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A randomized controlled trial investigating experiential virtual reality communication on prudent antibiotic use

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Antimicrobial resistance (AMR) is a global health threat. This randomized controlled trial evaluates the impact of experiential virtual reality (VR) versus information provision via VR or leaflet on prudent antibiotic use. A total of 249 (239 analyzed) participants were randomized into three conditions: VR Information + Experience, VR Information, or Leaflet Information. All participants received AMR information, while those in the VR Information + Experience condition additionally engaged in a game, making treatment decisions for their virtual avatar's infection. Participants in the VR Information + Experience condition showed a significant increase in prudent use intentions from baseline (d = 1.48). This increase was significantly larger compared to the VR Information (d = 0.50) and Leaflet Information (d = 0.79) conditions. The increase in intentions from baseline remained significant at follow-up in the VR Information + Experience condition (d = 1.25). Experiential VR communication shows promise for promoting prudent antibiotics use.

Antimicrobial resistance (AMR) occurs when microorganisms, such as bacteria, viruses, and parasites, stop responding to antimicrobial medicine, resulting in antibiotics not being effective in treating infections. In 2019, AMR was attributed to 4.95 million deaths worldwide[1]. Projections indicate that, without decisive action, AMR is expected to cause 10 million deaths a year by 2050[2], positioning AMR as a major threat to public health[3]. Despite AMR being a complex issue with diverse causes, the role of behavioral drivers is well acknowledged[4]. A primary driver is the overreliance on antibiotics in primary care through inappropriate prescribing by clinicians and mis- and overuse by patients, including the use of leftover antibiotics[5]. The issue can be further exacerbated by patient demand for antibiotics and the availability of over-the-counter antibiotics in some countries[5].

Therefore, fighting the spread of AMR requires changing people's knowledge and attitudes related to AMR, eventually reducing inappropriate antibiotic use. However, there is a lack of research developing novel ideas for theory-informed and yet innovative behavioral interventions in the context of antibiotic use. Testing their effectiveness as well as the underlying psychological processes in randomized controlled trials is crucial for the effective mitigation of AMR spread[6]. Contributing to close this research gap, we rigorously investigate the effectiveness of a novel approach—experiential communication in Virtual Reality (VR)[7]—to promote intentions of prudent antibiotic use in the general public.

Whereas current public campaigns addressing antibiotic use are usually limited to information provision via leaflets, posters, or television and radio spots[8,9], scholars have called for a more comprehensive behavioral change perspective when designing educational AMR interventions[10]. Relatedly, although some studies aim to provide detailed insights into people's perceptions and attitudes towards antibiotics use, they often lack appropriate research designs that allow drawing causal inferences on the effectiveness of interventions addressing these psychological insights[8,11]. Furthermore, many campaigns adopt a one-size-fits-all approach, targeting both the general public and clinicians simultaneously, even though these groups differ substantially in their knowledge and attitudes regarding AMR[12,13].

Here, we address all of these issues to help overcome the associated limitations. First, we utilize VR to develop a theory-informed educational AMR intervention that promotes behavioral change. Established theoretical frameworks such as the Protection Motivation Theory[14] and the Extended Parallel Process Model[15] have proven successful in health promotion campaigns[16]. Key components of these approaches include threat appraisal—comprising perceived severity and vulnerability to the threat—and coping appraisal, which involves response efficacy, i.e., perceived effectiveness of the coping behavior to reduce the threat, and self-efficacy, i.e., perceived ability to perform the coping behavior. These elements play a central role in driving behavioral change after exposure to persuasive messages. However, threat and coping appraisals are often regarded as experiential parts of our reasoning, relying on intuition and emotions rather than probability analysis or formal logic[17,18]. Previous

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studies have shown that both threat appraisal[17] and coping appraisal[18] are relatively resistant to change via information-based interventions and verbal persuasion but are more responsive to imagery[18] or virtual experiences[19].

VR is a particularly promising tool for experiential communication. VR has been recognized as a crucial tool in global health promotion, offering immersive, hands-on experiences[7,20], including the investigation of practitioners' reactions to patients' demands for antibiotics[21]. VR elicits a profound sense of presence—the feeling of being in the simulated environment—and agency, where users feel in control of their actions[22]. By immersing individuals in a first-person perspective through avatars, VR facilitates a deeply emotional and visceral engagement with content, enabling a realistic mastery experience[23]. These characteristics of VR make it a powerful tool for experiential communication, especially when behavioral theories inform the design. Unlike standard communication methods such as leaflets or virtual doctor visits, VR experiential communication can provide a direct experience of the consequences of personal actions on one's health (e.g., certain treatment decisions) by incorporating elements such as time progression or gamification. For instance, individuals can experience a series of simulated infections, make choices on how to treat them with antibiotics, and observe the diminishing effectiveness of antibiotics over the course of the simulation. In contrast to receiving factual information about the urgency of AMR, individuals in VR can have a vicarious experience of responsibly treating the infection. Previous research has demonstrated that immersive VR experiences informed by behavioral change theories[7] can effectively stimulate behavioral change by enhancing both coping[24] and threat[25] appraisals compared to traditional information provision. Although digital AMR communication using mobile phones and websites has yielded some positive results[26], to the best of our knowledge, immersive virtual reality using VR has not been used as a communication tool in this context yet. Examining the impact of VR as a health communication medium is particularly relevant in anticipation of the forthcoming metaverse, the next stage of the internet. The metaverse will introduce novel avenues for mass communication, making it crucial to understand the potential role and effectiveness of VR in mitigating societal challenges[7].

