



Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.



A self-administered virtual reality intervention increases COVID-19 vaccination intention



Aske Mottelson^{a,*}, Clara Vandeweerd^b, Michael Atchapero^c, Tiffany Luong^f, Christian Holz^f, Robert Böhm^{c,d,e}, Guido Makransky^c

^a Department of Digital Design, IT University of Copenhagen, Denmark

^b Department of Political Science, University of Copenhagen, Denmark

^c Department of Psychology, University of Copenhagen, Denmark

^d Faculty of Psychology, University of Vienna, Austria

^e Copenhagen Center for Social Data Science (SODAS), University of Copenhagen, Denmark

^f Department of Computer Science, ETH Zürich, Switzerland

ARTICLE INFO

Article history:

Received 9 July 2021

Received in revised form 2 October 2021

Accepted 4 October 2021

Available online 8 October 2021

Keywords:

Vaccination
Vaccine hesitancy
Vaccine advocacy
Virtual reality
COVID-19
Corona virus
Body ownership
Embodiment

ABSTRACT

Effective interventions for increasing people's intention to get vaccinated are crucial for global health, especially considering COVID-19. We devised a novel intervention using virtual reality (VR) consisting of a consultation with a general practitioner for communicating the benefits of COVID-19 vaccination and, in turn, increasing the intention to get vaccinated against COVID-19.

We conducted a preregistered online experiment with a 2×2 between-participant design. People with eligible VR headsets were invited to install our experimental application and complete the ten minute virtual consultation study at their own discretion. Participants were randomly assigned across two age conditions (young or old self-body) and two communication conditions (with provision of personal benefit of vaccination only, or collective and personal benefit). The primary outcome was vaccination intention (score range 1–100) measured three times: immediately before and after the study, as well as one week later.

Five-hundred-and-seven adults not vaccinated against COVID-19 were recruited. Among the 282 participants with imperfect vaccination intentions (< 100), the VR intervention increased pre-to-post vaccination intentions across intervention conditions (mean difference 8.6, 95% CI 6.1 to 11.1, $p < 0.0001$). The pre-to-post difference significantly correlated with the vaccination intention one week later, $\rho = 0.20$, $p < 0.0001$.

The VR intervention was effective in increasing COVID-19 vaccination intentions both when only personal benefits and personal and collective benefits of vaccination were communicated, with significant retention one week after the intervention. Utilizing recent evidence from health psychology and embodiment research to develop immersive environments with customized and salient communication efforts could therefore be an effective tool to complement public health campaigns.

© 2021 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The World Health Organization (WHO) has identified vaccine hesitancy as one of the ten biggest threats to global health [32]. Accordingly, effective interventions for decreasing vaccine hesitancy and, thus, increasing vaccination intentions are crucial for public health. Considering the COVID-19 pandemic, large-scale vaccination is of utmost importance to end the pandemic and its

associated social and economic costs. Most vaccinations provide a personal benefit to the vaccinated individuals as well as a collective benefit due to reducing the spread of pathogens by increasing community immunity [10]. Previous research suggests that communicating the personal or collective benefit of vaccination increases people's vaccination intention [7,11,15,27].

Motivating people to participate in effective health interventions is challenging. Immersive virtual reality (VR) has the potential to increase access to state-of-the-art health interventions [11,29], and provides an opportunity to engage the audience on terrain salient to them [11]. Using novel technology, such as VR, for vaccine advocacy may help by reaching particularly younger

* Corresponding author.

E-mail address: asmo@itu.dk (A. Mottelson).

people, who are more likely to be hesitant against COVID-19 vaccination [21], potentially due to a lower likelihood to suffer from a severe course of the disease [8].

As an illustration of this potential, Freeman et al. [11] showed encouraging results in using self-administered VR therapy for treatment of fear of heights. More recently, Nowak et al. [22] used VR to communicate the collective benefit of vaccination and found only weak evidence of attitude changes in a lab study. As the study had low statistical test power, the potential effectiveness of VR in vaccine advocacy for larger samples remains an open question.

Inducing illusory ownership of a virtual body is an effective paradigm for designing engaging and effective VR interventions that changes people's attitudes and behavior [1,17,23]. For instance, two studies from 2013 and 2016 showed a reduction in implicit racial bias following exposure to an immersive body illusion experience [2,23]. Banakou et al. [3] similarly reported a reduction in age bias following embodiment of an old avatar.

Building on the insights from vaccine advocacy and immersive technology, we developed a self-administered VR intervention effective for increasing people's intention to get vaccinated against COVID-19. We carried out an online VR study with a large number of participants. The primary goal of this study was therefore to investigate the effectiveness of a novel automated intervention strategy for decreasing vaccine hesitancy targeted at a young audience.

The results show that the VR intervention increased immediate vaccination intentions that sustained even one week after the study. As such, our study provides proof-of-concept of using VR as an effective tool for promoting vaccination intentions.

Digital interventions delivered using VR consumer hardware can become an effective tool for vaccine advocacy, complementing more traditional communication channels. Accordingly, combining health communication with experiential learning through bodily self-consciousness could be used in future health campaigns for tailoring communication efforts. Adopting novel technology in vaccine advocacy by relying on evidence-based intervention practices may thus help to decrease the spread of infectious diseases.

