Personalized Feedback about Immunity Corrects

Risk Misestimation and Motivates Vaccination

Alyssa H. Sinclair[1,2,3]*, Morgan K. Taylor[3,4], Stephen J. Beckett[5,6], Aroon T. Chande[7],

Joshua S. Weitz[5,6,8], & Gregory R. Samanez-Larkin[3]

[1] Annenberg School for Communication, University of Pennsylvania, Philadelphia, PA, USA

[2] Annenberg Public Policy Center, University of Pennsylvania, Philadelphia, PA, USA

[3] Department of Psychology and Neuroscience, Duke University, Durham, NC, USA

[4] Department of Psychology, Brandeis University, Waltham, MA, USA

[5] Department of Biology, University of Maryland, College Park, MD, USA

[6] School of Biological Sciences, Georgia Institute of Technology, Atlanta, GA, USA

[7] Applied Bioinformatics Laboratory, Georgia Institute of Technology, Atlanta, GA, USA

[8] Institut de Biologie, École Normale Supérieure, Paris, France

Corresponding Author: Alyssa H. Sinclair, sinclair.allie@gmail.com

Keywords: *vaccination, risk perception, immunity, health communication, digital health*

Note: AHS and MKT were affiliated with Duke University during the time period in which the studies were conducted, but are no longer affiliated with Duke University. Similarly, SJB and JSW were formerly affiliated with the Georgia Institute of Technology.

Abstract

Few individuals are up-to-date on COVID-19 vaccines, leading to widespread gaps in protection. Current vaccine communication strategies emphasize availability, with limited effectiveness for recurring vaccinations and vaccine-hesitant individuals. Previously, we identified a leading factor limiting vaccine uptake: misconceptions about immunity. To address this gap, we developed an intervention that targeted beliefs about immunity, providing personalized feedback about likely protection against COVID-19. In an online sample of participants (N=882, stratified by age and gender), this intervention effectively changed immunity beliefs and increased vaccination intentions. Our personalized intervention was particularly effective for older adults, who are at greater risk of severe illness if not sufficiently protected by vaccination. Two months later, belief changes endured, and self-reported vaccine uptake was approximately 8x higher than the national rate in the United States during the same time period. Crucially, our intervention was substantially more effective than existing, non-personalized interventions used by national public health organizations. We then scaled our intervention to a public website and replicated our findings in an independent sample that was stratified to approximate the demographic makeup of the United States (N=553). Overall, our novel psychological intervention changed immunity beliefs and motivated vaccination, of relevance for COVID-19, influenza, and future pandemic threats.

1   **Introduction**

2   Beliefs about immunity have important implications for health behaviors. If an individual

3   is aware that they are vulnerable to a disease, they might stay up-to-date on vaccines, take a

4   diagnostic test if they experience symptoms, or take precautions to protect themselves and

5   others. Routine vaccines, such as for COVID-19 or influenza, can safely restore and update

6   immunity to account for evolving viruses. However, uptake remains low—as of December 2024,

7   only 21.0% of U.S. adults were up-to-date on COVID-19 vaccines, and 40.8% were up-to-date

8   on influenza vaccines[1,2]. In the present studies, we tested interventions designed to correct

9   misconceptions about waning immunity and motivate uptake of COVID-19 vaccines.

10   Immunity conferred by COVID-19 infections or vaccinations wanes over time,

11   potentially at different rates[3–8]. *Hybrid immunity* acquired through both vaccination and infection

12   also wanes over time, but at a slower rate than immunity developed through vaccination or

13   infection alone[7,9–11]. Irrespective of whether individuals have been infected, vaccinated, or both,

14   protection against infection declines more rapidly[4,5,12], whereas protection against severe illness

15   declines at a slower rate[6,7,13]. Updated COVID-19 vaccines, reformulated for evolving viral

16   variants, help restore and maintain protection[12–15]. Restoring protection is particularly important

17   for older adults and individuals who are at higher risk of severe illness[13,16,17].

