also on broad public engagement (Kumpu, 2022). In practice, however, societal changes and energy transitions in particular frequently encounter resistance from the public and engagement is often limited (Emmerich et al., 2020). This may be due to their complex and technological nature, which can be difficult for laypeople to understand and may give rise to uncertainties, perceived risks, and general skepticism (Hilgard and Li, 2017; Emmerich et al., 2020; Arlt et al., 2023a). Therefore, insufficient public engagement poses a significant barrier to the successful implementation of energy transitions.

Science communication is considered a vital tool for increasing public engagement with complex issues, ultimately fostering people's support for large-scale societal changes (Weingart et al., 2021; Kumpu, 2022). Science communication encompasses a wide range of different forms, including science journalism as well as more strategic communication activities (for an overview see Jamieson et al., 2017). Yet, bringing scientific issues closer to the citizens remains challenging due to their complexity and the potential for biased interpretation of evidence by humans (Hilgard and Li, 2017). In addition, scientific issues are often controversially discussed, value-laden, and emotionally charged (Moser and Dilling, 2011; Cain and Rader, 2017), which further complicates efforts to foster engagement. Moreover, declining trust in traditional mass media, the spread of misinformation on social media platforms, and audiences trapped in echo chambers may hinder the effectiveness of mediated science communication (Rosenthal, 2020).

In light of these challenges, scholars predict that *interactive exhibitions* in museums or science centers are a promising form of strategic science communication (Fähnrich, 2017; Stofer et al., 2019). Specifically, interactive exhibitions are considered to uniquely influence visitors' public engagement by fostering shared learning and eliciting positive experiences that can be transferred to the scientific issue at hand (e.g., Mujtaba et al., 2018). Moreover, museums are widely regarded as trustworthy sources of information (Cain and Rader, 2017), making them particularly valuable in societies increasingly plagued by misinformation. Still, the actual impact of science exhibitions remains largely unexplored in science communication research (Cain and Rader, 2017). One of the field's most significant research gaps is the lack of methodologically rigorous evaluation studies of real-world science communication activities (Weingart et al., 2021).

Therefore, the present study aims to contribute to close this research gap by evaluating the impact of an interactive science exhibition on visitors' public engagement with the energy transition in Germany. In this context, we also examine the role of *gamification*—an increasingly used feature of interactive exhibitions that is believed to have strong potential for effective science communication (Jia and Dai, 2022). Beyond assessing the overall effect of the exhibition, this study investigates whether participants who played an integrated game exhibit higher changes in engagement than those who did not. Finally, it explores whether this effect is direct and/or mediated by immersive visit experiences, as suggested by prior literature on gamification and museums (Stanković Elesini et al., 2023).

With this focus, the present study seeks to add to current science communication research and practice in five ways: (1) Our evaluation study aims to overcome the lack of knowledge about the impact of science communication activities, particularly in the context of environmental issues. (2) We use a comprehensive perspective on engagement—considering cognitive, affective, and behavioral aspects—, which is mostly absent so far. (3) Our study aims to enhance the understanding of gamification effects in the field of exhibit-based science communication by addressing two central research gaps (e.g., Geiger et al., 2017a). First, it explores whether the inclusion of a game has an *additional* impact. Second, it seeks to gain initial insights into the underlying mechanisms by scrutinizing whether, and how, positive visitor experiences mediate the potential effects of game use on visitors' public engagement. (4) Methodologically, we address key challenges in conducting an evaluation study in a real-world context (Ziegler et al., 2021)—specifically, in museums, where visitors spend their leisure time and may be less willing to participate (Tucker et al., 2011). (5) Practically, our findings show whether science exhibitions can serve as an effective strategy for supporting energy transitions as one of the most important measures in combatting climate change, and thus if they can act as a driver of broader societal transformations.

2 Encouraging public engagement with science in the context of energy transitions

2.1 Public engagement and energy transitions

To successfully advance large-scale changes, such as energy transitions, active public engagement is essential (Devine-Wright, 2012; Kumpu, 2022). Public engagement means to empower citizens to participate meaningfully in these processes (Devine-Wright, 2012; Weingart et al., 2021; Kessler et al., 2022; Kumpu, 2022). Accordingly, many scholars criticize deficit approaches—such as the information deficit model—which assume that simply increasing public knowledge is sufficient to generate peoples' support (Kessler et al., 2022). Consequently, in our study, we build on a multidimensional concept of public engagement that comprises cognitive (i.e., knowledge), affective (i.e., interest and confidence), and behavioral (i.e., perceived self-efficacy and behavioral intention to actively participate) components (Moser and Dilling, 2011; Geiger et al., 2017b).

Energy transitions are a prime example of complex scientific issues that that are difficult for the general public to understand. Yet, they have far-reaching societal impacts, making public engagement imperative. Specifically, energy transitions extend beyond the familiar use of wind and solar power. They involve complex processes such as restructuring electricity grids and decarbonizing sectors that have long depended on fossil fuels, including industry and transport (Ragwitz et al., 2023). Significant research efforts are underway to address these challenges, such as developing technologies and concepts for hydrogen storage and for industrial energy flexibilization (BMBF, 2024). At the same time, these advances bring profound changes to individuals' daily lives, including adopting electric transport, shifting from demand-based to supply-based energy consumption, and improving energy efficiency. Moreover, they influence collective values by prioritizing affordability and sustainability over market efficiency (Milchram et al., 2019). Still, public engagement remains limited. For example, studies in Germany revealed that many scientific advances and emerging technologies are largely unknown to the public, while scepticism regarding both the benefits (Emmerich et al., 2020; Arlt et al., 2023a) and the technological feasibility of the energy transition persists (Arlt et al., 2024). These findings demonstrate that increasing public engagement with energy transitions is of major public importance.