2. Related work

There is growing evidence that communicating the personal and collective benefit of vaccination increases participants' vaccination intentions [7,11,15,27]. A recent study by Freeman et al. [12] with more than 18,000 participants from the UK found increased vaccination intentions, among those strongly hesitant, by providing text-based information about the personal benefit of vaccination, more so than when informing them about collective benefit or about both personal and collective benefit. In a cross-national study with more than 2,000 participants, Betsch et al. [7] found that informing participants about community immunity improved participants' intention to get vaccinated in Western countries, whereas participants in Eastern countries had a priori higher collective responsibility with regard to vaccination. This study also reports an increased vaccination intention particularly after exposure to a more engaging interactive simulation compared to a text-based explanation. With regard to the latter finding, a review article from 2005 [17] shows how immersive technology can induce illusory ownership of virtual bodies, and that implicit biases related to the body can be underpinned by such a multisensory experience via a process of self-association. Such immersive interventions, including body ownership illusions, are increasingly being used for behavior and attitude change interventions, as they create realistic and engaging learning environments. For example, a randomised controlled trial from 2018 reported encouraging

results using virtual reality (VR) as a psychological intervention for treatment of fear of heights [11].

VR has specifically been used for vaccine advocacy interventions [9,22,25]. Ellerton et al. [9] used VR for pain relief during vaccination of children [9] and Real et al. [25] trained physicians in vaccination using VR [25]. Nowak et al. [22] report on a study conducted with 171 US participants, of which 48 were immersed in a VR intervention that provided information about the collective benefits of influenza vaccination, whereas the others either received the same content via video or e-pamphlet, or received no information on community immunity at all. The VR intervention increased participants' presence compared to the other conditions, which in turn increased vaccination intentions. Yet, there was no direct effect of the VR intervention on vaccination intentions. Hence, there is no evidence of whether communicating the personal and/or collective benefit of vaccination using VR can increase vaccination intentions due to a lack of studies with sufficient statistical test power.

3. Methods

3.1. Study design

The study employed a 2×2 between-participant design. The two independent variables were **avatar age** with the levels *young* and *old*, and **vaccination communication** with the levels *personal benefit* and *personal + collective benefit*. The study experimentally manipulated age of participants' embodied avatar to underpin the increased personal risk COVID-19 poses for seniors, which we hypothesized to increase vaccination intentions. The study design, procedures, hypotheses, and statistical analyses were preregistered and are available together with the data set via the Open Science Framework¹.

3.2. Deviation from preregistration

We preregistered to exclude participants with a negative mean embodiment, that is, participants who did not experience their avatar's body as theirs. We realized that excluding participants based on a post-intervention measure was not ideal because this could be influenced by the experimental condition. Therefore, we decided to apply a more conservative strategy by including participants irrespective of their self-reported embodiment. We report statistical analyses using the original preregistered criteria in the [Supplementary Material](#).

3.3. Participants

We aimed at recruiting a final sample used for analyses of 200–300 adult participants. All participants had access to VR equipment to self-administer the intervention. After the preregistered exclusion of participants with a perfect vaccination intention prior to the intervention (i.e., 100 on a scale from 1 to 100), the final sample consisted of $n = 282$ participants, of which $n = 244$ participants also completed the follow-up survey one week later (13.5% attrition; for sample characteristics, see [Table 1](#)).

The participants were recruited to participate in a VR study on COVID-19 vaccination via social media (most notably VR communities at [Reddit](#)² and [Twitter](#)³), and installed the VR application onto their own VR devices using the [SideQuest](#)⁴ software. The call for participation clearly stated the eligibility criteria for study participation,

¹ <https://osf.io/uyevs>.

² <http://reddit.com:/r/OculusQuest,/r/SideQuest,/r/oculus>.

³ <http://twitter.com>.

⁴ <http://sidequestvr.com>.

Table 1
Participant characteristics. Data are shown as n (%).

	Data (n = 282)
Age, years as M (SD)	28.9 (9.7)
Age group, years	
18–21	50 (25.3)
22–25	44 (22.2)
26–29	29 (14.7)
30–34	25 (12.6)
35–39	18 (9.1)
40–44	14 (7.1)
45–49	5 (2.5)
50–59	11 (5.6)
60–99	2 (1.0)
Gender	
Female	20 (7.1)
Male	255 (90.4)
Non-binary	7 (2.5)
Country	
United States	89 (31.6)
United Kingdom	22 (7.8)
Germany	21 (7.4)
Canada	20 (7.1)
France	19 (6.7)
Spain	14 (5.0)
Poland	10 (3.5)
Netherlands	9 (3.2)
Italy	8 (2.8)
Sweden	7 (2.5)
Mexico	5 (1.8)
Denmark	4 (1.4)
Ireland	4 (1.4)
Turkey	4 (1.4)
Argentina	3 (1.1)
Brazil	3 (1.1)
Japan	3 (1.1)
Educational level	
Bachelor's	84 (29.8)
High school/GED	82 (29.1)
Associate/2-year college	50 (17.7)
Master's	36 (12.8)
Professional degree	14 (5.0)
PhD	8 (2.8)
Primary/middle school	8 (2.8)
Prior VR experience	
More than 100 times	118 (41.8)
51–100 times	67 (23.8)
21–50 times	55 (19.5)
11–20 times	28 (9.9)
4–10 times	9 (3.1)
1–3 times	5 (1.8)

namely (i) not previously vaccinated against COVID-19, (ii) at least 18 years of age, (iii) not having previously participated, (iv) and having access to a VR device of the type Oculus Quest (1st or 2nd generation). Participants received IRB-approved information describing the study, the data collection procedures, and information on informed consent.