18   However, few Americans are up-to-date on COVID-19 vaccines[1]. The CDC currently

19   recommends that nearly all individuals at least 6 months of age should receive an updated

20   COVID-19 vaccine[18]. Previously, we found that many individuals chose not to receive a booster

21   vaccine because they believed they still had strong protection against infection and/or severe

22   illness[19]. These individuals likely overestimated their protection—72% had not been infected or

23   vaccinated in the previous 6 months, and 51% reported no prior documented infections.

1   Prior studies have investigated strategies for increasing COVID-19 vaccine uptake[20–25].

2   Existing recommendations for motivating vaccination emphasize dialogues with trusted

3   messengers, such as healthcare providers and community leaders[26]. This approach can help

4   address vaccine hesitancy, but is difficult to scale. Text-message reminders (focusing on vaccine

5   availability or ownership) can increase vaccination shortly after vaccine rollout[27], but are not

6   effective for hesitant individuals and less relevant to routine vaccinations[28,29]. Importantly,

7   promoting booster vaccines requires different strategies, relative to motivating primary

8   vaccinations[21,30]. To our knowledge, prior interventions have not aimed to address the unique

9   challenges associated with motivating uptake of updated COVID-19 vaccines (e.g.,

10 misconceptions about waning immunity, viral variants, safety, or effectiveness[19]). For instance,

11 an individual who mistakenly believes that they still have strong immunity may conclude that the

12 expected value of a booster vaccine is outweighed by the expected costs (e.g., mild side effects,

13 inconvenience, or rare adverse events)[31]. We propose that changing beliefs about immunity is an

14 important understudied mechanism for motivating vaccination.

15   Beliefs about immunity are conceptually related to beliefs about risk. Numerous studies

16 have investigated risk perception during COVID-19[32,33]; perceived risk of COVID-19 is related

17 to vaccine uptake, mask wearing, social distancing, and risk taking[34–39]. Furthermore, political

18 attitudes strongly influence perceived risk of COVID-19 and behavioral intentions[40–43]. Prior

19 studies have shown that COVID-19 risk perception is inaccurate, such as when participants

20 attempt to estimate the risk of viral exposure in social distancing scenarios[44] or in public

21 gatherings[39,45]. Importantly, improving the *accuracy* of risk estimation—as opposed to

22 unilaterally increasing perceived risk—is necessary to balance public health goals with mental

23 health and societal well-being[46–48].

1   How might beliefs about immunity and risk influence health behaviors? Two theoretical

2   frameworks of behavior change offer potential mechanisms. The *Theory of Planned Behavior*

3   proposes that attitudes, subjective norms, and perceived behavioral control shape intentions and

4   behavior [49]. Changing beliefs about immunity—such as by informing people that immunity

5   wanes over time—could change attitudes by increasing the perceived value of vaccination[50,51].

6   An alternative framework, *Fuzzy-Trace Theory*[52–54], proposes that "gist" representations, which

7   capture the general meaning and emotional context of information, endure in memory and guide

8   decision making (even when verbatim details, like risk statistics, are forgotten). A prediction that

9   arises from this framework is that clearly conveying a gist concept (e.g., "I am vulnerable to

10   COVID-19"), such as by using a meter to illustrate categories of risk or protection, may be more

11   effective than providing detailed information about risk statistics or vaccination guidelines.

12   Previously, we developed an interactive online intervention designed to change perceived

13   risk of viral exposure[39]. Imagining the possible consequences of risky actions (hosting an indoor,

14   unmasked gathering) enhanced learning from feedback in a subsequent "risk quiz" about local

15   viral exposure risk. This intervention corrected risk underestimation and overestimation, and

16   decreased willingness to take risks. Importantly, we also found that imagining a personalized

17   scenario (featuring yourself and close others) was particularly effective for older adults, who

18   were less likely to learn from numerical risk information[55]. Drawing on these findings, we later

19   developed a public website with risk assessment tools, again showing that quiz feedback (paired

20   with illustrations that contextualized risk) decreased risk-taking intentions[45,56,57].