Drawing on theoretical literature (Moser and Dilling, 2011; Katz-Kimchi and Atkinson, 2014), we conceptualize public engagement with energy transitions to encompass three dimensions: First, the cognitive dimension refers to people's knowledge and understanding of the necessary changes in energy production and supply. Second, the affective dimension involves issue-related interest and confidence in the technological feasibility of energy transitions. Third, the behavioral dimension includes both the intention to participate in energy transitions and the perception of self-efficacy—that is, the perceived ability to take meaningful actions (Bandura et al., 1999). Considering perceived self-efficacy is important, as various behavioral theories, such as the social cognitive theory (Bandura et al., 1999) or the theory of planned behavior (Ajzen, 1991), stress its significance in adopting new behaviors. Empirically, perceived self-efficacy has already been demonstrated to be a crucial prerequisite for climate change-related behavioral change (e.g., Geiger et al., 2017a).

2.2 The role of exhibit-based science communication in encouraging public engagement

Studies analyzing the effects of science communication have typically focused on informational media, such as online media or science journalism in mass media (Schäfer et al., 2019). However, media effects on fostering engagement have generally been found to be limited (Lee and VanDyke, 2015; Fähnrich, 2017), also for the energy transition (Arlt et al., 2023b). As a result, increasing attention has been given to strategic, exhibition-based science communication as a potentially more impactful alternative (e.g., Bandelli and Konijn, 2013; Katz-Kimchi and Atkinson, 2014; Stofer et al., 2019).

As a trusted source of scientific information (Cain and Rader, 2017), museums and science centers "constitute a critical communicative link between citizens, scientists, and governments" (Katz-Kimchi and Atkinson, 2014, p. 756). In recent years, they have increasingly evolved into interactive environments that actively engage the public (Heath and vom Lehn, 2008; Bandelli and Konijn, 2013). More specifically, interactive exhibitions—using, for example, digital technologies such as interactive displays or integrated games (Heath and vom Lehn, 2008)—are designed to do more than simply transfer scientific knowledge, as traditional mass media often do. Most importantly, they aim to promote public engagement by enabling visitors to interact with exhibits in ways that associate learning with positive, enjoyable hands-on experiences (Mujtaba et al., 2018). Such experiences can help visitors connect with scientific issues on an emotional level and make them more memorable (Geiger et al., 2017b; McGhie et al., 2018; Mujtaba et al., 2018; Solis et al., 2021). In addition, exhibitions provide an informal, 'safe space' for social interaction, scientific exchange, and shared learning—factors considered essential for fostering public engagement (Geiger et al., 2017b; McGhie et al., 2018; Mujtaba et al., 2018; Jia and Dai, 2022). Therefore, especially for value-laden topics like energy transitions, interactive exhibitions may serve as a strategic tool for communicating complex scientific and technological information in a uniquely engaging way.

However, rigorous evaluation studies that examine the impact of real-world science communication activities are rare, largely due to methodological challenges (Weingart et al., 2021; Ziegler et al., 2021). One key obstacle is the difficulty of recruiting participants during their leisure time (Tucker et al., 2011), which is particularly true for exhibit-based science communication (Tucker et al., 2011; Cain and Rader, 2017). Specifically, prior evaluation research on the impact of science exhibitions on public engagement is limited in several ways: First, many studies rely on qualitative designs (Kwan et al., 2019; Lundgren et al., 2019) which do not support conclusions about causal mechanisms. Second, to our knowledge, only one field experimental study (Gorr, 2014) has considered all three dimensions of public engagement. Gorr's (2014) pretest-posttest study found that students visiting a climate change exhibition showed increased emotional engagement, but no changes in knowledge, self-efficacy, or behavioral intention. Other studies concentrate on either cognitive and affective (Loizzo et al., 2019; Solis et al., 2021; Novak et al., 2023) or behavioral components of engagement (Geiger et al., 2017a). For example, Geiger et al. (2017a) used a laboratory experiment with students and a field study in informal science learning centers, finding that participation increased discussion about climate change and perceived self-efficacy.

Given this limited evidence, it remains unclear whether interactive exhibitions can effectively foster cognitive, affective, and behavioral public engagement with scientific issues. In consequence, evaluation studies are urgently needed, as "engagement without evaluation is of limited value" (Weingart et al., 2021, p. 17). Therefore, this study investigates whether an interactive exhibition on the German energy transition promotes all three components of public engagement. Based on this, our first hypothesis (H1) proposes the following positive exhibition effects:

> *H1 (exhibition effects)*: Exhibit-based science communication about the energy transition positively influences visitors' cognitive (i.e., knowledge), affective (i.e., interest and confidence in technological feasibility), and behavioral (i.e., intention to participate and perceived self-efficacy) engagement with the issue.

Finally, prior studies followed a rather simplistic stimulus–response logic and did not empirically test theorized underlying effect mechanisms. As noted earlier, interactive exhibitions are believed to influence public engagement by eliciting positive experiences (e.g., Mujtaba et al., 2018), suggesting a mediation process: Interactive elements foster positive experiences, which in turn promote engagement. To investigate these mechanisms, we focus on gamification elements, described in more detail in the next section.

