



Learning new recycling rules through virtual reality: a field study on knowledge, self-efficacy, and intentions

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ABSTRACT

Although environmental concern is widespread, sustainable behaviors often break down when individuals are confronted with new or changing rules. While virtual reality (VR) has emerged as a promising tool for sustainability interventions, most supporting evidence derives from controlled laboratory settings, leaving its real-world effectiveness largely unexplored.

The present field study addresses this gap by testing a VR training intervention in an eco-resort in Tuscany, Italy, during the rollout of a new color-coded waste-sorting system. In this context, where sustainability-related cues and norms were salient, the intervention focused on procedural uncertainty rather than general environmental concern.

In a single-group pre-post field study ($N=140$), participants completed measures of task-specific self-efficacy for correct sorting, behavioral intentions for the upcoming week, and objective knowledge of the new rules. They then experienced a brief gamified VR simulation reproducing the resort's new ecological stations and providing immediate corrective feedback, followed by post-test measures.

All three outcomes (i.e., self-efficacy, rule knowledge, and intentions) increased significantly from pre- to post-VR. A conditional process analysis further showed that increases in self-efficacy predicted increases in intentions only when participants also showed substantial knowledge gains, suggesting that confidence promotes commitment to act most effectively when supported by accurate rule learning.

Overall, this field study provides ecologically valid evidence of reliable pre-post improvements following a brief VR training delivered during a real transition in environmental infrastructure. These findings highlight VR as a practical tool for behavioral adaptation during rule changes, coupling mastery-based practice with contextualized rule learning.

1. Introduction

While environmental concern is widespread and has increased in many countries, the adoption of sustainable behaviors often remains lower than expected, a phenomenon commonly described as the intention-behavior gap [1,2]. This gap reflects the fact that sustainable behavior is rarely determined by motivation alone. Previous work has shown that pro-environmental action is shaped by a combination of individual, social, and contextual factors, including habits, social norms, perceived and actual convenience, infrastructure availability, contextual cues, and people's knowledge of how to perform the behavior in a

given setting [3–5]. Habits are especially relevant because many everyday sustainable behaviors are repeated in stable contexts and can become automatic; when contexts change, previously adaptive routines may no longer guide correct action [6]. Similarly, infrastructures and contextual cues can either facilitate or hinder behavior by making the appropriate action clear, convenient, and easy to perform [3,4]. Thus, failures to act sustainably should not be reduced to a lack of motivation alone.

Even when people endorse pro-environmental values and report strong intentions, they may still struggle to act consistently when the behavior is complex or when the environment suddenly changes [5,6].

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The present study focuses on one specific aspect of this broader problem: procedural uncertainty during changes in environmental infrastructure. When familiar routines are disrupted, cues change, or local rules differ from those people already know, correct behavior may depend not only on environmental concern, but also on clear procedural knowledge and confidence in one's ability to apply the relevant rules [7].

This issue is particularly relevant for waste sorting because incorrect disposal is not merely a harmless individual mistake. Mis-sorted waste can contaminate recycling streams (see also [8]), increase the need for manual correction by staff, reduce the efficiency of the collection system, and make newly introduced rules harder to consolidate into stable routines [9,10]. This makes waste sorting during infrastructure transitions a useful test case for interventions that aim to support procedural learning rather than simply increase environmental concern.

In line with this focus, the present study examines behavioral intentions as an immediate precursor of future behavior, alongside task-specific self-efficacy and objective rule knowledge as proximal action-enabling factors in a context where correct behavior required learning updated and context-specific rules.

The study was conducted in a real-world field context – a vacation eco-resort in Tuscany, Italy – shortly after the introduction of a redesigned on-site recycling system with updated stations, new bin colors, and revised sorting rules, which likely generated uncertainty for both returning guests (who needed to update previously learned routines) and first-time visitors (whose habitual recycling practices at home may not have aligned with the new system). This setting allowed us to examine VR training in a situation where the behavioral challenge was not only to endorse recycling as desirable, but to learn how to apply a new local system correctly [11–13].

Accordingly, the first goal was to test whether the VR experience increases task-specific self-efficacy, knowledge of the updated sorting rules, and intentions to sort waste correctly. The second goal was to examine the process linking these changes by testing whether gains in self-efficacy predict gains in intentions, and whether this association is moderated by learning gains in rule knowledge. Thus, the study tests VR as a training tool during a naturalistic infrastructure transition and examines whether knowledge acquisition strengthens the self-efficacy–intentions link beyond mean pre–post effects.

2. VR, procedural learning, and self-efficacy

A central challenge in sustainability research is the persistent gap between environmental concern and everyday behavior [2,3]. People may endorse pro-environmental values and still fail to act accordingly when the behavior is inconvenient, unfamiliar, or embedded in routines that are difficult to change [2,3]. This gap becomes especially relevant when sustainable action depends on knowing how to perform a specific behavior in a specific context, rather than simply being willing to do the right thing. Traditional communication tools can raise awareness but often provide limited support for action, partly because they do not offer the sensory richness and interactivity needed to engage people in concrete decision-making [14,15]. Against this background, VR has been described as a high-potential approach for sustainability interventions, because immersion can make environmental scenarios more concrete and personally engaging [16,17]. Its value may be particularly clear when the goal is not only to inform people, but to let them practice a behavior and receive feedback before performing it in the real setting [1,18].

Importantly, much of the existing evidence comes from laboratory and controlled settings, which may limit ecological validity when the goal is to support everyday sustainable behavior [1,19].

Waste sorting offers a clear example of this problem. Correct behavior requires people to recognize materials, interpret local rules, identify the correct bin, and carry out the action in a specific spatial context. When waste-sorting systems are updated, this task can become more difficult because familiar cues may no longer apply. New bin

colors, labels, iconography, or disposal layouts can disrupt previously learned routines and create uncertainty about what should be done [1,17]. Color cues may be especially relevant in this context because people develop expectations about how particular colors map onto waste categories. Research on color inference in recycling systems shows that these mappings are shaped by learned color–concept associations and by the configuration of the color-coding system as a whole [20]. Accordingly, changes in bin colors may require users to revise previously learned cue–category associations rather than simply retrieve an already familiar sorting rule. In such contexts, the challenge is not simply to make information available. People also need to connect new rules to visible cues and concrete actions. A simulated training environment may support this process by allowing users to practice the cue–category–action sequence before encountering the same system in everyday use. This does not mean that VR should replace conventional communication tools such as visual labels. These remain central elements of any recycling system. Rather, VR may complement them when the goal is to support procedural learning: users can make mistakes in a low-risk environment, receive immediate corrective feedback, and repeat the action until the correct response is consolidated [13].