21   Overall, prior studies indicate that beliefs about immunity and risk influence vaccine

22   uptake, but these beliefs are often inaccurate. Informational interventions can correct risk

23   misestimation and potentially motivate vaccination. Personalized interventions may be

1   particularly effective for older adults, who are at increased risk of severe illness due to COVID-

2   19, as well as other preventable diseases. Here, we tested new interventions to motivate uptake of

3   updated COVID-19 vaccines, targeting beliefs about immunity as a psychological mechanism.

4   **Present Studies**

5   We predicted that providing personalized information about immunity would correct risk

6   misestimation and motivate vaccination. In Study 1 (Session 1), we tested online interventions

7   with 883 U.S. residents across the adult lifespan (ages 18-93). After providing information about

8   all prior COVID-19 vaccine doses and documented infections, participants were randomly

9   assigned to one of three interventions (Figure 1). Participants in the *Immunity Estimator*

10   condition (n=296) received personalized feedback about estimated protection against COVID-19

11   based on each individual's history of vaccines and infections. We compared the Immunity

12   Estimator intervention with two alternative interventions. In the *CDC-Flyer* condition (n=292),

13   participants read a CDC-produced informational flyer that promoted the updated COVID-19

14   vaccine and described eligibility criteria. The purpose of this condition was to test whether the

15   Immunity Estimator condition was more effective than the existing standard treatment, a flyer

16   that was already widely used. In the *Alternative-Flyer* (Alt-Flyer) condition (n=295), we

17   modified the CDC-Flyer to add information about waning immunity. The purpose of this

18   condition was to test whether a minor modification to existing materials would be sufficient to

19   correct beliefs about immunity.

20   Before and after completing one of these interventions, participants answered survey

21   questions about **perceived risk** of COVID-19 infection and severe illness, beliefs about **safety**

22   and **effectiveness** of the updated COVID-19 vaccine, **intentions** to get a vaccine dose,

23   **awareness** of the updated vaccine and **eligibility** criteria, and **interest** in learning more about

1   COVID-19 risks. After a two-month delay (Session 2), we recontacted participants to assess

2   these beliefs again and investigate post-intervention vaccine uptake.

3   We predicted that the Immunity Estimator condition would be most effective at

4   correcting risk perception and motivating vaccination. We expected that the Alt-Flyer would be

5   modestly effective and the CDC-Flyer would be less effective, because it did not address beliefs

6   about immunity. Importantly, we assessed the effectiveness of each intervention by measuring

7   within-subjects changes in beliefs and intentions (comparing pre- and post-intervention

8   measures); the purpose of comparing the three intervention conditions was to determine whether

9   the Immunity Estimator condition was effective *above and beyond* the potential benefits of

10   existing, simpler communication strategies.

11   Following Study 1, we scaled the personalized Immunity Estimator intervention to a

12   public website (https://covid19immunity.com/). In Study 2, soon after the release of new updated

13   COVID-19 vaccines, we replicated our findings in a new sample of 553 U.S. participants

14   (stratified to approximate the demographic makeup of the United States) who interacted with the