Second, our randomized controlled trial utilizes several measures and intervention conditions that allow gaining insights into the potential (causal) mechanisms that underlie the effects of educational interventions. Specifically, following the Protection Motivation Theory[14], we measure not only participants' behavioral intention of prudent antibiotics use but also assess both threat and coping appraisal in order to capture how the different intervention conditions affect participants' perceptions and attitudes. Additionally, we test three different interventions against each other, all of them providing the same information regarding AMR. As only two of these conditions were conducted using VR, whereas the third one was displayed on a tablet, we can causally isolate the effect of the communication medium. Both VR conditions involved a virtual doctor's explanation of the AMR risks, while only the experiential VR condition applied elements of experiential communication. Adding a gamified experience to the simulation in one of the two VR conditions can further identify the causal impact of experiential communication on intended antibiotic use over and above mere information provision on AMR.

Third, our intervention explicitly targets young adults from the general public. Experiential learning through immersive VR not only attracts young populations with its gamified elements[27] but also facilitates an intuitive understanding of complex knowledge through "learning by doing,"[20] even for a lay audience[7]. Several studies have highlighted that both the patients' expectations of getting prescribed antibiotics and the clinicians' assumptions that the patient expects to receive antibiotics play a crucial role in (inappropriate) prescriptions of antibiotics[12,28]. Moreover, as the consequences of antibiotics overuse are delayed[29], young adults are especially affected by increasing AMR. Therefore, promoting prudent antibiotics use in young adults may improve their own (future) welfare.

Results

The recruitment of participants took place between the 23rd of May 2023 and the 27th of October 2023. A total of 245 participants were recruited for the trial and randomly assigned to the intervention conditions (Fig. 1). That is, 85 (35%), 80 (33%), and 80 (30%) participants were assigned to the VR Information + Experience condition, the VR Information condition, and the Leaflet Information condition, respectively. Of these participants, 239 were included in the main analysis, as 4 participants reported maximum intentions of prudent antibiotics use before the intervention, and 2 participants experienced technical difficulties that prevented them from finishing the post-intervention survey.

Overall, the intervention conditions were well-balanced with respect to baseline intentions and demographic characteristics (Table 1) except for the baseline experience with VR, where the Leaflet Information condition had disproportionately fewer VR naive participants (30%) compared to the VR Information (43%) and VR Information + Experience (52%) conditions. Given that the participants in the Leaflet Information condition, who were more experienced with VR, were not treated with VR, this difference is negligible for the reported effects.

Effect of the intervention on post-survey intentions of prudent antibiotics use

Our main analysis focuses on the effect of the intervention conditions on our main outcome measure: intentions of prudent antibiotics use. The change in intention from baseline to post-intervention and follow-up across different intervention conditions is depicted in Fig. 2. As hypothesized, the VR Information + Experience condition led to a significant increase in intentions in the post-intervention survey ($M = 4.60$, $SD = 0.35$) compared to the baseline survey ($M = 3.90$, $SD = 0.58$), $\Delta M = 0.71$, 95% CI [0.81, 0.60], $t(81) = 13.35$, $p < 0.0001$, with a large effect size, $d = 1.48$, 95% CI [1.13, 1.82].

A mixed ANOVA revealed a significant main effect of time on the post-intervention intentions, $F(1, 236) = 273.30$, $p < 0.0001$, $\eta_p^2 = 0.19$, and a significant interaction effect between time and condition, $F(2, 236) = 7.45$, $p = 0.0007$, $\eta_p^2 = 0.013$. As hypothesized, post-hoc independent t-tests indicated that the participants of the VR Information + Experience condition reported significantly higher intentions of prudent antibiotics use in the post-intervention survey ($M = 4.60$, $SD = 0.35$) compared to the participants in the Leaflet Information condition ($M = 4.23$, $SD = 0.56$), $\Delta M = 0.37$, 95% CI [0.22, 0.52], $t(127.83) = 4.97$, $p < 0.0001$, with a medium effect size, $d = 0.79$, 95% CI [0.47, 1.12]); and also compared to the participants in the VR Information condition ($M = 4.38$, $SD = 0.5$), $\Delta M = 0.22$, 95% CI [0.08, 0.35], $t(139.63) = 3.18$, $p = 0.0018$, with a medium effect size, $d = 0.50$, 95% CI [0.19, 0.82]. See Supplementary Results 1 for the effects of VR Information and Leaflet Information conditions on post-intervention intentions.

Effect of the intervention on follow-up intentions of prudent antibiotics use

As further expected, the intervention effect remained stable over time, as the paired t-test revealed a significant increase in intentions from the baseline survey ($M = 4.60$, $SD = 0.35$) to the follow-up survey in the VR Information + Experience condition ($M = 4.56$, $SD = 0.39$), $\Delta M = 0.67$, 95% CI [0.55, 0.79], $t(78) = 11.09$, $p < 0.0001$, with a large effect size, $d = 1.35$, 95% *CI* [1.00, 1.70]).