This action-oriented potential is particularly relevant when the target behavior depends on learning applied routines rather than endorsing general values [21]. In this regard, knowledge acquisition in immersive environments can be understood through the Cognitive Affective Model of Immersive Learning (CAMIL), which proposes that VR can support learning through spatial presence and agency [19,22]. Spatial presence, or the feeling of “being there” [23], may encourage users to process the virtual situation as if it were immediately relevant. Agency, understood as the sense of controlling one's actions and their consequences, can support active involvement and learning through practice [19,22]. These mechanisms are important for procedural learning because they link information to action. When users practice in an environment that resembles the real one, what they learn may become tied to realistic cues and action sequences, making it easier to retrieve later in a similar context [15,22]. In a recycling task, this means that users do not only learn an abstract rule, such as which material belongs to which category. They practice recognizing an object, selecting a bin, and receiving feedback on the correctness of the action.

Gamification may further support this process. In this context, gamification refers to the use of game elements, such as goals, feedback, and progress indicators, to structure a non-game learning activity. Indeed, clear goals can help users understand what they are trying to accomplish [24–26], while immediate performance feedback can sustain attention and guide correction after errors [27,28]. Higher levels of immersion have also been associated with better knowledge retention [29]. In this sense, a gamified VR task can combine practice, feedback, and repetition in a way that is difficult to achieve through static information alone. The main advantage is not that the task is playful per se, but that the game structure can organize learning around repeated attempts, visible progress, and corrective feedback. At the same time, VR also offers a methodological advantage: researchers can reproduce and manipulate relevant features of the environment, such as colors, shapes, or bin placement, while preserving a sense of ecological realism [1,19,30].

Self-efficacy is also relevant for understanding whether people feel able to perform a sustainable behavior correctly. It refers to the belief that one can successfully carry out the actions needed to achieve a goal, and it has been identified as an important predictor of pro-environmental behavior [15,31,32]. In the present context, the relevant form is not general environmental self-efficacy, but task-specific self-efficacy: the perceived ability to sort waste correctly under the local rules of the resort. Social Cognitive Theory emphasizes that self-efficacy is strengthened primarily through mastery experiences, that is, through direct evidence that one can perform the target behavior successfully [1,32]. This point is particularly important when rules change. New demands can make people uncertain about their ability to

act correctly, even if they are generally favorable toward the behavior [33]. A person may want to recycle but still hesitate when the categories, colors, or disposal rules are unfamiliar.

VR can support task-specific self-efficacy because it allows users to perform the relevant behavior in a realistic but controlled setting [1,15]. By requiring users to act, receive corrective feedback, and eventually complete the task successfully, VR can provide direct evidence of competence. Errors can be corrected without real-world consequences, and repeated attempts can help users feel more capable of applying the rule correctly [1,15,19]. When the simulation also makes the consequences of correct actions visible, it may reinforce response efficacy, namely the belief that one's actions can contribute to broader environmental outcomes [19,34].

Previous work has already demonstrated the feasibility of using immersive and serious-game environments to train recycling rules. For example, recycling serious games have been developed for CAVE-like immersive environments [35], while other immersive VR applications have allowed users to practice recycling behaviors while receiving visual and auditory feedback [36]. These contributions established recycling as a suitable domain for immersive training. The present study extends this work by moving beyond system development and demonstration to empirically examine a brief VR intervention under field conditions during an actual change in recycling infrastructure, while considering objective rule knowledge, task-specific self-efficacy, and behavioral intentions as theoretically relevant outcomes. Overall, the literature suggests that VR may be useful when sustainable behavior requires people to learn and apply new procedural rules in a concrete setting. This is especially relevant during infrastructure transitions, when existing routines are disrupted and users must update the link between environmental cues, rules, and actions. In these situations, the key question is not only whether people care about sustainability, but whether they know what to do and feel capable of doing it correctly. The present study applies this reasoning to a real-world recycling transition in an eco-resort, where a newly standardized color-coded waste-sorting system created a context in which guests needed to learn or update local sorting rules [1,15,17,19].

3. The present study

The present study was conducted in a real-world setting, “Le Esperidi”, an EU EcoLabel-certified eco-resort holiday village in Tuscany, Italy. During the season in which the study took place, the resort introduced a redesigned waste-sorting system: all waste bins were replaced, and a new signage and color-coding system was implemented

(see Fig. 1). Before this update, the village already had recycling stations in several areas, but the system was not fully consistent. Bins differed in shape and labeling: some used color codes that did not match municipal standards, some relied only on written labels, and others used colors that were inconsistent with the village's own scheme. The redesign standardized all collection points under a single, village-wide color code and aligned the system with the municipal sorting standard.

This transition created a concrete procedural challenge. Returning guests had to update previously learned routines, whereas first-time visitors may have encountered a local sorting scheme that differed from the one used in their home communities. Consistent with research on the intention-behavior gap, people may fail to translate intentions into effective action when they are unsure how to behave appropriately or when they lack confidence in their ability to do so [5,37,38]. In the present context, the relevant problem was therefore not only whether guests considered recycling desirable, but whether they knew how to apply the updated local rules correctly.

Accordingly, the first goal of the present research was to test, in a real-world field setting, whether a VR-based training experience was followed by increases in task-specific self-efficacy, knowledge of the updated sorting rules, and future intentions to sort waste correctly. The second goal was to examine the process linking these changes by testing whether pre-post gains in self-efficacy predicted pre-post gains in intentions, and whether this association was moderated by learning gains in knowledge of the redesigned recycling system.

We hypothesized that participants would show higher post- than pre-intervention levels of (a) task-specific self-efficacy for correct waste sorting at the campsite, (b) knowledge of the updated color-coded recycling rules, and (c) intentions to sort waste correctly during the stay. Beyond these main effects, we expected that increases in self-efficacy would predict increases in recycling intentions, with this association moderated by learning gains, such that the self-efficacy-intentions link would be stronger when participants acquired greater knowledge through the VR simulation.

To test these hypotheses in an ecologically valid way, we developed an immersive, interactive VR experience that simulated realistic recycling scenarios in the resort and provided opportunities for safe practice with immediate feedback [11,12]. The intervention was designed to reduce situational uncertainty by strengthening the practical knowledge and confidence needed to translate intentions into correct action under the new system.