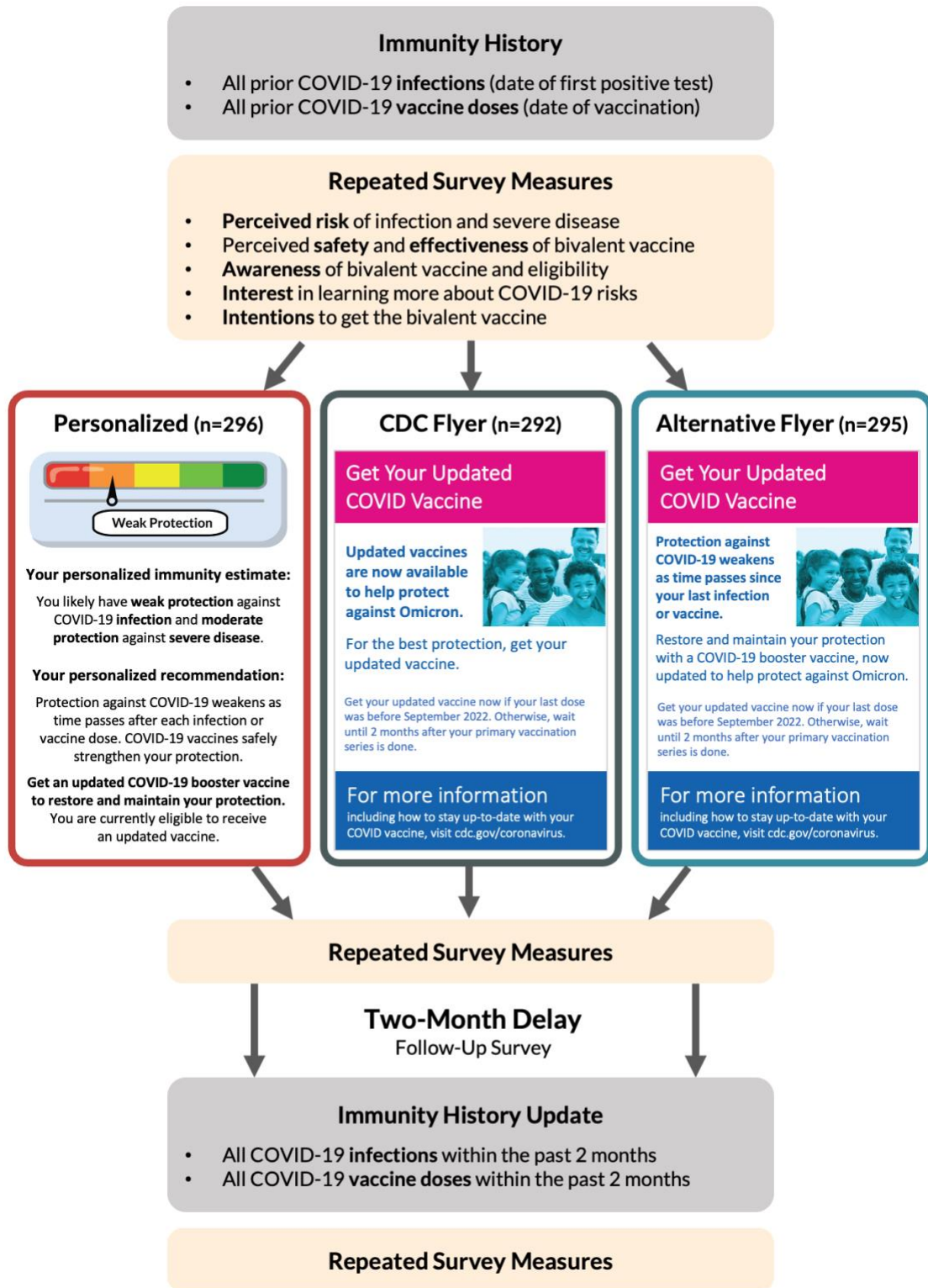15   website version of the intervention.

Figure 1. Overview of Study 1 procedure. Participants first provided information about all prior COVID-19 infections and vaccinations (Immunity History), followed by survey questions (Repeated Survey Measures). Participants were then randomly assigned to view one of three

informational interventions: the Personalized, CDC-Flyer, and Alt-Flyer conditions. After completing one of the three interventions, participants completed the Repeated Survey Measures again. After a two-month delay, we recontacted participants to return for a follow-up survey.

1

2   **Study 1 Results**

3   **Correcting Risk Misestimation**

4   To test whether baseline beliefs about risk were aligned with reality, we summed pre-

5   intervention ratings of perceived risk of *infection* (if exposed to COVID-19) and *severe illness* (if

6   infected with COVID-19) to obtain a composite score of *perceived risk.* We then correlated this

7   score with the immunity scores derived from each participant's history of COVID-19 infections

8   and vaccinations (Methods, *Measures*). There was no association between perceived risk and

9   estimated protection, suggesting that beliefs about immunity were miscalibrated (r=0.01, 95% CI

10   [–0.06, 0.08], t=0.31, p=0.757).