2.3 Gamification in science communication

According to the cultural theorist Johan Huizinga, playing a game can create so called play-spaces—temporary worlds within the ordinary world (Huizinga, 1956). Building on this idea, gamification refers to the strategic integration of game elements into non-game contexts (Buckley et al., 2019; García-Iruela et al., 2022). It does not involve creating a complete game, but rather borrowing mechanisms, such as levels, points, competitions, or narrative storytelling, and incorporating them into other settings (Buckley et al., 2019)—such as science exhibitions.

Gamification typically serves two main purposes: First, it aims to increase users' engagement with a given topic (Cesário and Nisi, 2023; Chen et al., 2023). In environmental contexts, for example, it has been shown to encourage behaviors such as energy reduction, waste management, and water conservation (Douglas and Brauer, 2021). Second, gamification seeks to make the primary task—such as learning, working, or visiting a museum—more enjoyable (Câmara and de Lima, 2021; Stanković Elesini et al., 2023). This is because players become so immersed in the game that the cognitive or physical demands of the task fade into the background (Huizinga, 1956). Research on video games shows that games frequently elicit states of flow, immersion, or presence, in which users are deeply focused and absorbed (for an overview see

Schumann, 2013). These experiences not only help explain why users engage in gamified activities (Hamari and Koivisto, 2015); they also act as *mediators* between game use and intended outcomes (AlMarshedi et al., 2014; Chen et al., 2023). Accordingly, gamification is viewed as a valuable tool for science communication (Schmidt et al., 2014), and museums are increasingly adopting it to enhance visitor experience and learning (Durán and Fuentes, 2024). In our study, we examine whether game elements function as a strategic component of interactive, exhibit-based science communication to additionally promote public engagement—both directly and indirectly through the creation of positive, immersive experiences.

However, to the best of our knowledge, the (indirect) effects of gamification on engagement in science exhibition contexts have been scarcely studied. López-Martínez et al. (2020), using a quantitative survey with 40 university students, found that a gamification platform had a positive, direct effect on cognitive engagement in a heritage museum. Also in a heritage museum, Nofal et al. (2020) used a mixed methods approach (*N* = 190 pupils) combining observations, group interviews, and a questionnaire. They showed that the use of gamification had a positive and direct effect on visitors' knowledge of the exhibit theme. In a study at a museum of post and telecommunications, Stanković Elesini et al. (2023) analyzed interviews, observations, and post-visit questionnaires with 44 college students and found an indirect effect: Gamification improved content recall through positive visit experiences.

These insights underline the potential of integrated games as tool for exhibit-based science communication. However, at least two research gaps remain: First, pretest-posttest designs that could offer robust insights into gamification's effectiveness (Ziegler et al., 2021) are rare. Second, no studies have examined whether games enhance exhibition effects beyond their immediate impact. It remains unclear whether gamification adds value, as most research compares different game elements rather than testing whether visitors who play games are more engaged after the exhibition than those who do not.

Taken together, we propose a direct effect of game use on public engagement (H2a) and a mediation effect through exhibition experience (H2b), as illustrated in Figure 1:

> *H2a (direct game effects)*: The use of a gamification element in exhibit-based science communication enhances exhibition effects on cognitive, affective, and behavioral public engagement with the energy transition.
>
> *H2b (mediation effect)*: Visitors' exhibition experience positively mediates the relationship between game use and cognitive, affective, and behavioral engagement with the energy transition.

3 Methods

3.1 Procedure and participants

We conducted our study in the context of the touring interactive exhibition "Power2Change: Mission Energiewende" (translated: Power2Change: Mission Energy Transition) on the German energy transition, planned and developed by a transdisciplinary team comprising (a) natural scientists and engineers working on technological solutions for the energy transition, (b) pedagogues and employees of museums where the exhibition was conducted, and (c) communication scientists working in the field of political and science communication.[1] The entire project—including this research—is funded by the German Federal Ministry of Research, Technology and Space (grant number: 03SF0625E). Following methodological recommendations for rigorous evaluation of science communication

