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On the benefits of explaining herd immunity in vaccine advocacy

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Most vaccines protect both the vaccinated individual and the community at large by building up herd immunity. Even though reaching disease-specific herd immunity thresholds is crucial for eliminating or eradicating certain diseases[1,2], explanation of this concept remains rare in vaccine advocacy[3]. An awareness of this social benefit makes vaccination not only an individual but also a social decision. Although knowledge of herd immunity can induce prosocial vaccination in order to protect others, it can also invite free-riding, in which individuals profit from the protection provided by a well-vaccinated society without contributing to herd immunity themselves. This cross-cultural experiment assesses whether people will be more or less likely to be vaccinated when they know more about herd immunity. Results show that in cultures that focus on collective benefits, vaccination willingness is generally higher. Communicating the concept of herd immunity improved willingness to vaccinate, especially in cultures lacking this prosocial cultural background. Prosocial nudges can thus help to close these immunity gaps.

The concept of herd immunity requires a deeper understanding of disease transmission and vaccinations — an understanding of the fact that the vaccine reduces not only the probability of infection, but also the likelihood of spreading the disease to others[2]. The more individuals who are vaccinated, the higher the indirect protection for non- or under-vaccinated individuals in the community, such as babies who are too young for vaccinations, or immune-compromised patients who cannot be vaccinated. On their website, the US Centers for Disease Control and Prevention (CDC), for example, only briefly mention the concept of herd immunity, providing a link to an external site that offers an interactive simulation[4]. Other forms of publications are similarly silent about herd immunity, such as the CDC's *Parents' Guide to Childhood Vaccinations*[5], which marginally refers to herd immunity only in the glossary and when explaining why schools require vaccinations. Thus, although herd immunity is crucial for the elimination of infectious diseases, its complexity and explicit relationship to health politics cause it to remain under-explained and under-used in vaccine advocacy. Additionally, understanding the concept of herd immunity might invite free-riding, based on the idea that it is individually rational to opt out and save costs (such as time, money or adverse events), given that a sufficiently large part of society takes up vaccination and builds up herd immunity[6–8]. Free-riding occurs when the individual intention to vaccinate declines, given generally high vaccine uptake in the community.

In this study, we pose the question of whether people will be more likely to vaccinate if they know more about herd immunity. Providing an answer will enable health communicators to create evidence-informed strategies for vaccine advocacy[9,10]. Moreover, it is also vital to address the question of whether — and if so, when — free-riding occurs, and how it can be prevented. Individuals differ in how they consider the benefit of others in their decisions[11–13]. These differences are rooted in their personalities as well as their cultural background[14,15], as has been shown in research on culture-specific psychological differences[14]. Hofstede's model of cultural dimensions, for example, is based on research from more than 70 countries. It proposes that people from collectivistic cultures (such as most countries in East Asia) are more relational and more strongly influenced by social obligations or group-norms[14–17] than people from countries with an individualistic cultural background such as the United States or western Europe. Members of eastern countries might thus be more concerned about the prosocial aspects of vaccinations. This would imply that they would be more likely to be vaccinated compared with members of western countries — given equal opportunity and access[18]. As access issues affect vaccination behaviour in real-life settings, decisions in fictitious scenarios will be more suitable for this purpose as they are unconstrained. Additionally, fictitious scenarios will eliminate effects of prior knowledge or misconceptions about existing diseases.

In an online experiment, we collected vaccination decisions in fictitious scenarios from more than 2,000 participants from South Korea, India, Vietnam, Hong Kong, the United States, Germany and the Netherlands. We clustered the countries as 'eastern' and 'western' to allow for cultural comparison based on collectivistic versus individualistic orientation, respectively. Participants were confronted with both a highly contagious and a less contagious fictitious disease. In each of the two scenarios, the participants read about the disease, the respective vaccine and the probability of vaccine adverse events. Vaccine uptake as well as the contagiousness of the disease varied, being either high or low, which in combination determined the risk of infection for each scenario (for the epidemiologic formalization, see Methods section). Participants' intention to vaccinate was the main dependent variable.