11   We then tested whether the interventions corrected risk misestimation. Ideally, a risk

12   literacy intervention should bidirectionally recalibrate perceived risk, with the degree of change

13   determined by the *magnitude* and *direction* of misestimation (i.e., prediction error [39,58,59]). After

14   an intervention, individuals who are *underestimating* risk should report *increases* in perceived

15   risk, whereas individuals who are *overestimating* risk should report *decreases* in perceived risk.

16   To test these predictions, we calculated a *risk error* score for each participant (Methods,

17   *Measures*). Positive risk error scores indicate overestimation, negative scores indicate

18   underestimation, and zero indicates accurate estimation. Using linear regression, we predicted

19   change in *perceived risk of infection* from *risk error* (continuous variable), *condition* (Immunity

20   Estimator, CDC-Flyer, or Alt-Flyer), *vaccination status* (0=unvaccinated, 1=one or more

21   COVID-19 vaccine doses) and all interactions.

1   There was a main effect of risk error on perceived risk of infection ($\beta=0.21$, 95% CI

2   [0.11, 0.30], $t=4.35$, $p<0.0001$), indicating that the intervention effectively corrected both

3   underestimation and overestimation of risk. There was also an interaction between risk error and

4   condition ($F_{(2,870)}=7.45$, $p=0.0006$, $\eta^2_p=0.02$) (Figure 2A). Risk error predicted change in

5   perceived risk in the Immunity Estimator ($\beta=0.48$, 95% CI [0.29, 0.66], $t=5.14$, $p<0.0001$) and

6   Alt-Flyer conditions ($\beta=0.14$, 95% CI [0.01, 0.28], $t=2.13$, $p=0.034$), but not in the CDC-Flyer

7   condition ($\beta=0.00$, 95% CI [-0.17, 0.17], $t=0.01$, $p=0.990$). The effect of risk error was

8   significantly stronger in the Immunity Estimator condition relative to the CDC-Flyer ($\beta=0.48$,

9   95% CI [0.18, 0.77], $t=3.77$, $p=0.0005$) and Alt-Flyer conditions ($\beta=0.33$, 95% CI [0.06, 0.60],

10   $t=2.89$, $p=0.011$); there was no significant difference between the two Flyer conditions ($\beta=0.14$,

11   95% CI [-0.11, 0.40], $t=1.31$, $p=0.389$). There was also an interaction between risk error and

12   vaccination status ($F_{(1,870)}=8.18$, $p=0.004$, $\eta^2_p=0.01$); the effect of risk error on change in

13   perceived risk was stronger for vaccinated individuals. There were no other significant effects;

14   all parameter estimates are reported in Table S1.

15   We then repeated the analysis described above, but predicted change in *perceived risk of*

16   *severe illness*. Overall, results were very similar to the analysis of perceived risk of infection

17   (Figure 2B). However, in this model, there was also a three-way interaction among risk error,

18   condition, and vaccination status ($F_{(2,870)}=3.61$, $p=0.028$, $\eta^2_p=0.01$); the effect of risk error on

19   change in perceived risk (in the Immunity Estimator and Alt-Flyer conditions) was stronger for

20   vaccinated individuals. Detailed results are reported in Table S2.

21   Results indicated that baseline beliefs about risk were not aligned with reality. The

22   Immunity Estimator condition was the most effective strategy for correcting perceived risk of

infection and severe illness. The Alt-Flyer condition was modestly effective, and the CDC-Flyer

condition did not correct perceived risk.

Individual Differences: Age and Politics

Next, we investigated potential moderators: age and political ideology. As none of the

interventions were effective at changing perceived risk in unvaccinated individuals, for the

following analysis we subset the data to individuals who had received at least one dose of a