1 For more information see project website: https://power2change-energiewende.de/

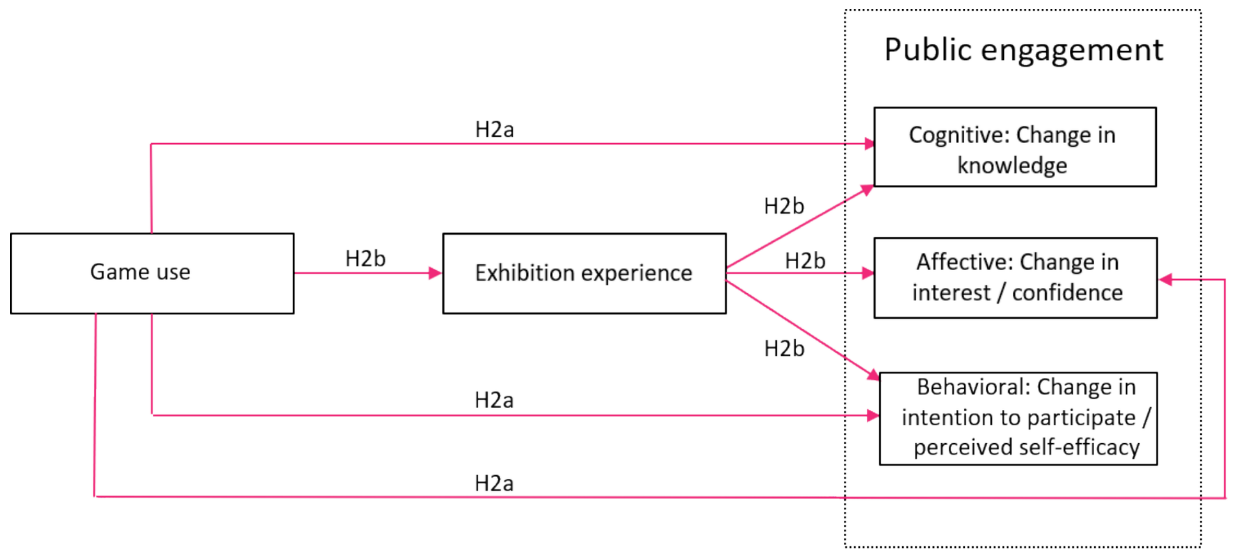

FIGURE 1
Research model, illustrating the assumed positive direct and indirect effects of game use (via positive exhibition experiences) on visitors changes in public engagement.

projects (e.g., Ziegler et al., 2021), we conducted a quantitative paper-and-pencil survey with a pretest-posttest design at 7 museum locations. Specifically, we assessed visitors' cognitive, affective, and behavioral public engagement with the German energy transition before (pretest [t_1]) and immediately after (posttest [t_2]) their visit. This was done to scrutinize whether visiting the exhibition led to changes in people's engagement compared to their baseline levels. The posttest also examined visitors' exhibition experience and whether they played the integrated game" What Energy Transition Type Are You?" (WETTAY, details see below).

However, conducting a pretest-posttest evaluation study poses several *methodological challenges:* First, these include the development of methodologically reliable instruments suitable for real-life settings (Volk and Schäfer, 2024; Ziegler et al., 2021). In particular, we needed to balance the accuracy of measurements on the one hand with the practical feasibility of our study on the other hand. We addressed this by limiting the questionnaire to essential items and avoiding lengthy or complex scales. This was necessary to keep the cognitive load at an ethically acceptable level, as the survey may require additional effort and add to the potentially cognitively demanding nature of a museum visit (Tucker et al., 2011). Moreover, visitors were expected to be more willing to participate if the time required—and thus the intrusion on their free time—was minimal. Lastly, we sought to avoid the survey disrupting too much the experience of the exhibition visit (Volk and Schäfer, 2024) and influencing its potential impact. For instance, a long, cognitively demanding questionnaire might lead participants to pay less attention or spend less time in the exhibition, thereby potentially also affecting their response behavior in the posttest.

Second, the recruitment of participants can be challenging, as a museum visit takes place during people's free time (Tucker et al., 2011). To increase participation in pre-and posttest, we offered sweets, a prize draw, and motivational incentives such as contributing to the improvement of the exhibition. Although not empirically tested, our observations suggest that the sweets were particularly effective in recruiting participants. This small gesture may have helped create a welcoming atmosphere and was especially appreciated in the cognitively stimulating context of a museum visit. Similarly, the opportunity to help improve the exhibition seemed to encourage visitors to take part in the study. In contrast, the prize draw seemed to have little impact on study-participation.

Finally, matching posttest responses to the corresponding pretest data is logistically challenging in an exhibition context, especially when many visitors participate simultaneously or when the entrance and exit are not the same. To address this, each participant received a badge with an identification number, enabling accurate data matching.

Ethical approval was obtained from the Ethics Committee of the Technical University Ilmenau (approval number: 2024-03-196_FoA-Schal.1). All participants were thoroughly informed about the purpose of the study, the exclusive scientific use of their data, the anonymity of responses, and the voluntary nature of their participation at all stages. This information was communicated both orally and in writing (as part of the questionnaire materials).

A total of 767 visitors participated in our study. Their mean age was 43 years (*SD* = 17.87), with 44% identifying as female and 56% as male. The majority of participants were adults (91%). For underage participants, agreement was obtained from their accompanying parents. In terms of education, 65% had the highest level of German education (i.e., higher secondary school diploma, university admission, or university graduation), 23% had a medium level of education (i.e., mid-level secondary school diploma), and 13% had the lowest education level (i.e., elementary school, lower secondary school diploma) or no school diploma at all.

3.1.1 Exhibition

The energy transition exhibition was developed by a team of recognized museum professionals, including educators and didactic experts in science and technology. It focuses on the industrial and transport sectors, utilizing a solution-oriented approach to climate change mitigation, as suggested by previous literature (e.g., Moser and Dilling, 2011). In particular, the exhibition presents research-based solutions for a secure, affordable, and climate-neutral energy supply in these sectors. It is structured around four main themes—electricity grids, industrial flexibilization in response to fluctuating energy supply, (re)utilization of industrial emissions, and transport—as well as two special topics: green electricity and hydrogen production. Each theme is presented in a distinct, spatially defined section with a cohesive color scheme. Special emphasis was placed on interactive elements that engage visitors with the content, such as digital displays allowing them to build a virtual electricity infrastructure.