Before reading the scenarios, some participants had learned about herd immunity through a text-based explanation; others had taken part in an interactive simulation (see Fig. 1 for details of the simulation). Independently, we compared the effect of the two possible bottom lines of herd immunity[19]. In one condition, the social benefit had been emphasized: "… when you get vaccinated, then you can protect others who are not vaccinated." In the other condition, the individual benefit had been emphasized, concluding that "… the more people who are vaccinated in your environment, the more likely you are protected without vaccination." A control group did not receive any

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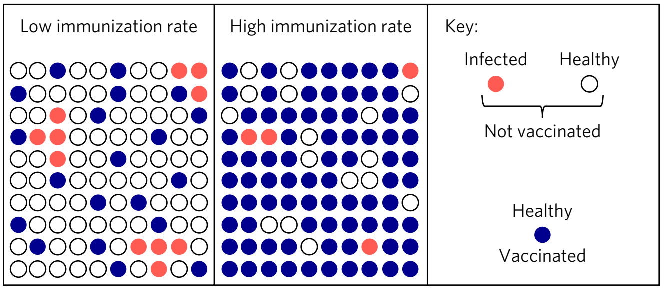


Figure 1 | Detail from the interactive herd immunity simulation used in the study. The simulation allowed observation of the spread of the infection given low coverage (left), or dying out of the infection because of herd immunity given high coverage (middle). By moving a horizontal slider bar below the pictures, participants saw past or future states of the environments. For an online simulation see http://rocs.hu-berlin.de/D3/herd/.

herd immunity information in order to serve as a benchmark. Hence, the experiment used a 2 (cultural background: collectivistic eastern countries versus individualistic western countries; quasi-experimental between-subjects) × 3 (communication format: interactive simulation versus text-based explanation versus no explanation of herd immunity; between-subjects) × 2 (bottom line that was emphasized in the herd immunity conditions: individual versus social benefit; between-subjects) × 2 (basic reproduction number of the disease determining the contagiousness, R_0: 3 versus 15; within-subjects with counterbalanced order of appearance) × 2 (vaccination uptake: 42% versus 62%; randomly selected for each scenario) mixed design.

For data analysis, we first assessed whether the countries could be clustered according to the underlying cultural differences such as the individualism–collectivism dimension, and whether the fictitious setting elicited responses that should be expected in real-world settings. In the main analyses, we then examined the effects of communicating herd immunity on the vaccination intention given different structural and contextual conditions.

A hierarchical cluster analysis suggests that the countries fall into two clusters. The analysis is based on country-specific values of individualism–collectivism, income, and an indicator of health system quality (for the analysis and the country-specific values, see Supplementary Table 1 and Supplementary Fig. 1). The first cluster contains the eastern countries South Korea, Vietnam and Hong Kong ($n_{\text{eastern}} = 915$), and the second cluster contains the western countries United States, Germany and the Netherlands ($n_{\text{western}} = 1{,}047$). Analyses of the individual-level data (individualism, collectivism, and societal tightness–looseness, indicating obedience in norms and punishment of norm deviance) confirmed the validity of the clusters (see Supplementary Notes). Thus, based on these results using both country-level and individual-level variables, we collapsed data across countries with the same cultural background and used culture as a dichotomous factor (eastern countries coded 0, versus western countries coded 1). We also assessed data of $n = 145$ participants from India. The cluster analysis revealed that India constituted a third cluster. To allow country comparison based on cultural background in individualism–collectivism[14,17], Indian participants were excluded from the main analyses (Supplementary Notes), with no qualitative changes in the results (Supplementary Tables 2–5).