4. Methods

4.1. Study design and power analysis

The study used a single-group pre-post field design. Participants first completed baseline measures of self-efficacy, intentions, and knowledge of the new sorting rules, then completed the VR training experience, and finally completed the post-intervention measures. To determine the minimum sample size required to achieve sufficient statistical power (≥ 0.80) for a conditional process model, we conducted an a-priori Monte Carlo simulation using R [39] with the lavaan package [40]. The simulation parameters were informed by prior evidence showing that immersive, action-oriented VR experiences can increase self-efficacy and that self-efficacy can, in turn, predict cognitive and behavioral outcomes. For example, in an operational training context, VR produced medium pre-post gains in self-efficacy (Cohen's $d \approx .60-.70$), and self-efficacy predicted learning gains ($r \approx .47$; $\beta \approx .30$; [41]). In the pro-environmental domain, a VR intervention targeting sustainable food choices showed moderate-to-large behavioral effects during the experience (Cohen's $d \approx .90$) and evidence consistent with self-efficacy mediating the link between immersion and behavioral intentions [15]. Converging findings also come from a quasi-experimental educational study reporting medium-to-large pre-post improvements in sustainable behaviors (approximately $d \approx .50-1.20$, depending on the behavioral



Fig. 1. Color-coded recycling system after the upgrading of on-site waste collection areas.

dimension; [42]) and from structural analyses in a university context showing sizable paths from VR to environmental knowledge/attitudes and, in turn, to pro-environmental behavior ($\beta \approx .30-.77$; [43]).

Based on this evidence, we set the model's main effects to medium-to-high values ($\approx .35$) and the interaction effect to .25, consistent with conditions in which VR affords agency, feedback, and situated engagement. Sample size varied from 50 to 200, with 1,000 iterations per N and $\alpha = .05$. The resulting power curve indicated that $N=140$ achieved power $\geq .80$ for the expected interaction effect.

4.2. Participants and recruitment

Data were collected between August 2 and August 13, 2025. This period coincided with the completion of the resort-wide rollout of the new waste-sorting system, which had just become the official on-site standard, making the setting especially appropriate for testing the hypotheses in a naturalistic phase of rule adaptation.

A research kiosk served as the operational base for the research team. Guests could freely join several scientific and outreach activities organized at the kiosk, and participation in the present study was therefore spontaneous and voluntary. As compensation for participation, respondents received a small eco-friendly gift, such as compostable sunglasses made entirely from corn fiber.

The study was conducted outdoors near the kiosk and away from the newly installed ecological stations, to ensure that participants could not see the actual bin colors before completing the pre-test measures. Given the field-based nature of the study and the vacation setting, we used abbreviated measures, including short scales or selected items from the original instruments, to minimize participant burden. This choice was made to maximize participation and to reduce the risk that the study would be perceived as long or demanding, which could discourage guests from taking part.

A total of 164 participants took part in the study. Of these, 24 failed an attention check included to verify attention to the survey and were excluded from subsequent analyses, yielding a final sample of 140 participants. All participants included in the final sample completed the VR training experience and the post-intervention survey. No participant took part in the study more than once.

The final sample had a mean age of 27.45 years ($SD = 14.47$) and included 74 female participants, 65 male participants, and 1 participant who preferred not to answer. Most participants were from Italy (93.6%), while the remainder were from Germany (2.9%), Switzerland (2.1%), Austria (0.7%), and Spain (0.7%). In terms of prior experience with the resort, 60.7% of participants were returning guests who had previously stayed there, whereas 39.3% were first-time visitors. At the time of data collection, participants had been staying at the resort for an average of 3.23 days ($SD = 1.53$). Education was mainly high school (55%), followed by bachelor's degree (20.7%) and master's degree (15%); fewer participants reported middle school (7.2%) or a PhD (2.1%).

4.3. Procedure

After agreeing to participate, guests scanned a QR code on their smartphone that redirected them to a Qualtrics survey. Given the resort's international guest population, the survey was administered in Italian, English, and German. Participants first viewed and signed the informed consent and then provided demographic information, including age, gender, and education.

Next, participants completed the control measures and the pre-intervention measures. The control measures assessed length of stay, previous experience with the resort, previous VR experience, and attitudes toward waste sorting. The pre-intervention measures assessed task-specific self-efficacy for correct waste sorting at the resort, behavioral intentions for the upcoming week, and objective knowledge of the new sorting rules.

After completing the pre-intervention measures, participants

completed the VR training experience. The VR task was administered immediately after the first part of the survey and was completed by all participants included in the final sample. After the VR task, participants resumed the second part of the survey. They completed the same main measures administered at pre-test, namely self-efficacy and behavioral intentions, now framed as post-intervention outcomes. They also completed a mirrored post-intervention knowledge test, designed to assess knowledge of the same sorting rules using different waste exemplars. Finally, participants completed the presence measure, were debriefed about the study aims, and none reported cybersickness.

4.4. VR experience

Participants completed the VR experience using a Meta Quest 3 headset. The full VR application is available in the OSF repository associated with the Supplementary Materials. As for the survey, the VR experience was developed in Italian, English, and German, and participants could select their preferred language at the beginning of the gameplay experience.

The Meta Quest 3 is a standalone VR device equipped with high-resolution pancake lenses (2064×2208 pixels per eye), a wide field of view of approximately 110° , and a refresh rate of up to 120 Hz. This allowed participants to complete the immersive experience without the need for an external computer.

The VR experience (see Fig. 2 for a screenshot) began with a short tutorial to familiarize participants with the controllers. They learned how to grasp objects by pointing at them with a ray and pressing the front trigger. Next, a brief narrative introduced the task: the campsite mascot, a small squirrel, explained that rubbish had been left overnight and asked participants to help restore order by sorting the waste correctly.

Participants were then placed in a stylized virtual representation of the campsite's new ecological stations. The environment was not intended as a photorealistic reconstruction; rather, it reproduced the task-relevant features of the actual stations, including the bin categories, color-coding system, and sorting rules. Throughout the experience, participants handled a total of 16 items representing different recyclable materials. The task was self-paced, and participants were not given any time limit to complete the experience.

Feedback was immediate and mastery-oriented. When an item was placed in the correct bin, participants received positive feedback through a brief success sound. Progress was also made visible through an in-world counter displayed on a wooden board within the virtual environment: the counter increased by +1 for each correctly sorted item and appeared in green. When an item was placed in the wrong bin, a red error message appeared and a voice-over indicated the correct bin for that specific waste type. The item then reappeared among the unsorted objects on the ground, allowing participants to try again. In this case, the counter did not increment and displayed the error in red. The task ended only when all items had been sorted correctly.

The following measures were administered before and, when relevant, after the VR experience described above. The full wording of all self-report items and their response anchors is reported in Table 1; means, standard deviations, and Cronbach's alpha for all measures are reported in Table 1).