3.1.2 Integrated game

To test H2, we focussed on the integrated game WETTAY (What Energy Transition Type Are You?), which visitors could voluntarily play during their exhibition visit. The game was conceptualized, designed, and implemented by museum professionals of our interdisciplinary team. Such games are participatory methods used by museum educators to foster dialogue in exhibitions and encourage behavioral engagement (Welpinghus et al., in press). The game is modeled after "psychotests" commonly found in lifestyle magazines, where participants respond to a series of scenarios, accumulate points based on their answers, and receive a personalized result (e.g., "What dating type are you?"). In WETTAY, participants choose how they would behave in eight everyday scenarios related to the energy transition, selecting from four options per scenario. Each option aligns with one of four Energy Transition Types. These types are based on scientific findings of the Regenerative Energy Model (REMod, Sterchele et al., 2020) and aim to enable a transfer from science to people's everyday lives (Welpinghus et al., in press). In particular, REMod simulates various prototypical pathways for the German energy transition, emphasizing the role of individual behavior (see Supplementary material A1 for details). The scenarios are designed to be realistic and relatable, illustrating how the energy transition may affect daily life. Some are set in the near future—for example, choosing whether to buy socks made from industrial exhaust gas—while others reflect options that are already in the early stage of adoption, such as installing a smart meter. The method and tone of the questions were deliberately chosen to lighten the seriousness of the topic "energy transition."

To play the game, participants received a card to record their responses to the eight scenarios and tally their points. At the end, they could print a 'receipt' showing their Energy Transition Type based on their score. They then watched a short film explaining the REMod paths, including the associated costs and infrastructure requirements. The game concluded with four boxes, each representing a REMod path. Visitors could drop their card into the box of their preferred path—regardless of their assigned type—allowing them to reconsider and potentially revise their views on the energy transition (see Supplementary Figures A1, A2).

Accordingly, WETTAY incorporated several game elements, known to create immersive experiences (Schumann, 2013; Buckley et al., 2019): storytelling and narration within the scenarios, point collection via the card, perceivable consequences of actions with the option to revise them by dropping the card, and social comparison through observing where others placed their cards.

3.2 Measurements

3.2.1 Public engagement (t_1 and t_2)

All components of public engagement were measured using five-point Likert scales (1 = *strongly disagree*, 5 = *strongly agree*). We assessed the cognitive component of public engagement as *subjective knowledge* about the energy transition. Unlike objective knowledge, which measures knowledge as either right or wrong (e.g., de Silva-Schmidt et al., 2022), subjective knowledge refers to people's subjective assessment of their own knowledge-level (Rogers, 2003). We used subjective rather than objective measures to avoid the impression of testing visitors, which could create pressure to answer correctly and introduce reactivity, thereby reducing the external validity of the study. We measured subjective knowledge with two items ("I know a lot about the energy transition" and "I know a lot about the energy and raw materials supply in Germany") and combined them into a mean value index (correlation between the two items $r = 0.65$ both at t_1 and t_2).

To examine the affective component of public engagement, we assessed *interest* in the energy transition ("I am interested in the energy transition") and *confidence in its technological feasibility* ("Innovative technologies will enable the energy supply to be secured entirely from renewable energies at all times") with one item each (Katz-Kimchi and Atkinson, 2014; Geiger et al., 2017b).

Behavioral intention and perceived self-efficacy regarding the energy transition were used as behavioral indicators of public engagement, based on prior research (e.g., Geiger et al., 2017a). *Behavioral intention* was assessed by asking respondents to what extent they would like to contribute to the success of the energy transition in their region. *Perceived self-efficacy* was measured with the following item: "I can actively participate in the energy transition of our region."

3.2.2 Exhibition experience (t_2)

We used five items (Othman et al., 2011) to assess exhibition experiences on a five-point Likert scale (1 = *strongly disagree*, 5 = *strongly agree*). Respondents rated the extent to which they found the exhibition "captivating," "fascinating," "boring" (reverse-coded), "informative," and whether it taught them "a lot of new things about the energy transition." The items were combined into a mean value index (Cronbach's $\alpha = 0.81$).

3.2.3 Game use (t_2)

Since participation in WETTAY was optional, some visitors completed the game, while others dropped out during the visit or did not play at all. Thus, assignment to the game condition was based on self-selection rather than randomization. To assess the impact of game use on public engagement, we compared game players to non-players. To do so, we examined which parts of the game the participants had completed. Based on completion data, we formed two groups: game users, who completed all parts of the game, and non-game users, who did not participate at all. Visitors who started but did not finish the game were excluded, as they could not be clearly assigned to either group ($n = 185$, 24%). The final sample included 256 game users (33%) and 274 non-game users (36%). Furthermore, we explored whether game-players and non-game players differed in gender, age, and education. Results showed that players were significantly younger than non-players, while there were no significant differences in gender and education level (see Supplementary Table B2[2]). As WETTAY was the main interactive element to encourage visitors to interact with the exhibition, we also examined whether game players spent more time in the exhibition than non-players. Indeed, we found a significant positive effect of game participation on visit duration (see Supplementary Table B2)—potentially indicating that WETTAY fostered more interaction.

Supplementary Table B1, contains an overview of all items and reliability values.

3.3 Analytical strategy

We used SPSS to analyze the effects of the exhibition visit on the components of public engagement (exhibition effects, H1). First, we conducted paired *t*-tests to assess changes in public engagement measures before and after the visit. We then ran analyses of covariance (ANCOVAs), including age, gender, and education level as between-subject factors, to examine whether the effects varied by sociodemographic characteristics and to test the robustness of our findings. As we formulated directional hypotheses for H1, we applied one-tailed significance tests with a 5% significance level.