We further investigated the impact of conditions on follow-up intentions. A mixed ANOVA with time (baseline vs. follow-up) and intervention condition as predictors confirmed a significant main effect of time on intentions, $F(1, 224) = 145.49$, $p < 0.0001$, $\eta_p^2 = 0.16$, and a significant interaction effect between time and condition, $F(2, 224) = 6.42$, $p = 0.0020$, $\eta_p^2 = 0.02$. Post-hoc independent t-tests confirmed our hypothesis that in the follow-up survey, participants of the VR Information + Experience condition reported higher intentions compared to the participants of the Leaflet Information condition, ($M = 4.15$, $SD = 0.65$), $\Delta M = 0.41$, 95% CI [0.24, 0.58], $t(117.75) = 4.70$, $p < 0.0001$, with a medium effect size, $d = 0.77$,

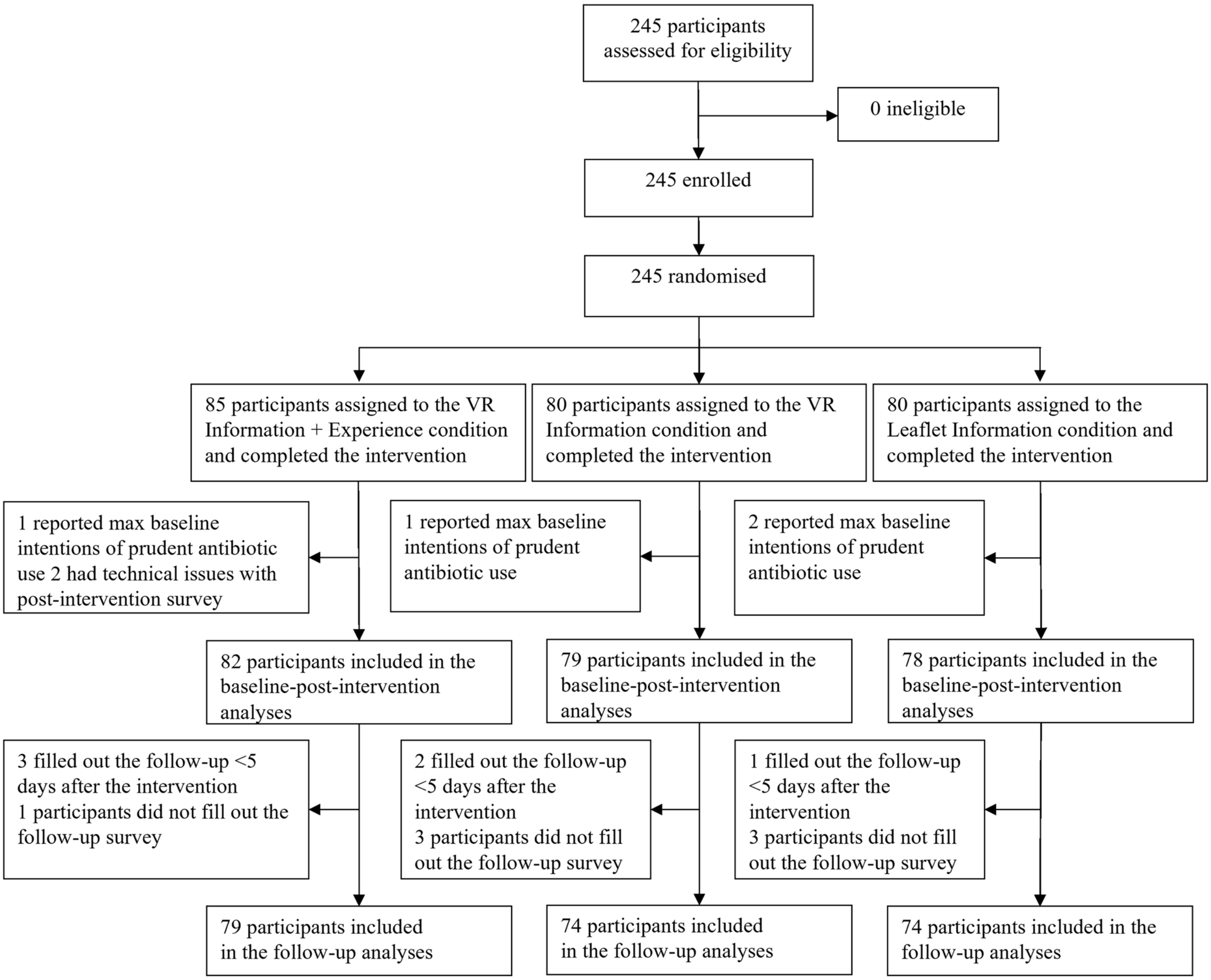

Fig. 1 | Trial profile. The diagram shows a schematic illustration of the allocation and flow of participants in the study.