COVID-19 vaccine (N=677). On the basis of our prior studies[39,55], we predicted that only the

personalized intervention (Immunity Estimator) would be effective for older adults. In contrast,

we expected that both the Alt-Flyer and Immunity Estimator interventions would be effective for

younger adults. We also predicted that intervention effects would be weaker for politically-
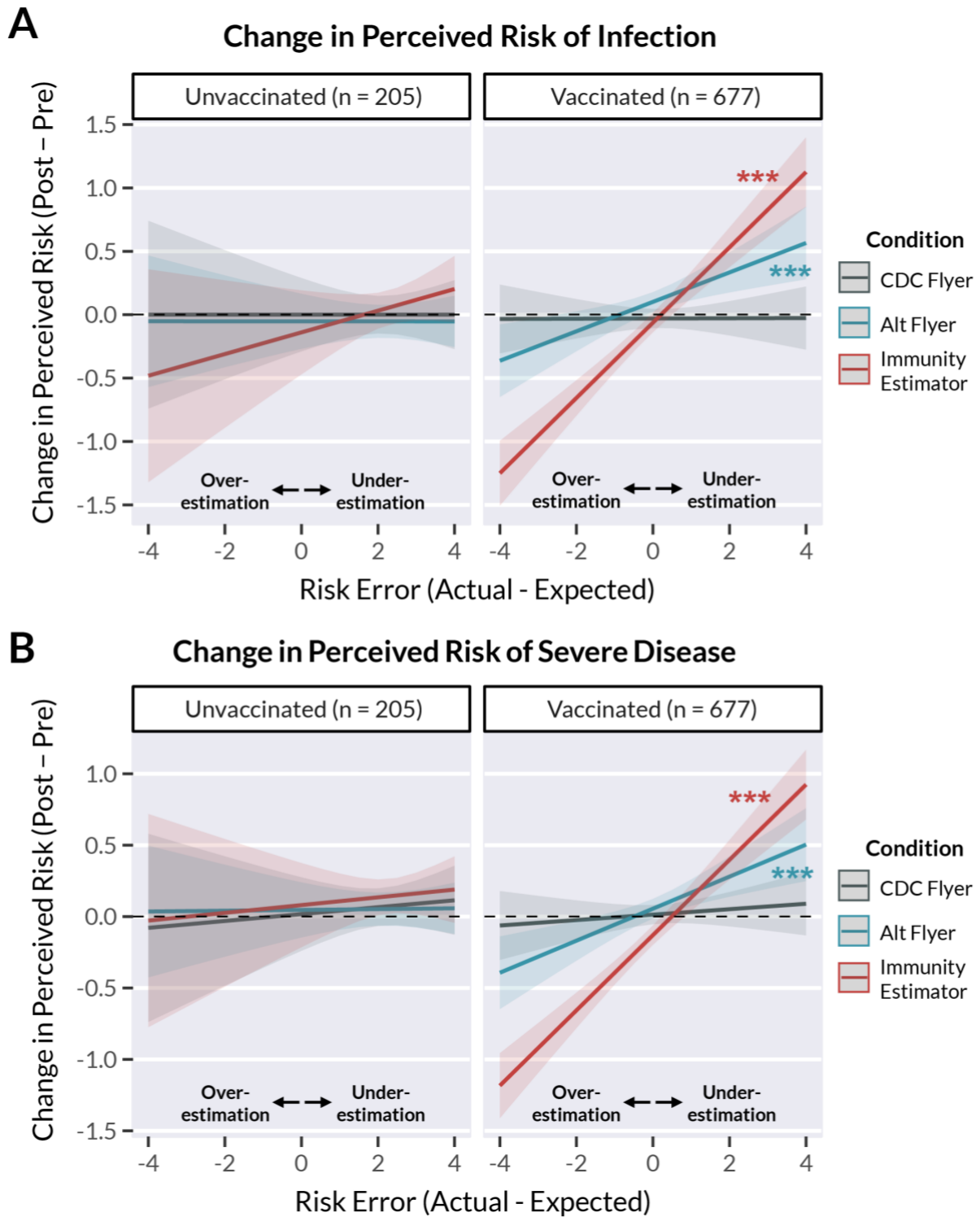
conservative individuals[40–43].