Length of stay was assessed with a single item asking how long participants had already been on vacation at Le Esperidi. Because many of the resort's visitors are returning guests who spend their summer holidays at the site each year, participants also indicated whether this was their first stay or a repeat visit. Previous VR experience was measured with a single item rating participants' prior level of experience with virtual reality technologies (1 = no experience to 5 = highly expert).

Attitudes toward waste sorting were assessed through a semantic differential [44,45] composed of three bipolar adjective pairs. Self-efficacy for correct waste sorting at the resort was measured with



Fig. 2. Screenshot of the game environment designed to support learning of the color codes in the new recycling system.

five ad-hoc items, one of which was reverse-worded; the same items were re-administered after the VR experience as post-intervention outcomes.

Behavioral intentions were adapted from Concari et al. [46] and comprised four items, introduced with a prompt referring to the upcoming week at the resort; these items were likewise re-administered after the VR experience.

Knowledge of the new recycling rules was assessed with six items presented as a single-choice matrix. At pre-test, participants were explicitly instructed to respond spontaneously and not to revise the rules or consult external information. For each waste item, participants selected one disposal option among the four color-coded bins (green, blue, yellow, gray) or "I am not sure." Although waste-sorting schemes differ across countries and municipalities, the task was designed to reflect the specific four-bin system in use locally at the time, prioritizing ecological validity over alignment with more generalized classification standards. Scoring was objective: each correct answer received 1 point, whereas incorrect answers and "I am not sure" responses received 0 points; an overall score was computed as the sum of correct responses (range 0–6), with higher scores indicating greater knowledge of the new sorting system. To mitigate memory bias and short-interval test–retest effects, post-intervention knowledge was assessed with a mirrored set of items following the same format but featuring different exemplars, designed to be comparable in everyday familiarity and ambiguity (pre- and post-test exemplars are listed in Table 1).

Sense of presence during the VR simulation was assessed using three items from Schubert's [47] Presence Questionnaire.

5. Results

5.1. Analytical strategy

Analyses proceeded in three steps. First, we inspected descriptive statistics and zero-order correlations among the focal variables and candidate covariates to document their empirical associations and motivate statistical adjustment (Table 1). Second, to estimate the average pre–post change in self-efficacy, knowledge, and intentions while accounting for within-person dependence, we fitted three separate linear mixed-effects models with time (POST vs. PRE) as the within-subject predictor and a random intercept for participant, including mean-centered covariates. Third, to test the hypothesized process, we estimated a conditional process model examining whether pre–post

changes in self-efficacy predicted corresponding pre–post changes in intentions, and whether this association was moderated by learning changes in knowledge, controlling for the same covariates; simple-slopes and Johnson–Neyman procedures were used to probe the interaction.

5.2. Preliminary analyses

Correlation analyses indicated that several control variables were significantly related to the focal outcomes (knowledge, self-efficacy, and behavioral intentions; see Table 2). Attitudes toward waste sorting were consistently associated with self-efficacy and intentions, particularly at baseline. Days already spent at the resort were linked mainly to post-intervention scores (especially post self-efficacy and intentions) and to baseline knowledge, consistent with the idea that longer exposure to the on-site infrastructure may provide additional opportunities to learn the updated rules outside the VR session. Age showed positive associations with baseline self-efficacy and intentions, whereas education level was primarily related to intentions. The sense of presence index showed a link to post-intervention knowledge. Previous experience with VR technologies was associated with both baseline measures for intentions and self-efficacy.

Given these empirical relationships and their substantive relevance, all subsequent analyses included the following covariates: age, education level, days already spent at the resort (staying), attitudes toward waste sorting, previous VR experience (VR familiarity), and sense of presence in VR. Indeed, beyond their statistical associations, these covariates were included to account for stable individual differences in comprehension and learning (e.g., age, education level), differential exposure to the new recycling system prior to the VR training (e.g., days already spent at the resort), baseline predispositions (i.e., attitudes) that can shape confidence and intentions. Moreover, to account for the potential "novelty effect" associated with immersive technology, participants' prior familiarity with VR was also included as a covariate. This allowed us to isolate the impact of the training content from the psychological impact of using a novel technological medium. Finally, presence was included to account for variability in experienced immersion/engagement during the simulation that could affect learning and self-efficacy.

5.3. Average pre–post change

To estimate the average pre–post change in the focal constructs while

Table 1
Constructs, items, and response scales.

Construct	Item(s)	Response scale
Length of stay (pre)	How long have you already been on vacation at the Esperidi?	1 = 1 day; 2 = 2 days; 3 = 3 days; 4 = 4 days; 5 = more than 5 days
Prior visit (pre)	Have you stayed at this resort for your holidays before today?	0 = No; 1 = Yes
Previous VR experience (pre)	How would you rate your previous level of experience in using Virtual Reality technologies?	1 = no experience; 2 = beginner; 3 = competent; 4 = expert; 5 = highly expert
Attitudes toward waste sorting (pre)	easy–difficult; pleasant–unpleasant; useful–useless	Bipolar 5-point (-2; +2) semantic differential
Self-efficacy for correct waste sorting (ad-hoc; pre & post)	1. Here at Le Esperidi, it's easy for me to separate waste correctly. 2. Here at Le Esperidi, I find it simple to understand how to separate waste properly. 3. Here at Le Esperidi, I find correctly separating waste complicated. (R) 4. Here at Le Esperidi, I'm confident in my ability to sort waste correctly, even if the rules weren't clear. 5. Here at Le Esperidi, I know exactly what to do when I need to sort different types of waste correctly.	1 = Completely disagree; 5 = Completely agree
Behavioral intentions (pre & post)	prompt: "Now think about your upcoming week at Camping Le Esperidi. How likely are you to do the following during your stay?" 1. I expect to correctly separate my waste this week. 2. I intend to separate my waste accurately this week. 3. This week, I intend to follow the campsite's waste-sorting rules correctly. 4. This week, I plan to properly sort my waste in the common areas of the campsite.	1 = Not at all likely; 5 = Extremely likely
Knowledge of the new recycling rules (single-choice matrix; pre & post, mirrored exemplars)	Pre-test exemplars: sheet of paper; apple core; plastic bottle; aluminum can; take-away food box from the internal bar; glass bottle. Post-test exemplars: paper tissue; orange peel; plastic food tray; aluminum container; take-away food box; glass cup.	For each item, one option among green / blue / yellow / gray bin, or "I am not sure" (correct = 1, incorrect or "not sure" = 0; total 0–6)
Sense of presence (post)	1. In the computer generated world I had a sense of "being there." 2. Somehow I felt that the virtual world surrounded me. 3. I felt present in the virtual space.	1 = Strongly disagree; 5 = Strongly agree

Note. (R) = reverse-worded item.

accounting for the non-independence of repeated observations within participants, we fitted three separate linear mixed-effects model with time (POST vs. PRE) as the focal within-subject predictor and a random intercept for participant (see also Fig. 3). All models included the following mean-centered covariates: age, education level, days spent in

the village prior to the study, prior experience with the resort, attitudes toward recycling, sense of presence in VR, and VR familiarity. The models were estimated using the package GAMLj [48] for Jamovi v.2.6 [49].