Table 1 | Baseline sample characteristics by intervention condition

		VR Information + Experience ($n = 82$)	VR Information ($n = 79$)	Leaflet Information ($n = 78$)
Age		22.6 (5.57)	22.0 (5.11)	21.7 (3.54)
Gender	Men	21 (26%)	23 (29%)	26 (33%)
	Women	59 (72%)	54 (68%)	50 (64%)
	Non-binary	2 (2%)	1 (1%)	2 (3%)
	Not stated	0 (0%)	1 (1%)	0 (0%)
Intentions		3.90 (0.58)	3.84 (0.68)	3.84 (0.66)
Experience with virtual reality	Never	43 (52%)	34 (43%)	23 (30%)
	Once	23 (28%)	31 (39%)	22 (28%)
	2–5 times	9 (11%)	9 (11%)	28 (36%)
	5–10 times	6 (7%)	1 (1%)	2 (3%)
	>10 times	1 (1%)	4 (5%)	3 (4%)
Baseline AMR knowledge		7.88 (3.44)	7.92 (4.21)	8.10 (3.39)
Honesty–humility		28.4 (5.70)	27.2 (4.81)	27.3 (5.49)

95% CI [0.44, 1.10]). As further hypothesized, the participants of the VR Information + Experience condition also reported higher intentions in the follow-up survey compared to the participants in the VR Information condition ($M = 4.39$, $SD = 0.56$), $\Delta M = 0.17$, 95% CI [0.01, 0.32], $t(128.67) = 2.11$, $p = 0.0370$, with a small effect size, $d = 0.35$, 95% *CI* [0.02, 0.67]). See Supplementary Results 1 for the effects of the VR Information and Leaflet Information conditions on the follow-up intentions.

Effect of the intervention on donations

Analysis of the amount donated to an AMR-related charity revealed no significant differences between the VR Information + Experience condition ($M = 3.88$, $SD = 1.83$), the VR Information condition ($M = 3.64$, $SD = 1.95$), and the Leaflet Information condition ($M = 3.79$, $SD = 1.88$), $F(2, 235) = 0.32$, $p = 0.7257$, $\eta_p^2 = 0.003$, 90% CI [0.00, 0.02]. Furthermore, there was no significant correlation between the amount donated and change in intentions from baseline to post-intervention survey, $r = 0.02$, 95% *CI* [−0.10, 0.15], $t(236) = 0.13$, $p = 0.7072$, indicating that the two measures captured conceptually distinct constructs and, thus, going against our hypotheses. As a robustness check, we completed all the confirmatory analyses on the complete sample, including the participants with maximum baseline intentions, and the interpretations and conclusions of the results remain unchanged; for details, see Supplementary Results 2.