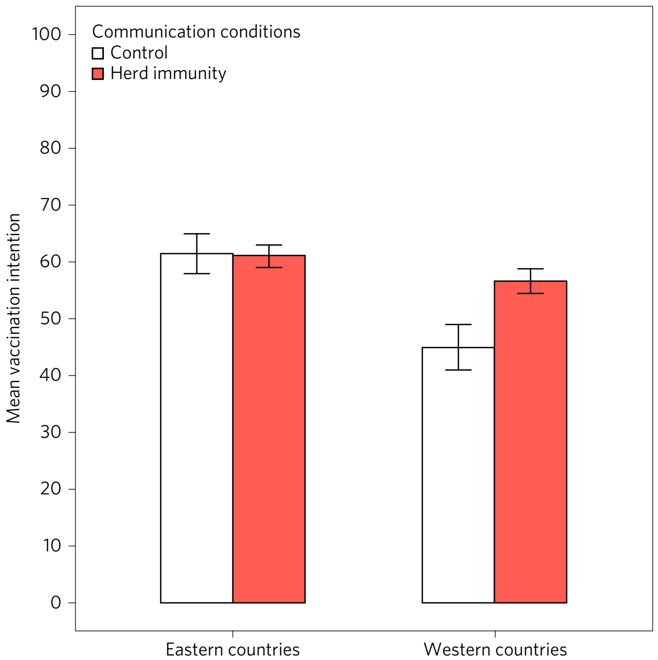
Intention to vaccinate and risk perceptions were measured with a scale ranging from 0 to 100, with higher numbers indicating higher intentions and risk perceptions (see Supplementary Methods). There was a considerably higher intention to be vaccinated against a highly contagious disease (mean $M_{\text{high contag.}} = 76.23$, standard deviation SD = 24.36) compared with a less contagious one ($M_{\text{low contag.}} = 57.43$, SD = 29.41), repeated-measures ANOVA: $F(1, 1{,}962) = 935.03$, $p < 0.001$, effect size $\eta_p^2 = 0.323$. This is also mirrored by the finding that disease risk was perceived to be higher for the highly contagious disease ($M_{\text{high contag.}} = 77.98$, SD = 20.12) than for the less contagious one ($M_{\text{low contag.}} = 55.39$, SD = 25.49), $F(1, 1{,}962) = 1{,}248.51$, $p < 0.001$, $\eta_p^2 = 0.389$. In the herd immunity communication condition, participants were three times as likely to recall that herd immunity provides an individual benefit when there had been an emphasis on the individual benefit (coded 1; compared with any other recalled information, coded 0) than participants in the social benefit condition (logistic regression: non-standardized coefficient $B = 1.14$, standard error SE = 0.12, $p < 0.001$, odds ratio OR = 3.14). In contrast, they were less likely to recall the social benefit of herd immunity ($B = -1.36$, SE = 0.12, $p < 0.001$, OR = 0.26). In sum, both the manipulation of the disease contagiousness and the herd immunity communication proved successful.

In the first set of main analyses, we predicted vaccination intention by vaccine uptake in society, cultural background, and the communication of herd immunity, separately for the highly and less contagious disease using ANOVAs (for ANOVA tables, see Supplementary Table 2). For the highly contagious disease, the intention to vaccinate did not depend on the population's vaccination rate. This indicates that free-riding did not occur. Participants from eastern countries had higher intentions to vaccinate than participants from western countries ($M_{\text{eastern}} = 80.00$, SD = 19.26; $M_{\text{western}} = 72.95$, SD = 27.68). The intention to vaccinate was marginally higher when herd immunity had been explained to participants ($M_{\text{herd immunity}} = 76.71$, SD = 24.27) than in the control group, where herd immunity was not explained ($M_{\text{control}} = 74.47$, SD = 24.67). No interaction effects were significant.

The pattern differs for the less contagious disease. When there was high vaccine uptake in society, vaccination intentions were lower ($M_{\text{high}} = 54.62$, SD = 30.75) compared with when there was low vaccine uptake ($M_{\text{low}} = 60.30$, SD = 27.70). This main effect indicates free-riding on the indirect protection due to vaccination of others. Vaccination intentions in eastern countries were again significantly higher than in western countries ($M_{\text{eastern}} = 61.10$, SD = 26.19; $M_{\text{western}} = 54.21$, SD = 31.63). Most importantly, the vaccination intention was significantly higher in conditions in which herd immunity had been explained ($M_{\text{herd immunity}} = 58.64$, SD = 29.37) compared with the control condition ($M_{\text{control}} = 52.95$, SD = 29.16). Furthermore, the intervention was particularly effective in western countries, but had no effect in eastern countries, where the prior willingness to be vaccinated was higher (see above). This was indicated by a significant interaction, which is displayed in Fig. 2.

To further explore the robustness of the findings, we repeated this analysis and replaced the dichotomous culture variable (east versus west) with Hofstede's country-specific values for individualism[20]. Each participant was assigned his or her country's value on the individualism scale. In the regression, all predictors were z-standardized before the interactions were calculated[21]. The analysis shows the same pattern of results: participants from countries with a more individualistic cultural background had lower vaccination intentions; higher vaccination rates led to lower vaccination intentions (that is, free-riding); and communicating herd immunity had an overall significant positive effect on vaccination intentions. The intervention was particularly effective in individualistic countries and was weaker in collectivistic countries (see Supplementary Table 6 for full regression results).