Changes in perceived Self-efficacy. Self-efficacy increased from pre- to post-VR, $F(1, 137)=59.032$, $p < .001$ ($\Delta=0.44$, $SE=0.058$, $t(137)=7.68$, $p < .001$, Cohen's $d_z=0.65$). Days already spent at the resort positively predicted changes in self-efficacy ($b=0.06$, $SE=0.03$, $p=.031$), as did attitudes toward recycling ($b=0.27$, $SE=0.05$, $p < .001$). Age, education, sense of presence, familiarity with VR, and prior experience with the resort were not significant (all $ps \geq .103$). Model R^2 was .28 (marginal) and .492 (conditional), and the ICC was .295.

Changes in behavioral Intentions. Intentions to sort waste correctly increased from pre- to post-VR, $F(1, 137)=47.34$, $p < .001$ ($\Delta=0.355$, $SE=0.0516$, $t(137)=6.88$, $p < .001$; Cohen's $d_z=0.59$). Education ($b=0.08$, $SE=0.03$, $p=.018$), attitudes toward recycling ($b=0.29$, $SE=0.04$, $p < .001$), and VR familiarity ($b=0.07$, $SE=0.03$, $p=.048$) were positive predictors of changes in intentions. Age, days already spent and prior experience with the resort were not significant (all $ps > .065$). Model R^2 was .345 (marginal) and .451 (conditional), and the ICC was .161.

Changes in knowledge. Knowledge of the new waste-sorting system increased from pre- to post-VR, $F(1, 137)=225.213$, $p < .001$ ($\Delta=2.35$, $SE=0.15$, $t(137)=15.00$, $p < .001$; Cohen's $d_z=1.28$). Age negatively predicted changes in knowledge scores ($b=-0.02$, $SE < .007$, $p=.013$), whereas days already spent at the resort was a positive predictor ($b=0.18$, $SE=0.06$, $p=.006$). Attitudes toward recycling, education, VR familiarity, and prior experience with the resort (all $ps \geq .068$) were not significantly associated. Model R^2 was .420 (marginal) and .539 (conditional), and the ICC was .206.

Further, as a sensitivity analysis, we also examined whether baseline levels predicted the magnitude of pre–post change (i.e., room-for-improvement), to assess potential ceiling-related constraints on bounded scales and to document heterogeneity in gains. Importantly, this check was used to qualify (not replace) the primary mixed-effects results, which focus on average pre–post change at the population level; it shows that mean improvements can coexist with baseline-dependent changes. Results are reported in the Supplementary Materials.

5.4. Conditional process analyses

After showing average pre–post improvements in the mixed-effects models, we next examined the process underlying these changes. Because gains varied across participants (see also the Supplementary material), we tested a conditional process model [50] to determine whether the link between self-efficacy gains and intention gains depended on knowledge gains. Specifically, we examined whether individual increases in self-efficacy for correctly sorting waste predicted corresponding increases in intentions to sort waste correctly, and whether this association was conditioned by the magnitude of knowledge acquired during VR (pre–post gains). This analysis controlled for sense of presence in VR, pre-existing attitudes toward waste sorting, age, educational level, days spent in the holiday village prior to participating, prior experience with the resort, and VR familiarity (See Supplementary Materials for a robustness check in which the same conditional process model was estimated without covariates; the key interaction remained significant and the pattern was unchanged).

The overall model was significant, $F(10, 127)=8.27$, $p < .001$, accounting for 39.4% of the variance in changes in intentions ($R^2=.39$). The interaction between changes in self-efficacy and changes in knowledge was significant, $b=0.08$, $SE=0.04$, $t(127)=2.08$, $p=.040$, and explained additional variance ($\Delta R^2=.02$). The main effects of changes in self-efficacy ($b=0.07$, $SE=0.14$, $t(127)=0.55$, $p=.580$) and changes in knowledge ($b=0.03$, $SE=0.027$, $t(127)=1.28$, $p=.204$) were not significant.

Simple-slopes analyses (see Fig. 4) indicated that increases in self-

Table 2

Descriptive statistics and correlations among study variables.

	α	<i>M</i>	<i>SD</i>	1	2	3	4	5	6	7	8	9	10	11	12
1. Age	—	27.46	14.48	—											
2. Educational level	—	2.50	0.91	-.09	—										
3. Days already spent at the resort	—	3.23	1.53	.18*	.04	—									
4. Prior experience with the resort	—	—	—	.22**	-.05	.24*	—								
5. Attitudes	.71	4.30	0.76	.20*	.11	.05	.00	—							
6. Sense of presence	.58	3.75	0.70	.02	-.00	.02	-.07	-.13	—						
7. Previous VR experience	—	1.67	0.90	-.11	.08	.04	-.03	.15	.13	—					
8. Self-efficacy (PRE)	.84	4.12	0.75	.23**	.15	.16	.09	.60***	-.13	.26**	—				
9. Self-efficacy (POST)	.63	4.55	0.49	.10	-.00	.24**	.14	.06	-.01	-.02	.44***	—			
10. Behavioral intentions (PRE)	.94	4.42	0.67	.22**	.18*	.08	.18*	.59***	-.16	.23**	.70***	.19*	—		
11. Behavioral intentions (POST)	.84	4.77	0.38	.13	.17*	.29***	.17*	.32***	-.08	.10	.48***	.39***	.45***	—	
12. Knowledge of new sorting rules (PRE)	—	3.08	1.89	-.09	.09	.24**	.07	.19*	-.05	.15	.27**	.22**	.28***	.21*	—
13. Knowledge of new sorting rules (POST)	—	5.36	1.17	-.13	-.09	-.04	-.01	-.10	-.20*	-.00	-.06	.21*	-.13	.08	.24**

Note. N=140. * $p < .05$; ** $p < .01$; *** $p < .001$. Gender was measured as a nominal variable (0=male, 1=female, 2=Non binary, 3=Prefer not to answer) and was therefore not included in the correlation matrix. Because prior experience with the resort was coded as a binary variable, correlations involving this measure are reported as Spearman's rank-order correlations.