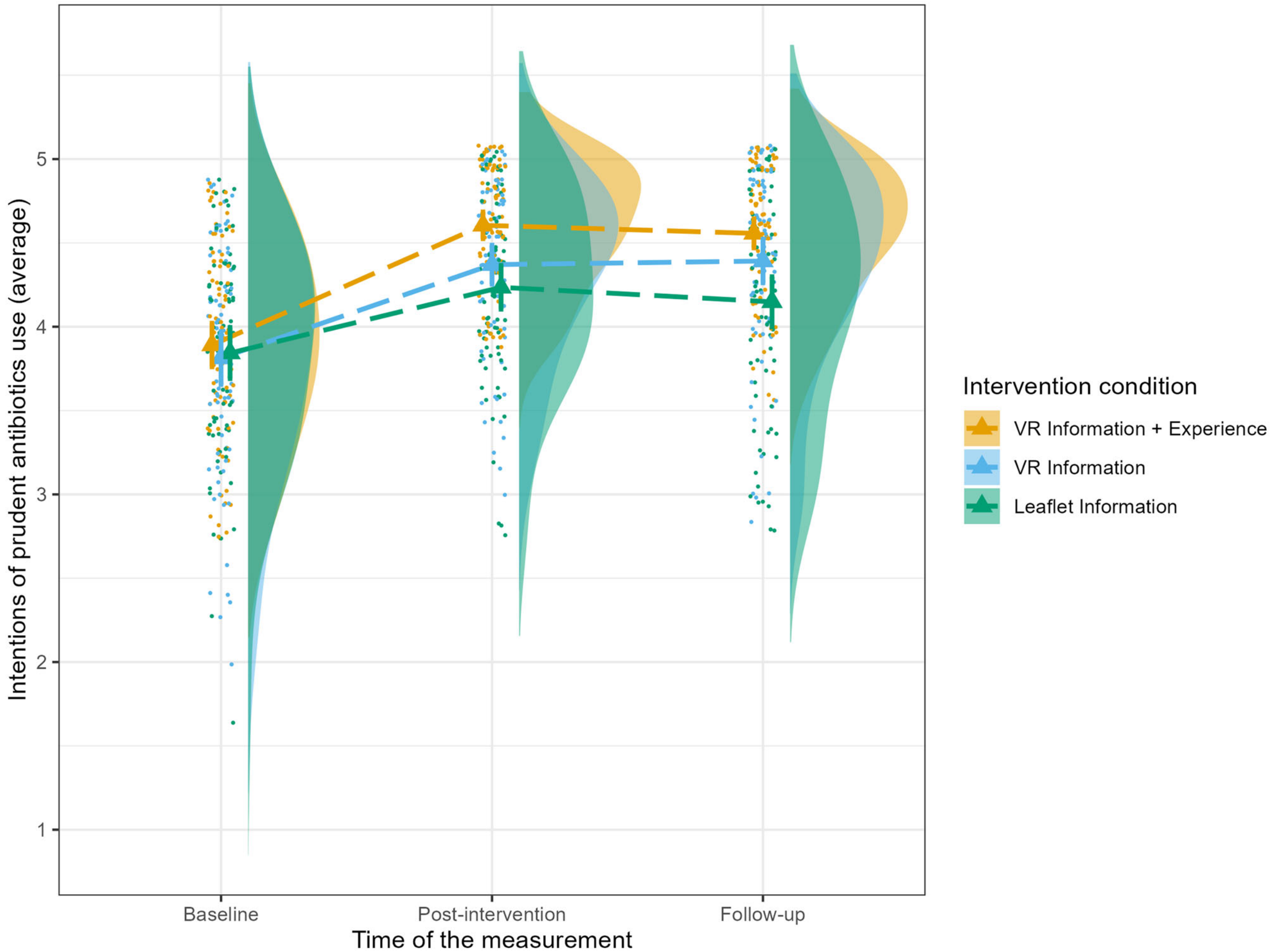

Fig. 2 | Intentions of prudent antibiotics use by intervention condition across measurements over time. Dots indicate single data points, triangles represent means, and error bars indicate 95% confidence intervals.

Exploratory analyses

To further shed light on the underlying mechanisms of the interventions on the intentions of prudent antibiotics use, we ran an exploratory mediation analysis with coping appraisal and threat appraisal as mediators of the effect of VR Information + Experience condition (vs. VR Information and Leaflet Information conditions coded as 0) on intentions measured in the post-intervention survey while controlling for baseline survey intentions. The analysis revealed that the effect of VR Information + Experience condition on intentions was partially mediated by coping appraisal (unstandardized coefficient = 0.05, 95% CI [0.02, 0.10]) but not by threat appraisal (unstandardized coefficient = 0.00, 95% CI [−0.02, 0.02]); see Supplementary Table 1 for details. For additional exploratory analyses of differences between conditions and moderation effects, please refer to Supplementary Results 3 and 4.

The adverse effects of the VR interventions were very low, with only one participant (VR Information condition) reporting a severe headache. The participants did not report any other severe symptoms. Four (2%) and thirty (13%) participants reported moderate and mild headaches. Two (1%) participants reported moderate nausea, and 13 (5%) reported mild nausea. Additionally, two (1%) participants and 44 (18%) reported moderate and mild dizziness, respectively.

Discussion

In this study, we evaluated the effectiveness of experiential AMR communication in VR to promote prudent antibiotic use, comparing it with mere information-based VR and leaflet communication. To the best of our knowledge, this is the first study investigating the effectiveness of VR as an intervention promoting intentions for prudent antibiotic use. Our results are promising, demonstrating that all three interventions enhance intentions of prudent antibiotic use despite their short duration. Notably, the VR Information + Experience condition had a significantly greater effect on immediate and delayed intentions compared to the VR Information and Leaflet Information conditions. This suggests that the VR Information + Experience effect goes beyond mere exposure to information or immersive technology, indicating that gaining personal experience with the long-term effects of antibiotics (over)use on AMR may be particularly helpful in promoting intentions of prudent antibiotics use. Furthermore, the observed intervention effect of the VR Information + Experience condition persisted in the follow-up survey several days after the intervention exposure.

The VR Information + Experience intervention presented in this study was developed based on behavioral change theories, specifically targeting participants' threat and coping appraisal[14,15]. More precisely, the intervention design allowed participants to experience the diminishing effectiveness of antibiotics over the course of a simulated lifetime and witness the consequences of their choices regarding antibiotics use from a first-person perspective. This approach aimed to personalize the threat of AMR, making it more tangible and manageable through responsible antibiotics usage. In addition to the causal evidence that experiencing the negative long-term consequences of

AMR increases the intention of prudent antibiotics use, we found exploratory evidence for the role of increased coping appraisal in intention shifts. These findings underscore the importance of experiential communication in promoting coping appraisal, aligning with the notion that coping appraisal requires more experiential and emotional processing to induce behavioral change[23,24]. Additionally, our findings further support the assumption that mastery experiences, which can be simulated in VR[24], serve as a crucial source of self-efficacy[23]. Nevertheless, despite our predictions, we found no differences between the intervention conditions in participants' donations.