Study recruitment took place from April 14 to May 14, 2021 during mass roll out of national COVID-19 vaccination programs. We excluded 198 participants for already being vaccinated (with one or more doses, see Fig. 1).

Participants were reimbursed with a gift certificate of USD \$10 of value (or the equivalent in their preferred currency), with an additional USD \$5 for filling out an online follow-up survey sent out one week following study participation.

3.4. Randomisation and masking

The participants were randomly⁵ assigned to either of four experimental conditions during application run-time (see Fig. 1), after providing informed consent. Participants were unaware of the

existence of any other conditions. As the research team had no contact with research participants (except for reimbursement after study completion), the research team can be considered as masked in relation to outcome assessments.

3.5. Procedures

The study was conducted as an online and unsupervised VR study as has previously shown feasible [16,30,31]. We followed recent recommendations for running studies this way [20]. Participants downloaded an experimental installation file, and installed it to their Oculus Quest headsets using SideQuest⁴. Instructions on how to complete the study as well as data collection were carried out exclusively inside VR. Upon completing the intervention, an in-VR prompt collected participants' email addresses. These were used for reimbursement and for sending follow-up questionnaires a week later (that were carried out using a traditional desktop PC browser-based questionnaire).

The study began as participants wore their headsets and launched the VR application. In a pre-study scene, informed consent was acquired. Here, a virtual questionnaire asked participants if they had already received (any doses) of COVID-19 vaccine to verify participation eligibility. Then, their gender identity was prompted, to match the virtual avatar with the participant. As a last step before the intervention initiated, pre-intervention measures were acquired (vaccination intention, vaccination recommendation, vaccination readiness, COVID-19 empathy). All of the pre- and post study questionnaire responses were collected using an in-VR floating interface, where participants selected relevant buttons by tapping (see [Supplementary material](#)).

3.6. Immersive environment

The narrative of the immersive experience was situated around a visit to a virtual general practitioner (GP) in order to receive information about COVID-19 vaccination. The environment consisted of three virtual scenes. First, participants entered a blue pre-study scene where they would complete the pre-study survey. Here, only disembodied hands were rendered. As the intervention was designed as a standing experience, to proceed to the main study, we here required participants to target a button that was out of each reach if they were sitting down.

The main study was situated in a bathroom (see Fig. 2, left) where participants were directed to put on a face mask, wash hands, dry hands, and finally to enter the consultation room by activating a door. During these tasks a mirror rendered the participant's avatar in synchrony with the participant's movements. An inverse kinematics model computed the avatar's body posture using three stable tracking points (headset, left and right controllers). The purpose of this scene was to induce body ownership of the assigned virtual avatar in line with Maselli and Slater [19].

After leaving the bathroom, participants entered a consultation room (see Fig. 2, right) where a standing female GP would greet the participant and continue with information about COVID-19 vaccination. Depending on the assigned experimental condition, the GP would either explain the personal benefit of vaccination, or both the personal and collective benefit of vaccination. Explanation of the collective benefit of vaccination entailed an animated visualization shown on a tablet (see Fig. 2, right) inspired by Betsch et al. and Betsch and Böhm [7,5]. The animation explained the concept of community protection, by showing the difference in spread of virus between high and low immunization populations. The GP made multiple remarks related to the assigned age condition to explain the heterogeneous risk profile regarding age [8] (e.g., "young/old people, like you, are less/more vulnerable to the coronavirus").

⁵ The random assignment was allocated using `Random.Range` from the Unity SDK.