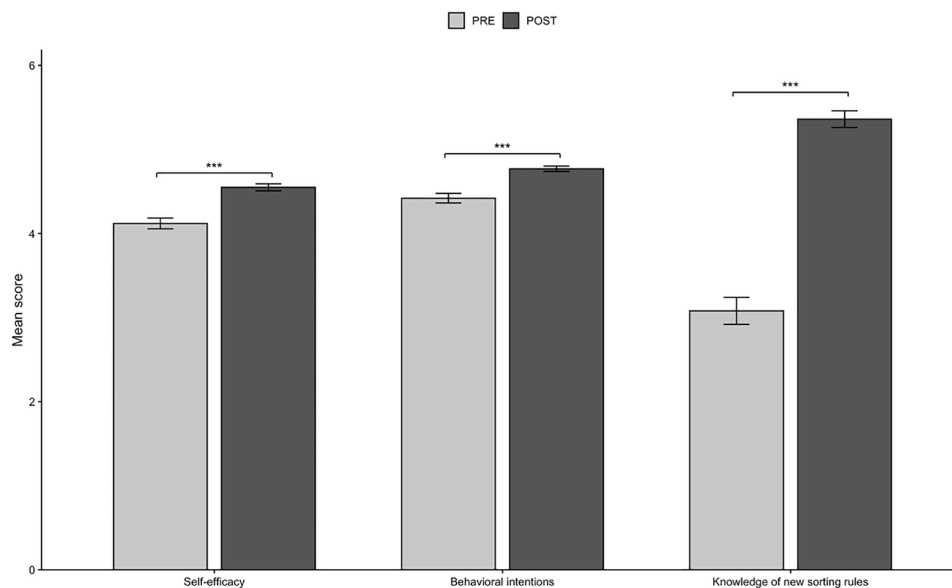


Fig. 3. Mean scores for pre- and post-VR assessments of self-efficacy, behavioral intentions, and knowledge of the new sorting rules. Error bars represent ± 1 standard error of the mean. *** $p < .001$.

efficacy were not associated with increases in intentions when knowledge gains were low (e.g., at knowledge gains equal to 0, $b=0.07$, $SE=0.136$, $t(127)=0.55$, $p=.580$), but the association became positive and statistically significant at higher levels of knowledge gains (at knowledge gains of 2: $b=0.23$, $SE=0.09$, $t(127)=2.58$, $p=.011$; at knowledge gains of 4: $b=0.38$, $SE=0.09$, $t(127)=4.20$, $p < .001$). Johnson-Neyman results (see Fig. 5) indicated that the conditional association between self-efficacy change and intention change became significant for knowledge gains greater than 1.52, corresponding to 65.2% of the sample. Among covariates, time already spent at the resort was a significant positive predictor of increases in intentions ($b=0.07$, $SE=0.03$, $t(127)=2.33$, $p=.021$), whereas the remaining covariates were not significant (all $p \geq .070$).

6. Discussion

The present field study examined whether a brief, gamified VR training deployed in a real vacation context was followed by improvements in (a) knowledge of the updated color-code rules for sorting waste, (b) task-specific self-efficacy for sorting correctly, and (c)

intentions to sort correctly during the stay. Consistent with our expectations, all three outcomes showed significant pre-post increases. These improvements occurred in a field setting characterized by salient sustainability-related cues and by an ongoing transition in the resort's waste-sorting infrastructure. Because recycling motivation, environmental identity, and prior recycling habits were not directly measured, we cannot conclude that participants were already highly motivated to recycle. Rather, the findings should be interpreted as pre-post improvements in rule knowledge, task-specific self-efficacy, and intentions within a sustainability-salient field context.

From an applied environmental perspective, these results support a "situational uncertainty" view: when rules change, people may hesitate or make mistakes because they are unsure what to do and do not feel confident [51]. In our ecological setting, the resort had recently introduced a new color-coding and signage system, meaning that returning guests had to update previously learned routines, while first-time visitors could not rely on the sorting rules and cues used in their home communities. Under these conditions, correct sorting requires accurately executing the right action in the right place, not only endorsing recycling as desirable. The VR experience offered a short and focused

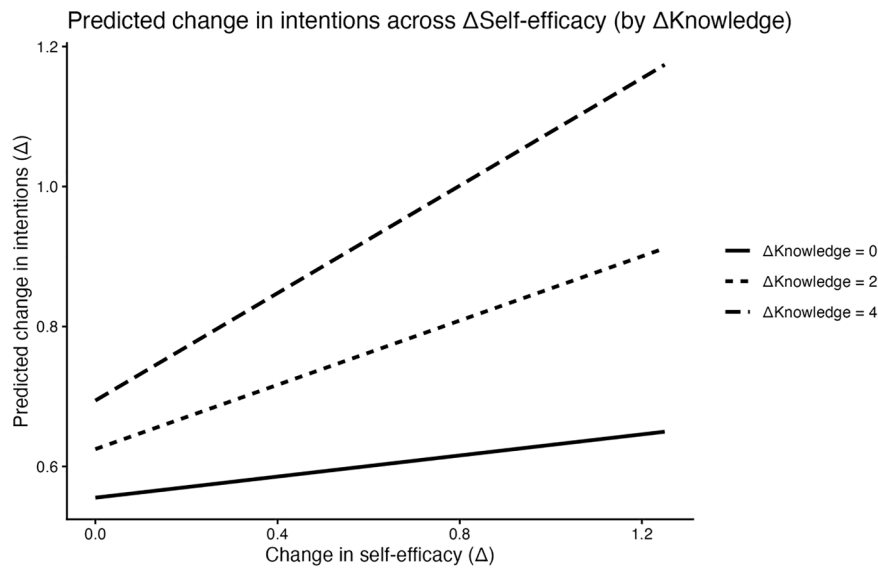


Fig. 4. Predicted change in behavioral intentions as a function of change in self-efficacy, plotted at three values of knowledge gain (Δ knowledge=0, 2, and 4). Shaded bands represent 95% confidence intervals.