In the next step, we tested the robustness of the findings and added gender, age, the respective country's gross income per capita, the health system quality and the country's mean vaccine confidence as covariates in the ANOVA. For the latter three variables, each participant was assigned the respective country's value retrieved from World Bank data[22,23] and from the Vaccine Confidence Project[24]. Supplementary Tables 1 and 7 present the countries' values and the extended ANOVA tables, respectively. All covariates had a significant influence (values of $F > 3.9$, values of $p < 0.05$). Importantly,



	Eastern countries		Western countries	
Mean	61.43	61.02	44.99	56.61
SD	25.67	26.35	30.04	31.61
n	203	712	216	831

Figure 2 | Communicating herd immunity has an overall positive effect on vaccination intention against the less contagious disease in western countries with individualistic cultural backgrounds. $N = 1{,}962$. Data displayed are for the less contagious disease. Data in herd immunity conditions are collapsed across the variations of the communicated bottom lines (individual versus social benefit) and communication formats (interactive simulation versus text-based explanation). Data are measured on a scale from 0 to 100. Error bars indicate 95% confidence intervals.

however, the pattern of results described above remained stable and significant. Thus, even though other factors such as health system quality or vaccine confidence have a significant influence on the variance of vaccination intentions between countries, communicating herd immunity has additional value, the effect of which can differ depending on the cultural background of the recipients of the communication.

In a second set of analyses, we further investigated whether the methods of providing information about herd immunity differ in their effectiveness in increasing vaccination intention. To do so, we estimated the independent and joint effects of the different herd immunity communication conditions: that is, the communication format (interactive simulation versus text-based explanation) and the bottom line of herd immunity that was emphasized (individual versus social benefit). The vaccination intention in the communication conditions was centred on the mean of the intention in the control condition matching the structural conditions (the appropriate combination of contagiousness of the disease, vaccination rate and cultural background). Positive values therefore indicate an increase in vaccination intention when herd immunity was communicated, relative to the structurally equivalent control condition where the concept of herd immunity was not explained.

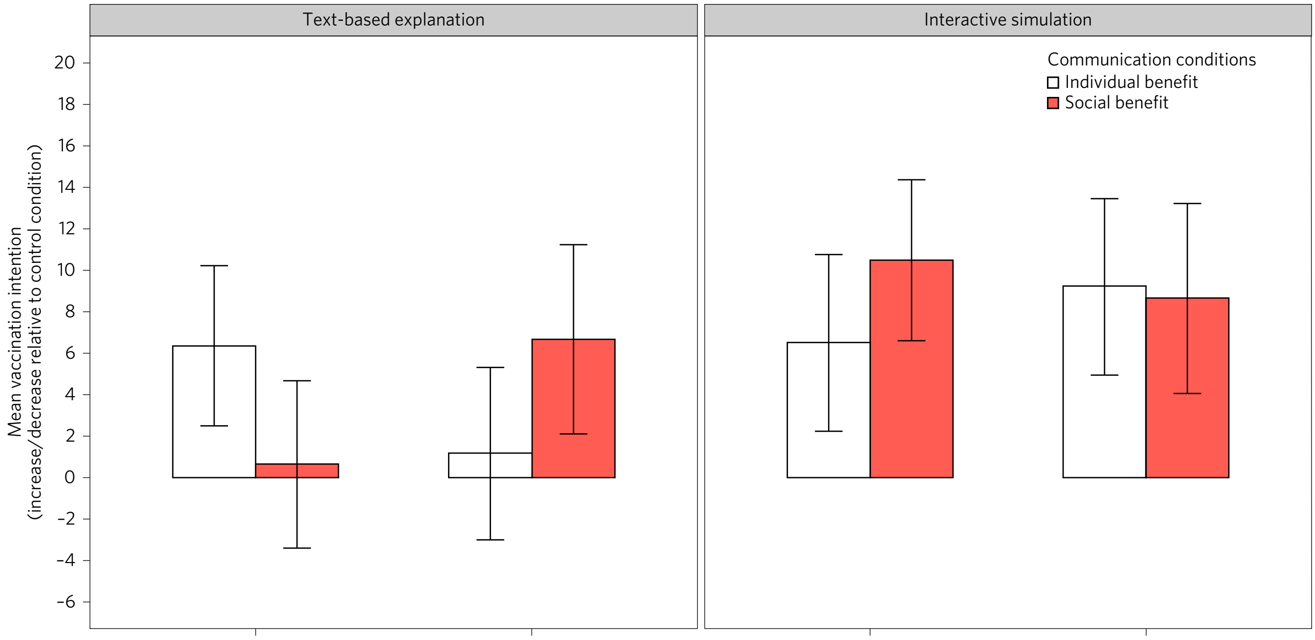
First, it is noteworthy that although there was considerable variation between the conditions, none of the interventions significantly decreased the intention to vaccinate. Explaining herd immunity increased participants' vaccination intention more in western countries than in eastern countries (increase in vaccination intention relative to control condition: $M_{\text{western}} = 11.27$, SD = 31.45; $M_{\text{eastern}} = 1.18$, SD = 26.03; see Supplementary Table 4 for statistics). Additionally, the intention increased more strongly when the intervention used an interactive simulation ($M_{\text{interactive}} = 8.71$, SD = 28.91) than for a text-based explanation ($M_{\text{text}} = 4.05$, SD = 29.55), as indicated by a main effect of communication format. Figure 3 further illustrates that the success of the communication depended on context variables (uptake, communication content) when a text-intervention was used: when low uptake suggested vaccination as the selfish-rational strategy (see Methods for details), emphasis of the individual benefit increased vaccination intentions. When uptake was high and vaccination was no longer selfish-rational but only collectively optimal, social benefit salience helped to reduce free-riding and increased prosocial vaccination. The success of the interactive simulation did not depend on such specific context factors. Across all conditions, the interactive simulation increased vaccination intentions substantially and more strongly than the text-based explanation. This overall pattern of results is substantiated by the significant three-way interaction of vaccination rate, communication format and the emphasized bottom line of the herd immunity information. No other main effects or interactions were significant.