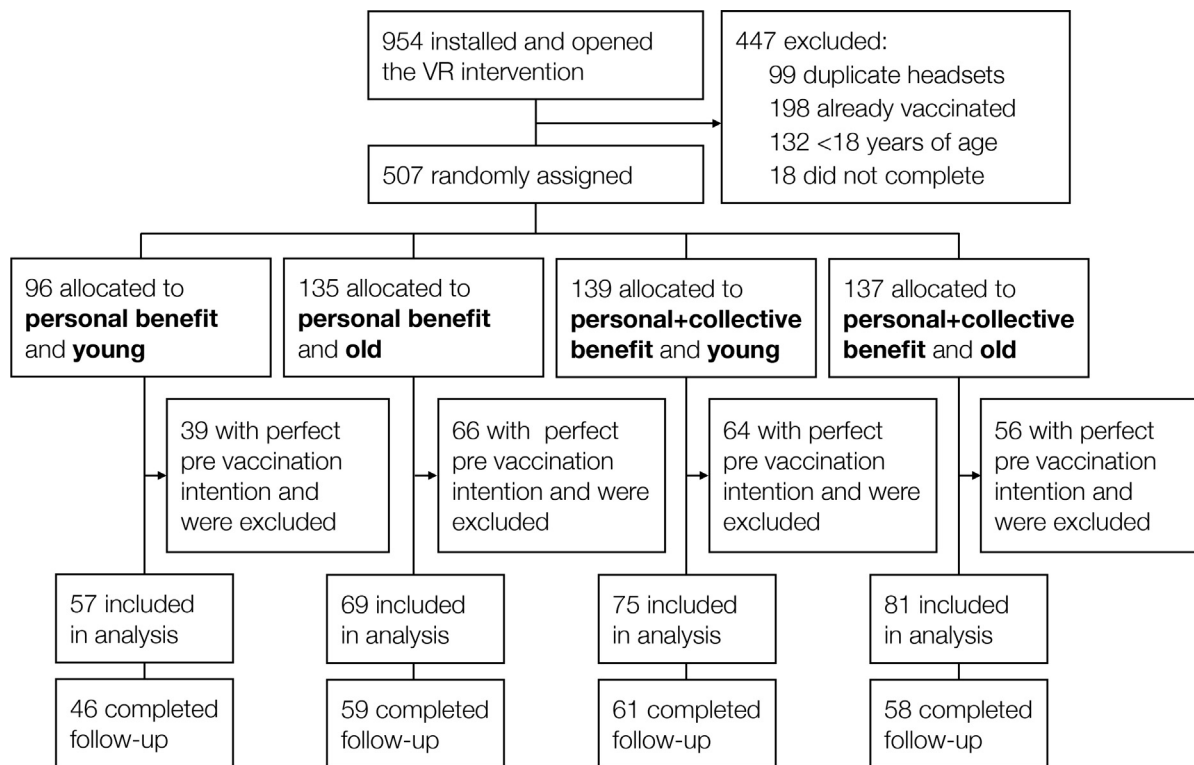


Fig. 1. Trial profile.

3.7. Implementation

The VR environment was developed in Unity 2019⁶, deployed for Oculus Quest 1 and 2. For avatars we used 3D models available through the RocketBox library [14]; for the two old avatars we commissioned a 3D artist to modify existing avatars to look older (see [Supplementary Material](#)). A female voice actor was hired to record the GP’s narration. The posture of the avatar was computed using the VR inverse kinematics library VRİK⁷.

The environment allowed participants to move around freely to the extent that their physical surroundings allowed it. It was not a requirement for the progression of the study to physically move.

3.8. Outcomes

The primary outcome was COVID-19 vaccination intention, as measured by Betsch et al. [7] on a 1–100 scale (1 = “I would definitely not get vaccinated”, 100 = “I would definitely get vaccinated”). This measure was collected in two contexts; while immersed in the virtual body (henceforth *as-avatar* vaccination intention), and during times without a self-avatar (henceforth *as-self* vaccination intention). The *as-self* vaccination intention was emphasized to relate to the participant’s personal vaccination intention, and was measured a total of three times: before the intervention, after completing the intervention, and one week subsequent to completion. The first two were collected during the intervention, and the latter in an online survey sent to participants’ email addresses.

For a secondary analysis we collected three additional measures related to vaccination: vaccination readiness [13], COVID-19 empathy (towards those most vulnerable to coronavirus) [24], and vaccination recommendation. These were all collected on 5-point Likert-type scales. As part of the secondary analysis, we also

investigated whether the effect of experimental condition was moderated by age, gender, country of residence, and experience with VR. We furthermore collected embodiment [4] and presence [18]. Finally, for exploratory purposes we collected objective measures related to movement and gaze. The complete list of measurements can be found in the [Supplementary Material](#).

3.9. Statistical analysis

Differences in intervention effects by experimental condition on the primary outcome, i.e., vaccination intention, were analyzed using a two-way ANOVA on the pre-to-post difference in vaccination intention. Intervention effectiveness was tested by a *t*-test on participants’ pre-to-post differences in vaccination intention against zero. We used Pearson’s correlation coefficient for analyzing correlations.

Further analyses were conducted to ascertain if effects of the intervention varied by individual characteristics (age, gender, region, education, experience with VR). These analyses were conducted by including demographics variables as main and interaction terms in the regression models, or simply a correlation test for non-categorical variables.

All the analyses on the pre-to-post differences are based on *n* = 282 participants, whereas analyses including the follow-up measures are based on *n* = 244 who completed all three measurement occasions. Analyses were conducted in R (version 4.0.4).

4. Results

Successful embodiment was indicated by a significant interaction effect of the two experimental factors on the *as-avatar* vaccination intention. Specifically, vaccination intention when embodied as a young avatar, but not as an old avatar, increased when both the personal and collective benefit of COVID-19 vaccination was communicated, relative to the personal benefit only

⁶ <https://unity.com>.

⁷ <http://www.root-motion.com>.