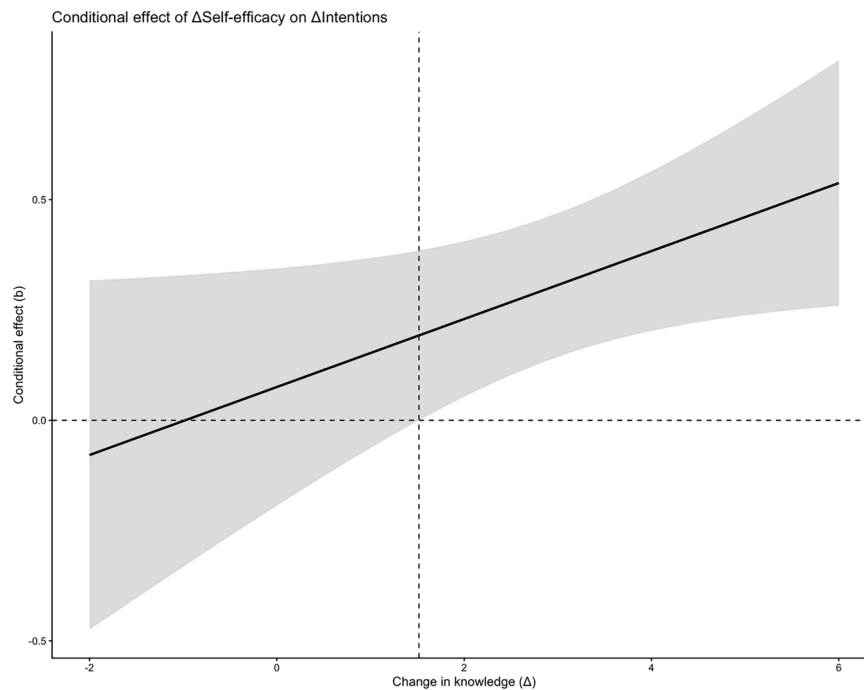


Fig. 5. Johnson–Neyman plot of the conditional effect of changes in self-efficacy on changes in intentions across knowledge gain. Shaded areas represent 95% confidence intervals. The vertical dashed line indicates the Johnson–Neyman region of significance ($p < .05$). All estimates are adjusted for the considered covariates.

training cycle: people practiced, received immediate corrective feedback, and successfully completed the task. This kind of hands-on success may provide the “doing it yourself” evidence that Social Cognitive Theory [52] describes as a key source of self-efficacy, especially when people face new or changing situations.

The observed knowledge gain is also consistent with the idea that interactive practice can help users connect information to concrete environmental cues. Within the CAMIL framework, immersive learning is supported by spatial presence and agency, which may help users experience the task as situated and action-relevant [22]. In the present study, participants not only read or heard sorting rules. They practiced the cue–rule mapping in a virtual environment designed to resemble the actual ecological stations. This may have helped anchor the new rules to

concrete visual cues and action sequences. At the same time, because the study did not include a non-VR comparison condition, these findings should not be interpreted as evidence that VR is superior to simpler formats such as written instructions, videos, or quizzes. The results are instead consistent with a learning-by-doing interpretation, which future controlled studies should test directly [53].

The gamified structure of the task may also have contributed to engagement and learning, but this interpretation should remain cautious. The experience included a simple narrative, clear goals, visible progress, corrective feedback, and repeated attempts after errors. These features may have encouraged participants to attend to the sorting rules and continue practicing until they completed the task successfully.

Compared with purely informational formats (e.g., signs or short

instructions), VR may offer the possibility to practice the full cue–decision–action sequence and receive immediate corrective feedback until the procedure is learned. However, because we did not include an informational control condition, this interpretation should be treated as a plausible explanation rather than as evidence that VR is superior to simpler communication formats. This framing may also help interpret the increase in intentions: rather than necessarily changing general environmental concern, the VR experience may have reduced uncertainty and increased perceived control, making it easier to commit to performing the task correctly under the new system. Nevertheless, while this pattern is consistent with a “procedural support” account, future controlled designs are needed to rule out alternative explanations.

Analytically, this pattern suggests that self-efficacy gains may not be equally meaningful in all cases. Feeling more capable after the VR task was most clearly associated with stronger intentions when it was accompanied by objective learning. This distinction is important because confidence without corresponding knowledge gains could reflect general reassurance, task engagement, or demand characteristics. By contrast, confidence accompanied by improved rule knowledge is more consistent with competence-based confidence: participants may have felt more capable because they had actually learned how to apply the updated sorting rules. In this sense, the moderation pattern is consistent with the idea that self-efficacy is more likely to support behavioral commitment when it is grounded in accurate, task-relevant knowledge [21,52]. Nevertheless, this interpretation remains tentative and should be tested in future studies with comparison conditions and follow-up measures.

Although the VR task produced a positive average increase in knowledge, a small subset of participants ($N=4$) showed negative Δ knowledge scores. These decreases should not be interpreted as “unlearning,” but more plausibly reflect measurement noise and field-related factors such as distractions or reduced motivation in a holiday setting, or temporary confusion due to interference between the new sorting rules and previously learned routines (e.g., different color codes).

The pattern of covariates provides additional context for interpreting the findings. Attitudes toward waste sorting showed the most consistent positive links with the focal outcomes and remained a positive predictor in the mixed-effects models for both self-efficacy and intentions. Days already spent at the resort were related to some post-experience outcomes and, in the moderation model, positively predicted increases in intentions. One plausible explanation is that more time in the setting makes the task feel more relevant and easier to incorporate into daily routines, which can support stronger intentions going forward.

Regarding demographic factors, age was found to negatively predict changes in objective knowledge, suggesting that younger participants might have acquired the new sorting rules more rapidly during the brief VR session. However, age did not significantly influence changes in self-efficacy or behavioral intentions. This is a noteworthy finding, as it implies that even if learning speeds varied across generations, the intervention was equally successful in boosting confidence and commitment for both younger and older guests.

Finally, prior familiarity with the resort (i.e., first-time vs. returning guests) did not significantly affect either the outcomes or the moderation pattern, suggesting that the intervention supported behavioral adaptation equally well across groups. However, although the new system was designed to improve clarity and environmental impact, it may also have introduced an execution barrier by increasing uncertainty about “doing it right”: returning guests had to adjust to a sorting scheme that differed from previous seasons, while first-time visitors may have encountered rules and color codes that did not match those used in their home communities.

Overall, while the single-group pre–post design prevents strong causal conclusions, the present pattern is consistent with the idea that brief, situated VR training may support sustainability-relevant behavior

during infrastructure transitions that require users to learn and apply new, context-specific procedures. Therefore, the main contribution of the study is not to establish that VR is uniquely effective, nor to demonstrate a definitive psychological mechanism. Rather, the study provides field-based evidence that VR training was followed by improvements in rule knowledge, task-specific self-efficacy, and intentions, and offers preliminary evidence that self-efficacy gains may be more consequential when they are accompanied by objective learning. This interpretation remains bounded by the single-group pre–post design, the absence of behavioral outcomes, and the small incremental variance explained by the moderation effect.