For the highly contagious disease, there are no effects of the structural manipulations or communication conditions, presumably because of a ceiling effect. All the results remain stable and do not qualitatively change when controlling for demographic variables (age, gender).

What drives the higher vaccination intentions in eastern compared with western countries when facing a less contagious disease (Fig. 2)? Based on theory, we expect that higher levels of collectivism in eastern than in western countries are at least partially responsible for this difference. This type of self-construal (defining oneself in terms of 'We' instead of 'I') can cause a stronger focus on prosocial vaccination among eastern participants. Additionally, differences in risk perceptions regarding the disease and/or the vaccination could affect the intention to vaccinate. Such differences can be rooted, for instance, in different availability of or access to healthcare in case of an infection. We tested these alternative explanations simultaneously by means of a multiple mediation analysis, with cultural background as the independent variable, vaccination as the dependent variable, and collectivism, disease risk and vaccination risk as potential mediator variables[25] (visualized in Supplementary Fig. 2, results in Supplementary Table 8). The analysis revealed two significant mediation effects: one through perceived risk of the disease and one through collectivism. Participants from eastern countries perceived greater disease risk and had higher levels of collectivism. In turn, disease risk and collectivism increased vaccination intention. This finding thus supports the idea that participants from eastern countries had higher vaccination intentions partly owing to their higher collectivistic orientation than participants from western countries.

The results show that communicational interventions and contextual aspects affected the vaccination decision more strongly when the disease was less (rather than highly) contagious, and when the resulting infection risk was low rather than high. It is important to note that owing to the success of vaccinations, the actual risk of infection for most infectious diseases is low[26] (for the United States, see ref. [27]). This is also mirrored by low subjectively perceived risks, which are relevant in guiding behaviour (for the United States, see ref. [28]). Thus, the current epidemiological and psychological situation most resembles the conditions of this experiment, in which the communication interventions had the strongest impact. Additional studies should investigate the tipping point for which risks of disease are perceived as sufficiently high that communication measures become ineffective because uptake is already very high.

In western countries, explaining the concept of herd immunity led to higher vaccination intentions compared with the no-information control group. Understanding herd immunity entails an understanding of the social and individual consequences of high



	Low uptake		High uptake		Low uptake		High uptake	
Mean	6.35	0.63	1.16	6.65	6.50	10.48	9.22	8.65
SD	28.20	28.70	30.05	32.27	28.57	26.51	29.78	32.35
n	206	197	203	193	176	181	192	195

Figure 3 | The intention to be vaccinated against the less contagious disease increases when the concept of herd immunity is communicated, particularly in the interactive simulation condition. $N = 1{,}543$ (excluding the condition with no explanation of herd immunity). The index displayed in this figure indicates the increase or decrease in vaccination intention relative to the structurally equivalent control condition in which herd immunity was not explained (mean-centred at values of the control condition). Values greater than 0 indicate an increase in vaccination intentions after herd immunity was communicated. Data displayed are for the less contagious disease and collapsed across cultural backgrounds. Error bars indicate 95% confidence intervals.