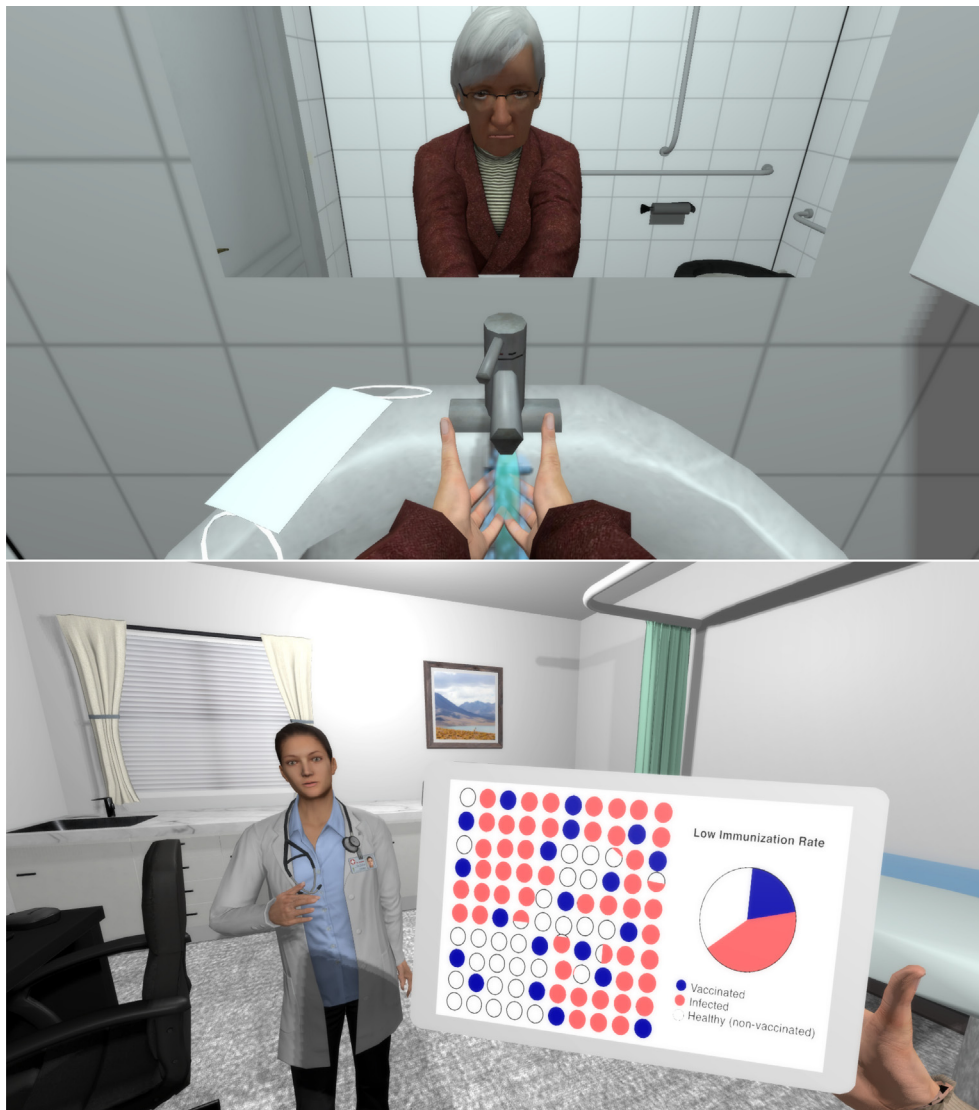


Fig. 2. Screens from the immersive intervention: the first scene in a bathroom intended as embodiment phase where the participant washes hands under a faucet (left); and a tablet showing an animated visualization about the concept of community immunity in the doctor's office during counseling (right).

condition. This is in line with previous research, showing that people at lower personal risk increase their vaccination intention when they are informed about the collective benefit of vaccination [7].

More importantly and as expected, the VR intervention also increased participants own (as-self) vaccination intention, regardless of the experimental condition, measured as the pre-to-post intervention difference, $t(281) = 6.8$, $p < 0.0001$, Cohen's $d = 0.29$ (see Fig. 3A). The intervention caused a substantial mean increase in vaccination intention of 8.6, 95% CI 6.1 to 11.1.

Further exploratory analyses suggested retention of the positive intervention effect even one week after the study (i.e., intervention-based increase in vaccination intention causes subsequent higher vaccination intention). In detail, we found that the pre-to-post difference in vaccination intention due to the intervention is significantly correlated with the vaccination intention measured in the follow-up survey, $\rho = 0.20$, $p < 0.0001$ (see Fig. 3B). This correlation was strongest among participants who were embodied with an old avatar compared to a young avatar ($\rho = 0.26$ vs. $\rho = 0.13$).

In addition to the intervention-based increases in vaccination intention, secondary analyses also revealed significant pre-to-post increases in COVID-19 empathy ($p = 0.0001$), vaccination recommendation ($p = 0.0001$), and vaccination readiness ($p < 0.0001$), further supporting the intervention's effectiveness.

Secondary analyses revealed an interaction effect between the two independent variables for this measure, $F(1, 278) = 5.0$, $p = 0.026$ (see Fig. 4). A similar result was found with the reduced sample of $n = 198$ using the pre-registered removal criteria: $F(1, 194) = 5.7$, $p = 0.018$. While embodied, vaccination intentions were higher when experiencing the provision of information about personal benefit of vaccination as a young individual, or respectively, information about collective benefit of vaccination in combination with an old virtual body.

Furthermore, exploratory analyses of the role of embodiment on the effect of the intervention were conducted. We did not find a correlation between level of embodiment on pre-to-post differences in vaccine intentions; neither for the reduced ($p = 0.35$), or full data set ($p = 0.80$).