One of the limitations of the presented trial lies in our secondary outcome measure: donations to the AMR-related charity. Despite this measure being commonly used in social sciences to capture tradeoffs between personal and collective benefits, previous studies showed that diverse factors influence charitable giving[30]. Therefore, this measure might not reliably reflect participants' antibiotic-related behavior. As donations were not related to intentions of prudent antibiotic use, these outcomes seem indeed to be triggered by different psychological processes, aligning with previous findings[31]. Another limitation of this study is the lack of a real-life measure focused on antibiotics use itself. Intentions were used as a proxy of the actual health behavior despite some findings indicating that intentions do not always align with actions[32]. Nevertheless, intentions can be considered the strongest psychological predictor of actual behavior[33]. Therefore, observed differences between intervention conditions and their stability over time are likely to be reflected in participants' real-life choices as well. Furthermore, the primary measure of intentions showed only a marginal level of internal consistency, likely due to the effort to capture various facets of the construct, such as the use of only prescribed antibiotics and the ability to abstain from antibiotics during mild infections. Lastly, investigating the effectiveness of the interventions with patients or their family members would provide valuable insights into the effectiveness of the interventions even during the presence of symptoms that might affect their antibiotic-related decisions. Although we intended to target healthy young adults, future research with more diverse samples (e.g., regarding education, age, or medical status) should test the findings' generalizability.

Despite these limitations, the findings have important implications for future AMR communication. We present compelling evidence that experiential communication, guided by behavioral change theory, can yield significantly superior results in terms of patients' intentions compared to traditional information provision campaigns. These results suggest complementing standard campaigns with more experiential and emotionally resonant communication methods to address the behavioral drivers of AMR effectively. The positive impact of all tested interventions, especially with the effectiveness of the VR Information surpassing the Leaflet Information condition and the VR Information + Experience condition exceeding the VR Information condition, suggests encouraging avenues for mitigating AMR through diverse strategies such as information provision, telemedicine, and experiential communication.

Immersive solutions, easily deployable in clinician's waiting rooms, offer an engaging format capable of capturing patients' attention. Moreover, the mass-media, identified by Finch and colleagues in 2004 as a potent source[10], continues to play a crucial role in disseminating interventions. While television was once the single most effective mass-media source, the internet has since taken over its role. Looking ahead, the metaverse—a hypothesized iteration of the internet relying on extended reality (XR)—is expected to introduce immersive communication channels, with 25% of people spending at least 1 hour daily in the metaverse by 2026[34]. This anticipated surge in immersive technologies presents an opportunity to leverage not only current online communication but also future immersive communications and telemedicine to amplify behavioral change through AMR communication campaigns. The current study presents promising results in this regard.

Methods

Study design

The study was conducted as a parallel randomized controlled trial to assess the effectiveness of experiential Virtual Reality in promoting prudent antibiotic use. The study's hypotheses, method, sample size, and analysis plan were preregistered via the Open Science Framework on the 22nd of May, 2023 under DOI: 10.17605/OSF.IO/A3Z6Q. The preregistration protocol can be accessed here: https://osf.io/a3z6q. The study was conducted at the University of Vienna, Austria, and approved by the Departmental Review Board of the Department of Occupational, Economic, and Social Psychology, University of Vienna, approval number 2023/W/012. Informed consent was obtained from all participants. The study followed the Consolidated Standards of Reporting Trials[35], and the CONSORT Checklist can be accessed in Supplementary Table 8.

Participants

As the target group was young adults, the majority of the participants were university students who signed up for the study via the university's internal recruitment platform. Additionally, 11 participants were recruited from outside the sample of students on the recruitment platform. This was done via ads on Facebook and the website of the Austrian National Union of Students, as well as through flyers and snowball sampling. Only participants over 18 years of age could participate. The participants reporting maximum intentions of prudent antibiotic use already in the baseline assessment were excluded from the analyses according to the trial protocol. The participants self-reported their gender in the survey, selecting from four options: male, female, non-binary/third gender, and prefer not to state.

Randomization and masking

Different conditions were assigned to different timeslots using a random number generator. All participants were assigned to one of the three intervention conditions: VR Information + Experience, VR Information, and Leaflet Information. Participants were masked as to which aspects of the intervention were varied. Trial administrators generated the allocation, enrolled the participants, and administered the interventions. Trial administrators and personnel analyzing data were not blinded.

Procedures

All the participants were invited to a dedicated timeslot based on their personal preferences. The study was conducted in a behavioral laboratory room with a maximum of two participants simultaneously, and the intervention was administered by research assistants trained in VR administration. All materials were provided in German language. Before the beginning of the intervention, participants read and signed an informed consent and completed a baseline survey on a tablet or smartphone by scanning a QR code. Participants in VR conditions completed the intervention using a VR headset (Meta Quest 2), while the intervention was embedded in the pre-post questionnaire for participants in the Leaflet Information condition. The intervention stimuli are available from the OSF study repository.