To analyze H2a and H2b, we first calculated change scores of all components of public engagement between pre-and posttest ($t_2 - t_1$) and used them as dependent variables. Positive values of the change scores indicate an increase in public engagement after the museum visit, while negative scores show a decrease and the value 0 indicates that there was no change at all. For testing potential direct (H2a) and indirect (H2b) effects of game use on public engagement via exhibition experiences, we performed a mediation analysis[3] using the R package lavaan (Rosseel, 2012). Following Hayes (2018), bootstrapping with 5,000 iterations was used to calculate bias-corrected 95% confidence intervals (CI) for the indirect effects. Model fit indices met the criteria proposed by Hu and Bentler (1999), see Supplementary Table B3.

4 Results

4.1 Exhibition effects (H1)

Paired *t*-tests (see Table 1) indicated that visiting the exhibition had a positive effect on participants' cognitive as well as aspects of their emotional and behavioral public engagement. Consistent with H1, respondents showed small (Cohen's d < 0.02) yet significant increases in subjective knowledge ($Mt_1 = 3.37$, $Mt_2 = 3.50$,

2 Supplementary Table B2 also includes sociodemographic information on dropouts.

3 We conducted a preliminary correlational analysis to identify relevant, significant control variables for the model. Results revealed that age, gender, and education level were significant and needed to be included in the mediation analysis, while visit duration was excluded from the subsequent analysis.

TABLE 1 Results of paired *t*-tests: exhibition effects on public engagement with the energy transition.

Dimensions of public engagement	n	M_{t1} (SD)	M_{t2} (SD)	M_{Diff}	One-tailed p
Subjective knowledge	754	3.37 (0.81)	3.50 (0.80)	0.13	< 0.001
Interest	747	4.34 (0.91)	4.37 (0.89)	0.04	0.084
Confidence in technological feasibility	707	3.66 (1.09)	3.79 (1.07)	0.13	< 0.001
Behavioral intention	727	4.11 (0.93)	4.10 (0.93)	0.01	0.400
Perceived self-efficacy	702	3.55 (1.11)	3.66 (1.07)	0.11	< 0.001

$t(753) = -5.211$, $p < 0.001$, $d = 0.19$), confidence in technological feasibility ($Mt_1 = 3.66$, $Mt_2 = 3.79$, $t(706) = -3{,}616$, $p < 0.001$, $d = 0.14$), and perceived self-efficacy ($Mt_1 = 3.55$, $Mt_2 = 3.66$, $t(701) = -3.495$, $p < 0.001$, $d = 0.13$) regarding the German energy transition after visiting the exhibition. However, contrary to our expectations, interest in the issue ($Mt_1 = 4.34$, $Mt_2 = 4.37$, $t(746) = -1.377$, $p = 0.084$, $d = 0.19$) and behavioral intention to actively participate in the transition did not change after the exhibition visit ($Mt_1 = 4.11$, $Mt_2 = 4.10$, $t(726) = 0.254$, $p = 0.400$, $d = 0.05$), and was therefore not included in subsequent analyses. ANCOVAs (see Supplementary material C) yielded that the observed exhibition effects remained stable when controlling for age, gender, and education level as between-subject factors.

4.2 Game effects (H2)

We used the change scores ($t_2 - t_1$) of only those variables with significant exhibition effect—namely, subjective knowledge, confidence in technological feasibility, and perceived self-efficacy—as dependent variables in our mediation analysis. The analysis (see Figure 2) revealed no significant direct effects of game use. Contrary to H2a, this indicates that change scores of game users were not significantly different from those of non-users. Thus, using the game did not enhance the exhibition's positive effects on public engagement.

However, we found that the use of the game positively influenced visitors' exhibition experience ($B = 0.031$, $SE = 0.015$; game user: $M = 3.87$, non-game users, $M = 3.59$) which, in turn, led to greater changes in subjective knowledge [indirect effect: $B = 0.029$, $SE = 0.014$, 95% CI (0.009, 0.064)] and confidence [indirect effect: $B = 0.056$, $SE = 0.025$, 95% CI (0.018, 0.117)] compared to non-game use. This indicates that game use indirectly resulted in 0.029 points more change in knowledge and 0.056 points more change in confidence compared to non-use. By contrast, the analysis did not yield a significant indirect effect of game use on changes in perceived self-efficacy [indirect effect: $B = 0.012$, $SE = 0.014$, 95% CI (−0.014, 0.045)]. Therefore, our results are partially in accordance with H2b that assumed a positive mediation effect of exhibition experiences.

5 Discussion

5.1 Discussion of the findings

The aim of this study was to examine the effects of strategic science communication via an interactive exhibition on visitors' public engagement with the German energy transition. Drawing on a multidimensional understanding of public engagement, we assessed all three components: cognitive (subjective knowledge), affective (interest and confidence in technological feasibility), and behavioral (perceived self-efficacy and behavioral intention to actively participate) engagement. Additionally, we investigated the potential role of gamification in exhibit-based science communication—both directly and indirectly through visitors' individual exhibition experiences, using a mediation model.