vaccination rates. Explaining the concept via an interactive simulation led to an overall higher vaccine uptake. Importantly, decisions were independent from other contextual factors, such as the vaccine uptake in society. Following a text-based explanation of herd immunity, the vaccination decision was highly dependent both on the vaccine uptake in society and the bottom line that accompanied the explanation of herd immunity. Free-riding could be observed with increasing vaccination rates when the individual benefit was emphasized, whereas vaccination increased when the social benefit was salient. Hence, simple framing of the vaccination decision and its consequences as a social decision may affect vaccination intentions. It is important, however, to note that average vaccination intentions in herd immunity conditions never fell below the level observed when herd immunity was not communicated at all. In total, the interactive communication format seems to aid a better understanding of herd immunity's societal consequences, independent of particular message frames. We can only speculate about the reasons for the excellent performance of the interactive simulation. One pertinent factor might be the fact that participants spent about 2 minutes with the simulation and only about 30 seconds with the text, which could have led to better encoding and deeper understanding of all implications. Moreover, visualizing the dynamics of herd immunity over time and the comparison of societies with different uptake probably assisted this understanding. Using an interactive simulation may have increased motivation to engage with the topic, as is suggested in literature on 'gamification' (the use of typical elements of game playing to encourage engagement)[29,30].

People from eastern countries generally showed higher vaccination rates, partially because of their collectivistic rather than individualistic self-construal. We argue that collectivism does assist in a consideration of others, including in vaccination decisions. This may be rooted in very old traditions such as agricultural habits or large family clans[31]; recent evidence shows, for example, that within China, collectivism is more pronounced in areas that have long traditions of growing rice, which is a highly social and interdependent endeavour, than in areas of wheat agriculture[32]. Over time, these traditions crystallize into psychological differences that influence perception and behaviour. Communicating the concept of herd immunity increases vaccination especially where this collectivistic perspective is lacking: in cultures that habitually focus on individual rather than collective benefits. Evidence from the experimental manipulations of herd immunity, as well as from the individual differences in culture-bound inclinations to collectivism, indicates that considering others in the vaccination decision can increase the willingness to be vaccinated. Nevertheless, other factors (such as how willing people are to follow recommendations, or how easily they can access vaccination) are also important, potentially varying as a function of cultural background, and should not be ignored in herd immunity communication campaigns. In fact, in the present study, collectivism explained only part of the difference in vaccination intentions between eastern and western countries. Future research should identify further factors responsible for health-related perceptional or behavioural cultural differences to be considered in culture-sensitive health communication[33].

This study has several limitations. The data collection was conducted online. This can lead to distraction from the task and written instructions, which may result in an underestimation of effects. Nevertheless, the consistency check showed that intentions mirrored the information provided in the scenarios. The study also assessed the intention to vaccinate, instead of behaviour. Although the intention is usually a good predictor of behaviour, there may be a gap between the intention and behaviour[34,35]. Barriers can prevent intentions from turning into behaviour. Difficulties in access to vaccination, for example, could cause this obvious intention–behaviour gap[9,18]. Health system quality proved to be a significant predictor of

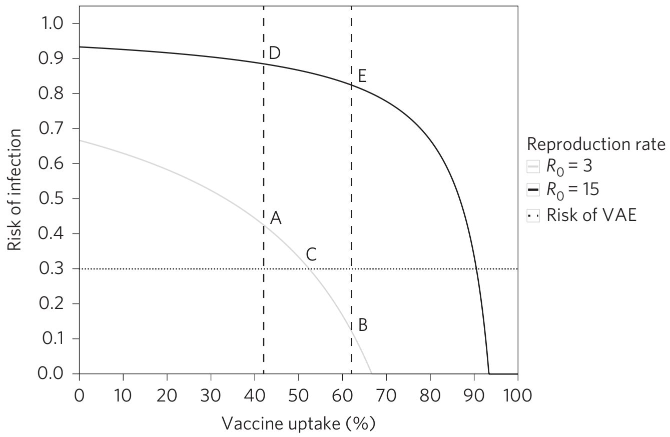


Figure 4 | Risks associated with diseases (solid lines, lifetime incidence in unvaccinated individuals) and vaccination (horizontal dotted line). Vaccine uptake (dashed vertical lines) and R_0 make either vaccination (A, D, E) or non-vaccination (B) the dominant choice. Risks are given on a scale of 0 to 1. Low vaccine uptake = 42%; high vaccine uptake = 62%. R_0, basic reproduction number. VAE, vaccine-adverse events.

vaccination intentions in the study, indicating that barriers could be relevant in different countries at different degrees. Additionally, we found that the perception of disease risks varied between eastern and western countries. There may be several structural factors responsible for this difference: for instance, different levels of disease burden within countries or different levels of vaccine confidence. Therefore, real-world intervention studies should assess the impact of herd immunity communication and compare its effect with pre-existing risk perceptions. Nevertheless, we controlled for these factors, which did not weaken the results. We are confident that scenario-based studies, such as the one presented here, outweigh the lower external validity by offering insights into psychological processes that cannot be drawn from more field-based, and allegedly more externally valid, studies.