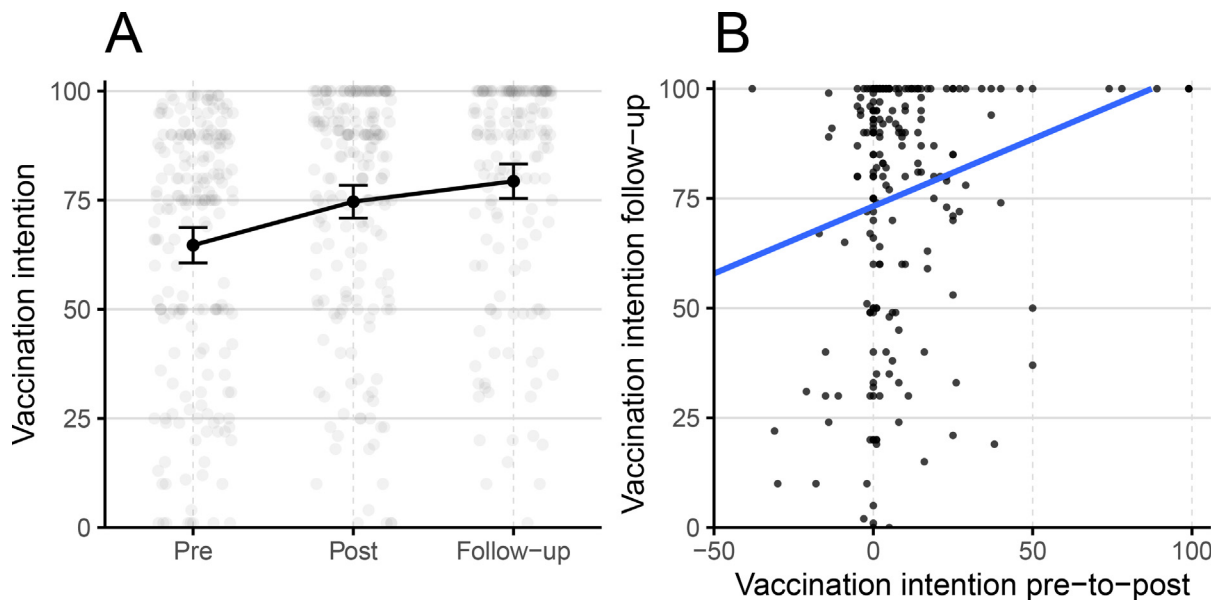


Fig. 3. Mean vaccination intention as measured directly before (pre) and after (post) the VR intervention, and in follow-up survey one week later with error bars indicating 95% CIs (A), and correlation of vaccination intention as measured pre-to-post and in follow-up, $\rho = 0.20$, $p < 0.0001$ (B).

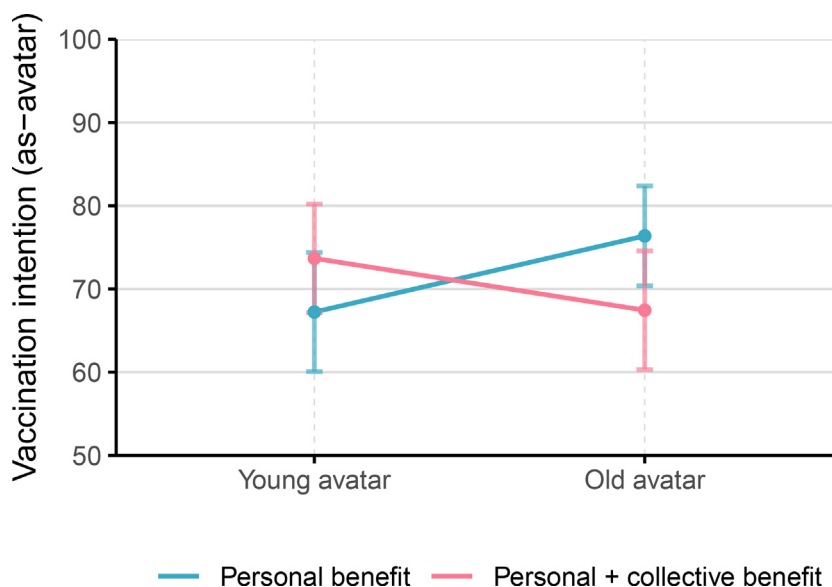


Fig. 4. Vaccination intention as measured directly after the VR intervention while the participant is embodied in either a young or old avatar.

5. Discussion

Designing effective health interventions for vaccine advocacy is challenging. Engaging participants using interactive technology has shown to increase vaccination intentions, compared to text-based alternatives [7]. Accordingly, we investigated the use of VR technology for its efficacy in increasing vaccination intentions as it is perhaps the most engaging technology available today, and because of effective VR health interventions in other domains [11,29]. Furthermore, VR affords replacing participants' bodies with virtual avatars, which has effects on attitudes through the process of self-association [17].

Our findings from one of the largest randomised VR intervention studies ever conducted show that a self-administered psychological intervention delivered using immersive VR is effective in increasing intentions to get vaccinated against COVID-19. Although

participants were sensitive to different experimental conditions when asked about their vaccination intention in the role of the avatar they were embodied as, we found that the intervention was successful in increasing their own vaccination intention across experimental conditions. This suggests that even a very short but highly immersive and engaging VR intervention has the potential to increase vaccination intentions. Furthermore, we provide exploratory evidence for increased vaccination intentions even one week after the intervention (linked to the immediate intervention effect). This suggests that vaccination information interventions using VR could lead to sustainable attitude change. Future research should further investigate the robustness and duration of such effects.