The results of our study demonstrate that exhibit-based science communication can effectively enhance public engagement. We found positive effects not only on cognition but also, to some extent, on affective and behavioral components. Specifically, visiting the interactive exhibition on research-based technological solutions for the German energy transition increased participants' subjective knowledge (cognitive), confidence in technological feasibility (affective), and perceived self-efficacy to actively contribute to this societal transformation (behavioral). Importantly, these effects remained stable after controlling for several sociodemographic factors, suggesting that the benefits apply across diverse visitor groups. Accordingly, our findings provide empirical support for theoretical assumptions (e.g., McGhie et al., 2018) that interactive exhibitions have the potential to communicate complex, value-laden scientific issues—such as energy transitions—to a broad audience. As such, interactive science exhibitions may serve as valuable tools for promoting public engagement in climate change mitigation and potentially other societal transformations.

However, we found no exhibition effects on visitors' interest and their intention to participate in the energy transition, which is in contrast to previous evaluation research on climate change exhibitions (Geiger et al., 2017a). One likely explanation is the nature of our sample, which showed high baseline levels of both interest and behavioral intention, suggesting a ceiling effect that limited potential change. Additionally, using single-item measures may have affected the results, as this may not fully capture the complexity of these constructs. Therefore, future research could benefit from developing concise, yet more precise, multi-item scales that balance the practical constraints of real-world evaluation—such as minimizing participant burden during museum visits—with the need for accurate measurement. Moreover, incorporating qualitative methods, such as interviews, could help uncover how science exhibitions might better foster interest and intentions to participate (Geiger et al., 2017b).

The second major aim of the study was to examine the impact of gamification as a tool for effective exhibit-based science communication. We analyzed whether and how the integrated game WETTAY (What Energy Transition Type are you?) influenced changes in public engagement, either directly or indirectly through visitor's experiences. Contrary to our expectations and prior research (e.g., Stanković Elesini et al., 2023), game use did not directly enhance the exhibition's positive effects. However, our analyses revealed positive indirect effects: Consistent with previous studies demonstrating that

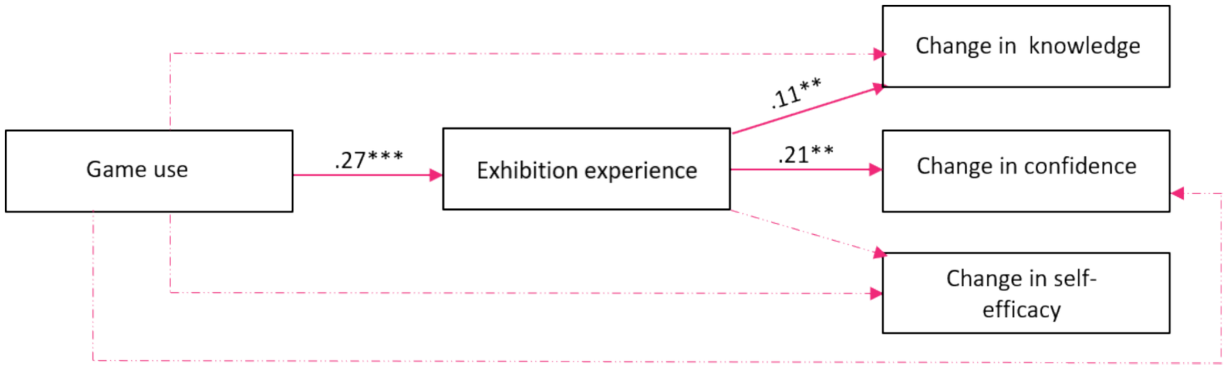

FIGURE 2
This figure illustrates the results of the mediation analysis. It shows that game use had no direct but rather positive indirect effects on changes in knowledge and confidence mediated by positive exhibition experiences. *n* (complete cases) = 444. Coefficients represent non-standardized *B* values. As the exhibition visit did not increase interest and behavioral intention, no mediation models were calculated for these indicators. Dashed lines indicate no significant effect. ****p* (two-tailed) < 0.001, ***p* (two-tailed) < 0.01.

games foster enjoyable experiences (Huizinga, 1956; Schumann, 2013; Hamari and Koivisto, 2015), WETTAY users reported a significantly more positive exhibition experience than non-game users. These experiences, in turn, led to greater increases in cognitive and, to some extent, affective public engagement. This suggests that gamification improves experiences with science communication activities (e.g., fascination) and is an effective strategy for promoting engagement through immersive experience—especially when communicating complex scientific topics. This insight is also relevant for museum and science center professionals, as positive visitor experiences may not "only" enhance engagement, but also increase return visits and word-of-mouth promotion.

Taking a closer look at the observed indirect effects, a positive exhibition experience predicted increased subjective knowledge about the energy transition and greater confidence in its technological feasibility. This supports the idea that enjoyable experiences created through gamification help individuals to better connect with complex scientific topics (Buckley et al., 2019; García-Iruela et al., 2022). However, our study did not find that the relationship between game use and changes in perceived self-efficacy was mediated by exhibition experience. This suggests that positive experiences primarily influence cognition and affect rather than behavioral outcomes. We attribute this to WETTAY's predominant gamification elements, which employ realistic narratives but focus on technologies that are not yet part of everyday life. Visitors enjoyed these "as-if-scenarios" which likely helped them learn about and imagine future developments and increased their confidence in the feasibility of the energy transition. Nevertheless, because the scenarios remained somewhat disconnected from their present-day realities, the game did not enhance visitors' sense of self-efficacy.