The provided information about AMR causes, impact, and management based on the World Health Organization (WHO) fact sheet and educational pamphlets[3] was identical across the intervention conditions. While the provided information in all conditions followed the Protection Motivation Theory (PMT) by communicating both the threat and coping appraisals in describing the consequences and management of AMR, the VR Information + Experience condition targeted experiential processing by offering participants a direct, immersive experience of the consequences of health-related decisions regarding antibiotic use. The conditions differed as follows:

Leaflet information condition. The text-and-picture pamphlet was embedded in the baseline and post-intervention survey. Completion took

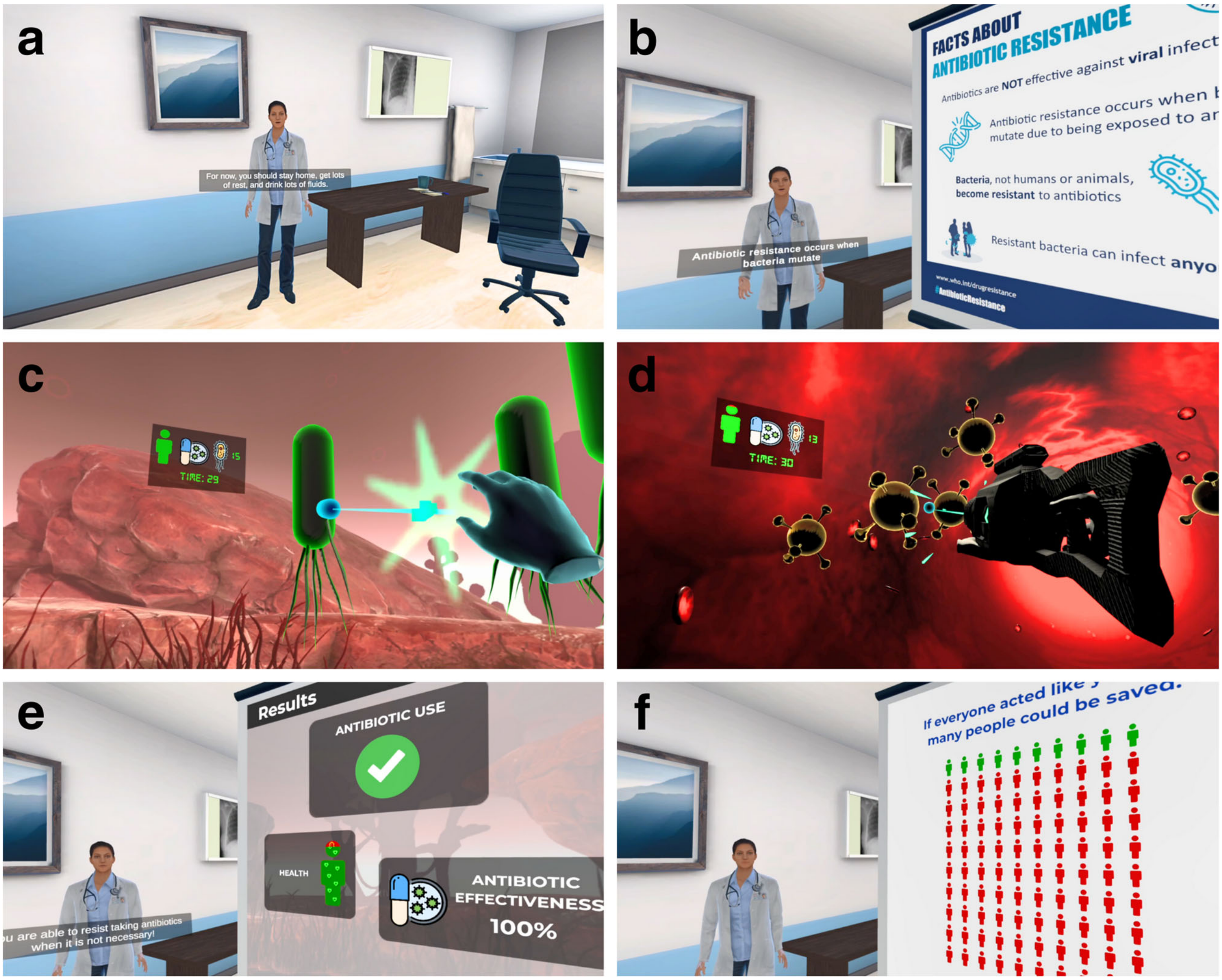

Fig. 3 | Screens from the VR simulations. The simulation started in a doctor's office where the participant received information about a hypothetical infection (**a**), followed by information about antibiotic resistance, its causes, management, and impact (**b**). In the VR Information + Experience condition, the participants engaged in five rounds of a one-person shooter game, where they made a choice to either rely on their immune system (**c**) or use antibiotics (**d**). After each round, the participant received feedback about their performance with regard to health and antibiotic effectiveness (**e**), and how their choices could impact future generations (**f**).

about two minutes. The intervention materials can be accessed via the OSF study repository (https://osf.io/a53cx).

VR information condition. The participants were immersed in a virtual doctor's office (Fig. 3) and received the same information about AMR and its management as in the Leaflet Information condition. Completion took about four minutes. The video footage of the simulation can be accessed via the OSF study repository (https://osf.io/m5zgy).

VR information + experience condition. The experience consisted of a virtual doctor visit and an educational game. The participants were first immersed in the same virtual doctor's office as in the VR information condition and received the same information. Additionally, they engaged in a five-round educational game using VR controllers. During the game, they experienced scenarios involving mild or severe bacterial infections, where they had to make decisions on whether to treat the infections with antibiotics or rely on their immune system. Implemented as a first-person shooter game (Fig. 3), participants experienced a gradual decline in the effectiveness of antibiotics over the simulated lifetime and faced the consequences of their choices regarding antibiotic use. Most participants correctly used the antibiotics only for severe infections as instructed by the virtual doctor, i.e., receiving five points for five correct decisions to use ($Med = 5$, $IQR = 1$). Completion took about 22 minutes. The video footage of the simulation can be accessed via the OSF study repository (https://osf.io/3twhv).