7. Practical implications

These findings extend mostly laboratory-based evidence by suggesting that VR may be valuable not only for raising awareness, but also for supporting behavioral adaptation during real infrastructural changes, such as when organizations introduce new rules or redesigned systems that require people to update familiar routines. Consistent with prior work, immersive environments can enhance procedural knowledge and environmental self-efficacy by helping users translate abstract awareness into concrete action [12,54–57].

Importantly, the moderation results imply that training should ensure *sufficient learning* (not just engagement). Interventions may therefore benefit from incorporating brief checks, adaptive practice, or “practice-until-correct” loops that continue until users demonstrate adequate rule knowledge, making self-efficacy gains more likely to support downstream intentions. More broadly, VR may be particularly well suited for settings in which the main challenge is practical: helping users understand how to behave correctly under updated rules.

From an applied perspective, such interventions may be most justified in contexts where incorrect sorting has practical consequences, such as contamination of recycling streams, increased correction work for staff, or confusion during the rollout of new disposal systems. In these settings, a brief VR training may complement signage by allowing users to make mistakes in a simulated environment rather than at the actual collection point.

8. Limitations and future directions

While running this study in the field increases ecological validity, it also comes with important limitations. First, we used a pre–post design with no comparison group, so we cannot make strong causal claims about the specific effect of the VR training. The observed improvements might partly reflect demand characteristics, novelty, repeated testing, or a general engagement effect of participating in a sustainability-focused activity. This issue may be particularly relevant in an eco-resort, where sustainability-related cues and pro-environmental norms were salient and participants were exposed to a context in which sustainability-related initiatives were highly visible. At the same time, the single-group design was largely due to practical constraints associated with conducting the study in an active vacation setting during the real rollout of a new recycling infrastructure. In this context, random assignment to a no-training or alternative-training condition would have created a high risk of treatment diffusion, because guests could interact with one another or share information about the task. Moreover, because the resort was actually introducing a new waste-sorting system, it would have been difficult to provide the training to some guests but not to others only for research purposes.

Future studies should therefore include comparison conditions designed to isolate the added value of VR. Possible control tasks could include a short informational video, a non-immersive desktop version of the same sorting task, or an interactive quiz with feedback matched to the VR condition in duration and informational content. Such designs would make it possible to test whether immersive, first-person practice provides benefits beyond exposure to the same rules and feedback in less

immersive or lower-cost formats. Future studies should also include direct measures of recycling motivation, environmental identity, prior recycling habits, and familiarity with local sorting systems. Although the present intervention was framed around procedural uncertainty during an actual infrastructure change, these measures would make it possible to distinguish more clearly between motivational barriers, habitual barriers, and procedural uncertainty.

Second, intentions were self-reported, and we did not measure actual sorting behavior. We avoided behavioral measurement because it would have required placing a waste station near the testing area, making bin colors and labels highly visible and potentially boosting knowledge in an artificial way. Future work should test whether the gains observed here translate into objectively measured sorting accuracy in settings where these cues can be better controlled, and whether effects last over time.

Third, some measurement limitations should also be acknowledged. To keep the procedure short and feasible in a vacation context, some constructs were assessed with ad hoc items or brief/adapted versions of existing scales. This may have reduced reliability and limit coverage compared to full instruments. Some of the scales showed modest internal consistency, which may partly reflect the use of brief instruments and, in the case of self-efficacy, an ad-hoc item set tailored to the resort context. Future research should therefore consider longer or multidimensional instruments to better capture the underlying constructs.

Fourth, our conditional process model used difference scores and was powered for the planned moderation, but not for more complex multi-level specifications (e.g., random slopes). Finally, participation was voluntary in a leisure setting, so self-selection may limit generalization to less engaged populations.

Finally, A further limitation concerns heterogeneity in participants' prior exposure to recycling cue–rule mappings. Because the resort's redesigned system was aligned with the municipal sorting standard, first-time visitors may have encountered a color-coding scheme that was more or less similar to the one used in their home communities. We did not measure or model this compatibility (beyond country of origin), which may contribute to variability in baseline rule knowledge and learning gains.

Future studies should therefore (a) include a control group, (b) add follow-up assessments (e.g., 2–7 days later) to test whether rule knowledge and self-efficacy are retained, (c) test design features that maximize learning (e.g., adaptive difficulty), given that knowledge gains appeared to be an important condition for self-efficacy gains to translate into stronger intentions in the present results, (d) assess perceived familiarity with the local color-code scheme or prior exposure to similar sorting systems, to test whether VR-based mastery training is especially beneficial when cue–rule mappings are less familiar and (e), because the present study did not compare VR with lower-cost alternatives, future research should directly examine whether VR provides added value over printed instructions, signage, videos, or interactive quizzes, also considering implementation costs and scalability.

9. Conclusions

In a real-world eco-resort undergoing a concrete change in waste-sorting infrastructure, a brief gamified VR training was followed by clear pre–post improvements in objective knowledge of the new rules, task-specific self-efficacy, and intentions to sort waste correctly. However, future studies with a comparison condition are needed to determine whether these gains are due to VR-specific features rather than general engagement or repeated measurement. In addition, the moderation analysis suggested that increases in self-efficacy were more strongly related to increases in intentions when participants also showed larger learning gains. Given the small incremental variance explained by the interaction, this finding should be interpreted as preliminary evidence that confidence may translate into stronger commitment when supported by rule knowledge. Overall, these findings point to VR as a promising applied tool for sustainability interventions that aim to help

people act correctly under new rules, by building practical knowledge and strengthening task-specific confidence through realistic, low-risk practice. If replicated, this approach could offer a simple, scalable way to support everyday sustainable action when real-world systems change.

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Patient consent statement

Participants for all studies provided informed written consent before study enrollment.

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No copyrighted material will be used in the present work.

Generative AI Usage Disclosure

During the preparation of this work, the authors used ChatGPT and DeepL exclusively to refine the English language and enhance the fluidity of certain sentences in this document. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRedit authorship contribution statement

Alessandro Gabbiadini: Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Tommaso Berni:** Writing – review & editing. **Anna Manfredi:** Writing – review & editing. **Giulio Puzella:** Writing – review & editing. **Laura Zapparoli:** Writing – review & editing, Formal analysis.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.sfr.2026.102163](https://doi.org/10.1016/j.sfr.2026.102163).

Data availability

data are available on OSF https://osf.io/k2azw/overview?view_only=3b8317f0245b487aa13596118916393a

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