Our study has some limitations. First, despite the effectiveness of a one-time VR intervention that lasted only approximately 10 min to balance discomfort of immersion and clear communica-

tion, the intervention effect might be even larger by extending the time or number of intervention exposures. Second, our main dependent variable was vaccination intention (using an established measure [7]). Although psychological or structural barriers may create an intention-behaviour gap [6,28], intentions are still considered to be an important predictor of actual preventive behaviors [26]. Further, we present anecdotal evidence for the causal effect of exposure to our intervention and subsequent vaccination against COVID-19 (see participant comments in panel below).

Third, we did not compare the VR intervention's effectiveness with other, more traditional communication methods (e.g., via text or via interactive simulation). However, we argue that immersive VR may be a viable intervention method to complement other communication channels as long as it is effective per se (as demonstrated here) because it allows to attract and therefore target different target populations to engage with vaccination information in the first place. Nevertheless, it would be of great value for intervention planning if future research would investigate which intervention method is most appropriate for which target group. As a last limitation, we want to emphasize that our study focused on vaccination against COVID-19. Future research should aim to extent and adapt our VR intervention to promote other vaccinations, too (e.g., measles, influenza).

Comments from participants about the VR intervention

Although we did not inquire direct feedback from participants, several participants sent us emails with anecdotal evidence of the positive user experience as well as the effectiveness of the VR intervention in changing vaccination intention and behavior. Examples are shown here.

"The questions inside the game made me think more about whether or not to get vaccinated. In the end, 'The Vaccine' felt good because I felt like I was part of the solution to the world and in short I really liked the study."

"I enjoyed the study, and I had hard time deciding if I should get the vaccine or not. And as short as it was, it encouraged me a little bit and I felt more safe with my decision."

"I'd like to say what a cool experience 'The Vaccine' application was, I could see huge applications for things like this in the future."

"I did get my vaccine after participating in your study. You guys are awesome. Thank you!"

"First of all wow! This study let me think about the coronavirus for a month! And I did my first coronavirus vaccine two days ago and I felt like I saved the world or am part of the solution against the coronavirus."

"The game was amazing. I just love how you can teach more people about the situation and how you can help others. I played the game more than a week ago, and right after I finished the study I booked an appointment for coronavirus vaccination! And I wanted to share with you that it was because of you because last time I was afraid of the vaccine and its side effects and the game made me think more about the vaccine and I ended up doing the vaccine."

More generally, our study shows the potential of using immersive VR in health communication. People with access to a VR headset could self-administer our intervention, which caused younger and male participants to be over-represented in our sample. At the same time, however, this procedure allows targeting population groups who are otherwise difficult to reach with traditional health communication. Moreover, VR interventions could also be administered differently, such as in medical practices (targeting patients) or in medical education (targeting health care professionals).

Contributors

AM, GM, and RB conceived the study idea. AM led the design, and drafted the paper. CV, RB, and GM contributed to the design. All authors reviewed the design. MA and AM implemented the VR application. AM and CV carried out the statistical analysis. AM produced figures. RB, CH, and GM secured study funding. All authors contributed to the interpretation of the results and the draft paper. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Data sharing

Anonymous participant data will be available at the project's Open Science Framework repository without undue reservation, following the publication of results. The analyses plan and full statistical report are available in the [Supplementary Material](#). The source code and the employed 3D models are available upon request.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Robert Böhm reports financial support was provided by EIT Health.]

Acknowledgments

The study was funded by the European Institute of Innovation and Technology, under the EIT Health, Grant No. 210836. We are grateful to Philipp Sprengholz for helpful comments on an earlier draft.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.vaccine.2021.10.004>.

References

- [1] Banakou D, Groten R, Slater M. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proc Natl Acad Sci* 2013;110(31):12846–51.
- [2] Banakou D, Hanumanthu PD, Slater M. Virtual Embodiment of White People in a Black Virtual Body Leads to a Sustained Reduction in Their Implicit Racial Bias. *Front Human Neurosc* 2016;10:601.
- [3] Banakou D, Kishore S, Slater M. Virtually Being Einstein Results in an Improvement in Cognitive Task Performance and a Decrease in Age Bias. *Front Psychol* 2018;9:917. <https://www.frontiersin.org/article/10.3389/fpsyg.2018.00917>.
- [4] Banakou D, Slater M. Body ownership causes illusory self-attribution of speaking and influences subsequent real speaking. *Proc Natl Acad Sci* 2014;111(49):17678–83.
- [5] Betsch C, Böhm R. Moral values do not affect prosocial vaccination. *Nature Human Behaviour* 2018;2(12):881–2.
- [6] Betsch C, Böhm R, Chapman GB. Using behavioral insights to increase vaccination policy effectiveness. *Policy Insights Behav Brain Sci* 2015;2(1):61–73.
- [7] Betsch C, Böhm R, Korn L, Holtmann C. On the benefits of explaining herd immunity in vaccine advocacy. *Nature Human Behav* 2017;1(3):1–6.
- [8] Bhopal SS, Bagaria J, Olabi B, Bhopal R. Children and young people remain at low risk of COVID-19 mortality. *Lancet Child Adolescent Health* 2021;5(5):e12–3.
- [9] Ellerton K, Tharmarajah H, Medres R, Brown L, Ringelblum D, Vogel K, et al. The VRIMM study: Virtual Reality for IMMunisation pain in young children—protocol for a randomised controlled trial. *BMJ Open* 2020;10(8):e038354.
- [10] Fine P, Eames K, Heymann DL. Herd Immunity: A Rough Guide. *Clin Infect Dis* 2011;52(7):911–6.