In summary, the results provide clear evidence that communicating the concept of herd immunity increases the willingness to be vaccinated. Furthermore, the study has important practical implications for the question of how to design this communication. Interactive simulations are more effective than text-based explanations in increasing prosocial vaccination, and less prone to be undermined by free-riding intentions. Television advertisements demonstrating the concept of herd immunity could be a potential alternative to the online simulation in areas where access to the Internet is limited or when certain target groups that need to be reached (such as the elderly) may lack experience with interactive Internet tools. Overall, the present findings can be seen as optimistic evidence that the communication of herd immunity in vaccine advocacy materials can increase vaccine uptake in the population, therefore reducing the burden of infectious diseases, and finally eliminating them.

Methods

This work compares eastern countries that have a collectivistic cultural background with western countries that have an individualistic cultural background. We therefore selected countries that scored high versus low on Hofstede's dimension of individualism–collectivism[20,36]. Additionally, we selected countries where access to participants was possible owing to informal research partners in those countries. Originally, South Korea (Hofstede's individualism score 18), Hong Kong (25), Philippines (32), India (48) and Vietnam (20) were selected as representatives of eastern collectivistic countries, and Germany (67), the Netherlands (80) and the United States (91) for the western individualistic countries (Hofstede's scores of the individualism–collectivism dimension in brackets, where higher values indicate higher individualism[20]). Owing to a hurricane in the Philippines in 2014, we refrained from collecting data there.

The experiment was conducted as an online experiment, using an Enterprise Feedback Suite (EFS) survey by Questback. The invitation to participate was sent via mailing lists by researchers in the participating countries, as well as by advertisements in social media. This study conforms to the ethical principles for psychological research provided by the German Research Foundation. Participants gave their informed consent and could leave the study at any given time without consequences. A debriefing about the study's goals was offered at the end of the study. Because of the study's scenario-based, fictitious setup, we did not expect any negative consequences for the participants' health. The contact information for the responsible researchers was offered at the end of the study. As compensation, all participants took part in a raffle for gift certificates, where the value of the gift certificate was a multiplier of a country-specific research assistant's hourly wage (between US\$5.04 and US\$9.64). Additionally, Amazon Mechanical Turk was used to attract further participants from the United States and India, each participant being paid a fixed compensation of \$1. A total of 2,457 subjects from the United States, Germany, the Netherlands, India, Hong Kong, Vietnam and South Korea completed the questionnaire.

The average time required for finishing the experiment was 12.55 minutes (SD = 4.55), excluding participants with extremely long (>23.09 min in the no-information condition; >27.95 min in the herd immunity conditions) or short (<4.67 min in the no-information condition; <6.03 min in the herd immunity conditions) duration of participation, based on 5% and 95% percentiles ($n = 244$) to ensure good data quality. Furthermore, we excluded those participants whose nationality did not match the country in which the respective sample was drawn ($n = 66$) or who could not recall the correct condition-dependent vignette characteristics ($n = 40$). Therefore, the final sample consisted of $N = 2,107$ participants ($n_{US} = 650$; $n_{Netherlands} = 18$; $n_{Germany} = 379$; $n_{India} = 145$; $n_{Hong Kong} = 136$; $n_{Vietnam} = 61$; $n_{South Korea} = 718$). The participants' mean age was 28.56 years (SD = 9.83); 1,217 respondents were women (57.8%). Approximately 85% of the sample had a high school diploma or a higher level of education.

For randomization, the software first selected for each participant whether herd immunity was to be communicated. Within the herd immunity conditions, it was randomly determined whether the concept was explained by means of the text-based explanation or the interactive simulation, followed by a random selection of the core message that was emphasized (either the social or individual benefit). Then, participants successively learned about two fictitious diseases, 'cornosis' and 'holtosis'; the sequence of the diseases was determined randomly. For the first disease, R_0 was randomly selected (for example $R_0 = 3$), leaving the other R_0 (for example $R_0 = 15$) for the second disease. Finally, vaccine uptake in society was randomized (either 42% or 62%) independently for both diseases. Owing to the automatic randomization mechanism, the investigators were blind to the group allocation process.