Immediately after the intervention, all participants completed the post-intervention survey on a tablet or smartphone. Afterward, each participant was left in a room with a marked envelope (with their ID) containing 5 euros. They were instructed to take how much they wanted or leave it in the envelope to be donated to a charity fighting AMR (One Health Trust). Five days after the intervention, all participants received the invitation for a follow-up survey via email.

Outcomes

The primary outcome of our intervention was the participant's intentions of prudent antibiotics use. Intentions were measured with five items, such as "*I will be critical about just taking antibiotics when they are prescribed.*" (Cronbach's $\alpha = 0.64$). Responses were given on a five-point scale ranging from 1 = "Strongly disagree" to 5 = "Strongly agree." Intentions were measured immediately before the intervention (baseline survey), immediately after the intervention (post-intervention survey), and at least five days after the intervention (follow-up survey).

The secondary outcome was donations to a charity fighting AMR (One Health Trust), aimed at capturing objective behavior involving personal cost and collective benefit tradeoffs. To reduce socially desirable responses, participants were left in the room with an envelope containing 5 euros as a reward for their participation. They could decide how much they would like to donate to a charity by leaving the amount in the envelope.

Additionally, we assessed the following measures for exploratory purposes, for which we provide the exact items and response scales in Supplementary Table 9. First, due to the prosocial nature of prudent antibiotic use, i.e., the use of antibiotics minimizes the immediate risk for the individual but might have negative consequences for society[36], in the baseline survey, we assessed participants' Honesty–Humility from the HEXACO personality model previously linked to prosocial behavior[37]. For this, we used the 10 items from the German version of the HEXACO-60. Furthermore, participants' existing knowledge about AMR and experience with VR was assessed. Second, in the post-intervention and follow-up survey, we measured participants' threat and coping appraisal as well as factual and conceptual knowledge. In the post-intervention survey, we only assessed participants' agency and motivation. Additionally, we assessed participants' physical and social presence in the VR conditions. To measure adverse events, we assessed the level of cybersickness (headache, dizziness, nausea) among participants completing one of the VR interventions.

Statistical analysis

An a-priori power analysis indicated that a minimum of 158 participants would be needed to achieve a power of $1-\beta = 0.80$ for detecting a medium effect size difference ($f = 0.25$) between the intervention conditions. To account for potential dropouts and preregistered exclusions, we aimed to collect data from 200-250 participants.

Paired sample *t*-tests (two-sided) were employed to examine baseline-post changes in intentions (Hypothesis 1 according to the preregistration protocol) and baseline-follow-up changes (Hypothesis 6). Mixed ANOVA, with time as a within-participants predictor and intervention condition as a between-participant predictor, and independent *t*-tests were utilized to investigate differences between the conditions in terms of post-intervention (Hypotheses 2–3) and follow-up intentions (Hypotheses 7–8). Independent sample *t*-tests (two-sided) were employed as post-hoc tests to examine differences in intentions. Cohen's *d* was used to estimate the effect size for sample *t*-tests by dividing the mean difference between groups by the pooled standard deviation. One-way ANOVA was adopted to explore differences in donations between intervention conditions (Hypothesis 5). Pearson correlation coefficient was used to assess the relationship between the change intentions of prudent antibiotics use (baseline-post differences) and the amount donated (Hypothesis 4).

Additionally, exploratory mediation analyses explaining the observed effects of conditions on the main outcome variable were conducted using the PROCESS for R, Version 4.0.1. Indirect effects were tested for significance through bootstrapping procedures, computing unstandardized indirect effects using 10,000 bootstrapped samples and 95% confidence intervals determined by the 2.5th and 97.5th percentiles. All analyses were performed using the R software, version 4.3.2. The main analysis inclusion criteria involved participants who completed the intervention as well as baseline- and post-surveys, while follow-up analyses included participants who also completed the follow-up survey. There was no data monitoring committee.

Changes to the protocol

Changes to the protocol were implemented during the study, including the decision to expand the participant pool beyond bachelor's students of the University of Vienna to achieve the required sample size. In total, 11 participants were recruited from outside the campus. Additionally, a modification was made to the analysis approach: contrary to the initial plan of analyzing results for each intention item separately, if reliability fell below Cronbach's $\alpha = 0.7$, results are reported for the overall scale. This adjustment was made due to concerns that the single-item measure might inadequately capture different aspects of behavioral intentions. Nevertheless, analyses for each item separately are reported in the online Supplementary Tables 2–7.

Data availability

The datasets generated during and/or analyzed during the current study are available via the OSF repository https://osf.io/db7yh.

Code availability

The code generated and used during the current study is available via the OSF repository https://osf.io/db7yh/.

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A.P.: methodology, formal analysis, visualization, writing–original draft, writing–review & editing; G.M. and R.B.: conceptualization, methodology, resources, writing–original draft, writing–review & editing, supervision.

Competing interests

The authors declare no competing interests.

Additional information

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