- [11] Freeman D, Haselton P, Freeman J, Spanlang B, Kishore S, Albery E, et al. Automated psychological therapy using immersive virtual reality for treatment of fear of heights: a single-blind, parallel-group, randomised controlled trial. *Lancet Psychiatry* 2018;5(8):625–32.
- [12] Freeman D, Loe BS, Yu LM, Freeman J, Chadwick A, Vaccari C, et al. Effects of different types of written vaccination information on COVID-19 vaccine hesitancy in the UK (OCEANS-III): a single-blind, parallel-group, randomised controlled trial. *Lancet Public Health* 2021;6(6):e416–27.
- [13] Geiger M, Rees F, Lilleholt L, Santana A, Zettler I, Wilhelm O, et al. The 7Cs of vaccination readiness. *Eur J Psychol Assessm* 2021.
- [14] Gonzalez Franco M, Ofek E, Pan Y, Antley A, Steed A, Spanlang B, et al. The Rocketbox library and the utility of freely available rigged avatars. *Front Virtual Real* 2020.
- [15] Hakim H, Provencher T, Chambers CT, Driedger SM, Dube E, Gavaruzzi T, et al. Interventions to help people understand community immunity: A systematic review. *Vaccine* 2019;37(2):235–47.
- [16] Ma X, Cackett M, Park L, Chien E, Naaman M. Web-Based VR Experiments Powered by the Crowd. In: Proceedings of the 2018 World Wide Web Conference WWW '18, Republic and Canton of Geneva, CHE: International World Wide Web Conferences Steering Committee; 2018. p. 33–43. <https://doi.org/10.1145/3178876.3186034>.
- [17] Maister L, Slater M, Sanchez-Vives MV, Tsakiris M. Changing bodies changes minds: owning another body affects social cognition. *Trends Cognitive Sci* 2015;19(1):6–12.
- [18] Makransky G, Lilleholt L, Aaby A. Development and validation of the Multimodal Presence Scale for virtual reality environments: A confirmatory factor analysis and item response theory approach. *Comput Hum Behav* 2017;72:276–85.
- [19] Maselli A, Slater M. The building blocks of the full body ownership illusion. *Front Human Neurosci* 2013;7:83.
- [20] Mottelson A, Petersen GB, Liliija K, Makransky G. Conducting Unsupervised Virtual Reality User Studies Online. *Front Virtual Reality* 2021;2:66.
- [21] Murphy J, Vallières F, Bentall RP, Shevlin M, McBride O, Hartman TK, et al. Psychological characteristics associated with COVID-19 vaccine hesitancy and resistance in Ireland and the United Kingdom. *Nature Commun* 2021;12(1):1–15.
- [22] Nowak GJ, Evans NJ, Wojdowski BW, Ahn SJG, Len-Rios ME, Carera K, et al. Using immersive virtual reality to improve the beliefs and intentions of influenza vaccine avoidant 18-to-49-year-olds: Considerations, effects, and lessons learned. *Vaccine* 2020;38(5):1225–33.
- [23] Peck TC, Seinfeld S, Aglioti SM, Slater M. Putting yourself in the skin of a black avatar reduces implicit racial bias. *Conscious Cogn* 2013;22(3):779–87.
- [24] Pfattheicher S, Nockur L, Böhm R, Sassenrath C, Petersen MB. The emotional path to action: Empathy promotes physical distancing and wearing of face masks during the COVID-19 pandemic. *Psychol Sci* 2020;31(11):1363–73.
- [25] Real FJ, DeBlasio D, Beck AF, Ollberding NJ, Davis D, Cruse B, et al. A virtual reality curriculum for pediatric residents decreases rates of influenza vaccine refusal. *Academic Pediatrics* 2017;17(4):431–5.
- [26] Rosenstock IM. The Health Belief Model and Preventive Health Behavior. *Health Educ Monographs* 1974;2(4):354–86.
- [27] Sääksvuori L, Betsch C, Nohynek H, Salo H, Sivelä J, Böhm R. Information nudges for influenza vaccination: Evidence from a large-scale cluster-randomized controlled trial. *medRxiv* 2021;.
- [28] Sheeran P. Intention–Behavior Relations: A Conceptual and Empirical Review. *Eur Rev Social Psychol* 2002;12(1):1–36.
- [29] Singh RP, Javaid M, Kataria R, Tyagi M, Haleem A, Suman R. Significant applications of virtual reality for COVID-19 pandemic. *Diabetes Metabolic Syndrome: Clin Res Rev* 2020;14(4):661–4.
- [30] Steed A, Friston S, Lopez MM, Drummond J, Pan Y, Swapp D. An 'In the Wild' Experiment on Presence and Embodiment using Consumer Virtual Reality Equipment. *IEEE Trans Visual Comput Graphics* 2016;22(4):1406–14.
- [31] Steed A, Ortega FR, Williams AS, Kruijff E, Stuerzlinger W, Batmaz AU, et al. Evaluating Immersive Experiences during Covid-19 and Beyond. *Interactions* 2020;27(4):62–7. <https://doi.org/10.1145/3406098>.
- [32] The World Health Organization, Ten threats to global health in 2019; 2019. <https://www.who.int/news-room/spotlight/ten-threats-to-global-health-in-2019>.