In the control condition, participants received no information about herd immunity. In the two text-based explanation conditions, the definition of herd immunity was presented: "Herd immunity denotes the effect that occurs when acquired immunity against a pathogen within a population (the 'herd'), generated through infection or vaccination, has reached such a level that non-immune individuals in the population are also protected because the pathogen can no longer be transmitted." In the social benefit condition, it was followed by the phrase "Thus, if you get vaccinated, then you can protect others who are not vaccinated", to highlight the social benefit of herd immunity. In the individual benefit condition, the phrase "Thus, the more people who are vaccinated in your environment, the more likely you are protected without vaccination" was used to highlight the individual benefit of herd immunity. In the interactive simulation condition, the impact of herd immunity was demonstrated by a display showing two environments with two populations differing in vaccine uptake (see Fig. 1). By moving a slider beneath the simulation, the observer could travel back and forth in time and compare the development of the infection given low and high uptake. To prevent participants from skipping the demonstration, the 'continue' button was disabled for 30 seconds. The subsequent page also provided the definition of herd immunity and its condition-dependent bottom line, presented equivalently to the text-based explanation conditions.

To present disease and vaccine-related information, participants received vignettes of two fictitious diseases in counterbalanced order. These information sheets contained: (i) the name of the virus together with symptoms of the disease, either 'cornosis' (sudden high fever, rash, restlessness, severe vomiting, diarrhoea, extreme dehydration and kidney failure) or 'holtosis' (seizures, stomach ache, nausea, lack of concentration, tinnitus, shivering fit and tremors in different parts of the body); (ii) the path of infection (smear infection for both diseases); (iii) probability of infection with the disease (condition-dependent; see below); (iv) the vaccine's probability of side effects, both at a constant level of 30%; (v) the symptoms of vaccine-adverse events, which mirrored those of the respective disease; and (vi) vaccine uptake in society (42% or 62%; condition-dependent).

The mentioned combinations of symptoms presented along with the two diseases were pretested regarding their severity (1 being low severity, 5 high severity) in a battery of 65 symptoms and assembled in a way that assured equal mean severity for the diseases ($N = 35$, 77.1% women, $M_{age} = 28.83$ (SD = 7.16); $M_{severity\_cornosis} = 2.83$ (SD = 0.60), $M_{severity\_holtosis} = 2.84$ (SD = 0.54); $t(33) = 0.04$; $p = 0.967$).

The probability of infection (see Fig. 4) was calculated as the lifetime incidence in unvaccinated individuals, $p_{infection} = 1 - 1/(R_0 \times (1 - n_{vacc}))$, where n_{vacc} is the proportion vaccinated in society and R_0 is the basic reproduction number: that is, the number of secondary infections by an infected individual, given no immunity in the population[1]. For the less contagious disease, R_0 resembled a highly contagious version of influenza ($R_0 = 3$); that for the highly contagious disease resembled measles or pertussis ($R_0 = 15$).

The vaccine uptake in the population was set to either 42% or 62%. In the case of the less contagious disease, these coverage levels make either vaccination (42%) or non-vaccination (62%) the dominant choice (see A and B in Fig. 4, which lie above and below the risk of vaccine-adverse effects, respectively). More specifically, given hypothetical vaccine coverage of 52%, a selfish-rational decision-maker would be indifferent between vaccination and non-vaccination (C in Fig. 4). Thus, the manipulated coverage levels have an equal distance to the point of indifference, and therefore a roughly similar motivational force towards vaccination in the case of 42% and non-vaccination in the case of 62%. In the case of the highly contagious disease, vaccination is the dominant choice for both coverage levels (D and E in Fig. 4).

After the vignettes, the following measures were taken in the order of their presentation (for details, see Supplementary Methods): individual-level individualism and collectivism, tightness–looseness, scenario recall, manipulation check, vaccination intention (main outcome) and perceived risk of vaccination. As background factors, we assessed demographic variables (age, gender, education and nationality).

Data availability. The raw data including a data legend are available at https://osf.io/9a7sb/ (ref. [37]).

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Author contributions

C.B. and R.B. designed the study, analysed the data and wrote the article. L.K. and C.H. assisted in this process and were responsible for data collection and data management.

Additional information

Supplementary information is available for this paper.

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Competing interests

The authors declare no competing interests.