Overall, our findings suggest that gamification can be a valuable tool for fostering public engagement in science exhibitions. In our study, playing WETTAY indirectly enhanced the positive effects of the exhibition visit on cognitive and certain affective aspects by increasing positive experiences. However, since WETTAY was the only game tested, our results may not be generalizable to other games with different characteristics or other contexts. Moreover, developing an integrated game requires a significant effort and financial investment. Therefore, science communication practitioners should carefully consider their goals and whether gamification aligns with them. Future research should particularly explore how gamification can also foster behavioral engagement, for example, by testing a game that emphasizes action elements, such as tasks, missions, or level progression (Schumann et al., 2016). Empirically, this could be done through qualitative interviews or experimental designs that vary game elements.

5.2 Limitations and future research

The present study has several limitations. First, while our study design allows conclusions about short-term effects of the exhibition and the game, future evaluation studies could employ a pre-post-post design with an additional measurement a few weeks or months after the visit. This would help assess whether exhibit-based science communication can lead to sustained long-term changes in public engagement. Second, the study design might have led to potential pretest sensitization effects. For example, our pretest could have increased visitors' attention to the exhibition and its content (e.g., Tucker et al., 2011), if they felt they need to demonstrate in the posttest that they had learned something. As a result, sensitization may have partially influenced participant's scores on the public engagement variables in the posttest. Future studies could use a Solomon four-group design (Clark and Shadish, 2008) to compare, for instance, the responses of visitors who did and did not receive the pretest-survey before entering a science exhibition. This would help to control for the potential effects of sensitization caused by the pretest on both the exhibition visit and posttest responses. Third, the exhibition primarily attracted individuals with higher levels of formal education. This limits the generalizability of our findings, as little is known about the exhibition's impact on visitors with lower levels of formal education. Both researchers and science communication practitioners should address the challenge of reaching more diverse demographic groups to ensure broader accessibility and inclusivity (see, e.g., Humm and Schrögel, 2020). One potential approach is a mobile exhibition—using a van or truck—that reaches people in their everyday environments rather than requiring them to visit a museum (Li et al., 2015). Such an exhibition could visit locations such as market places, schoolyards, festivals, churches, farmers' markets, or fairs to engage audiences with greater sociodemographic diversity. Fourth, in our study, participants were not randomly assigned to the game condition, but self-selected whether to play or not. A comparison of sociodemographic characteristics between players and non-players showed that younger visitors participated significantly more often than older ones (see 3.2.3 and Supplemental material B2). This self-selection may have reduced the internal validity of the study. However, allowing participants to choose whether to play reflects a more naturalistic setting, as visitors in real-world museum environments also voluntarily decide whether to engage with interactive elements. Our approach thus avoids assigning participants to a condition they might not have chosen naturally, enhancing the external validity of the study. In this context, the higher proportion of younger participants among game players is not surprising (Cesário and Nisi, 2023). Finally, our findings focused on the impact of exhibit-based science communication and gamification on a specific topic—energy transitions—a key strategy for climate change mitigation in various countries. Future studies could explore the potential of science exhibitions in other domains (e.g., medical issues like large-scale viral outbreaks or new medical treatments). For gamification, future studies could also examine its potential in other formats of strategic science communication, such as social media.

6 Conclusion

By uncovering the positive effects of an interactive science exhibition on visitors' cognitive and aspects of their affective as well as behavioral public engagement with the German energy transition, the present study offers valuable insights for science communication evaluation research and practice. Our pretest-posttest design proved effective in capturing the effects on public engagement, addressing the notable lack of rigorous evaluation studies of real-world science communication activities (Tucker et al., 2011; Weingart et al., 2021). Since energy transitions are central to climate change mitigation, our findings suggest that science exhibitions can be effective tools for supporting large-scale societal transformations toward a more sustainable future. This role is especially critical in light of the limited effectiveness of one-way, mass media-based science communication in fostering public engagement (Fähnrich, 2017; e.g., Arlt et al., 2023b). The prevalence of misinformation, particularly on social media, further complicates mediated communication. Museums, as highly trusted institutions (Cain and Rader, 2017), may be well-positioned to act as guiding agents, providing reliable information and facilitating informed public engagement during complex societal transformations. Given the positive effects of an interactive exhibition and gamification demonstrated in our study, increased financial investment in museums or science centers appears to be a promising avenue for harnessing their potential in strategic science communication.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Ethics Committee of the Technical University Ilmenau (approval number: 2024-03-196_FoA-Schal.1). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin as we obtained it orally: In particular, all participants were thoroughly informed about the purpose of the study, the exclusive scientific use of their data, the anonymity of responses, and the voluntary nature of their participation at all stages. This information was included in the questionnaire and additionally communicated orally. We chose to obtain oral informed consent rather than written consent in order to minimize participation barriers and avoid placing additional burden on participants—an important consideration for conducting an evaluation study in a real-world setting, such as a public exhibition. As the participant population did not include any vulnerable groups, this approach was deemed ethically appropriate. The Ethics Committee of the Technical University Ilmenau approved this procedure.

Author contributions

SS: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Project administration, Conceptualization, Methodology. CS: Conceptualization, Writing – review & editing, Formal analysis, Methodology, Writing – original draft, Investigation, Funding acquisition. JW: Funding acquisition, Methodology, Conceptualization, Writing – review & editing.

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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.

Generative AI statement

The authors declare that Gen AI was used in the creation of this manuscript. In particular, ChatGPT (4.0, payed version) and DeepL write assistant (free version) were used for language improvement.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomm.2025.1657572/full#supplementary-material

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