Figure 2. Correction of risk misestimation. Providing information about waning immunity corrected misconceptions about risk of COVID-19 infection (A) and associated severe illness (B). X-axis indicates risk error scores; positive values indicate risk underestimation, zero indicates accurate estimation, and negative values indicate risk overestimation. Positive slopes indicate that perceived risk (y-axis) changed to correct risk misestimation. Among unvaccinated

participants (left panels), none of the interventions were effective (slopes did not differ from zero). Among vaccinated participants (right panels), the Immunity Estimator and Alt-Flyer conditions both effectively corrected risk misestimation in both directions, though the Immunity Estimator condition was substantially more effective (i.e., steeper slope). In the CDC-Flyer condition, perceived risk did not change, regardless of the degree of risk misestimation. Lines depict slope estimates derived from linear regression models. Shaded bands around lines indicate 95% confidence intervals. Dotted horizontal line marks zero change in perceived risk. Plots depict unstandardized variables. Note that here we plot slope estimates without individual points to improve comparison of slopes across conditions; plots including raw data from all 882 participants are included in the Supplementary Information (Figure S1, S2). *** $p < 0.001$

1

2   Using linear regression, we predicted change in *perceived risk of infection* from the

3 variables *condition*, *risk error*, and the interaction term. We also tested whether *age* (continuous

4 variable) or *political attitudes* (continuous variable) moderated these effects. There was an

5 interaction among age, risk error, and condition ($F_{(2,659)}$=4.81, p=0.008, η^2_p=0.01) (Figure 3A).

6 Follow-up tests sampled levels of the continuous age variable to compare younger (age=20),

7 middle-aged (age=40), and older adults (age=60). As predicted, older adults showed recalibration

8 of perceived risk in the Immunity Estimator condition (β=0.73, 95% CI [0.56, 0.90], t=8.31,

9 p<0.0001), but not in the Alt-Flyer (β=0.13, 95% CI [−0.04, 0.30], t=1.51, p=0.132) or CDC-

10 Flyer conditions (β=0.04, 95% CI [−0.11, 0.20], t=0.56, p=0.574). In contrast, younger and

11 middle-aged adults responded to both the Immunity Estimator (Younger: β=0.30, 95% CI [0.07,

12 0.54], t=2.53, p=0.012; Middle-Aged: β=0.52, 95% CI [0.39, 0.65], t=7.74, p<0.0001) and Alt-

13 Flyer (Younger: β=0.39, 95% CI [0.16, 0.63], t=3.33, p=0.001; Middle-Aged: β=0.26, 95% CI

14 [0.12, 0.40], t=3.74, p=0.0002) conditions.

15   There was also an interaction among political attitudes, risk error, and condition

16 ($F_{(2,659)}$=3.74, p=0.024, η^2_p=0.01) (Figure 3B). Follow-up tests sampled levels of the continuous

17 political attitudes variable to compare moderately-liberal (2/5 on political attitudes scale) and

18 moderately-conservative (4/5) participants. In the Immunity Estimator condition, liberals showed

1   a stronger effect of risk error on change in perceived risk than conservatives (β=0.37, 95% CI

2   [0.15, 0.58], t=3.36, p=0.0008). The effect of risk error did not differ by political attitudes in the

3   CDC-Flyer (β=0.14, 95% CI [−0.08, 0.35], t=1.26, p=0.207) or Alt-Flyer conditions (β=−0.08,

4   95% CI [−0.33, 0.16], t=−0.67, p=0.504). However, risk error still predicted change in perceived

5   risk among moderately-conservative participants in the Immunity Estimator (β=0.28, 95% CI

6   [0.05, 0.50], t=2.45, p=0.015) and Alt-Flyer conditions (β=0.29, 95% CI [0.05, 0.53], t=2.36,

7   p=0.018).

8   Other results from this model (testing the subset of vaccinated individuals), were

9   consistent with the previous model that included the full sample of participants without

10   moderators. Additional results are reported in Table S3. The effects of age and political attitudes

11   were specific to perceived risk of infection; there were no significant interactions for perceived

12   risk of severe illness (Table S4).

13   Overall, analysis of individual differences revealed that the Immunity Estimator

14   intervention was particularly effective for older adults, who did not respond to the Alt-Flyer.

15   Although conservatives were less responsive to the interventions, the Immunity Estimator and

16   Alt-Flyer conditions were still effective for moderately-conservative participants.
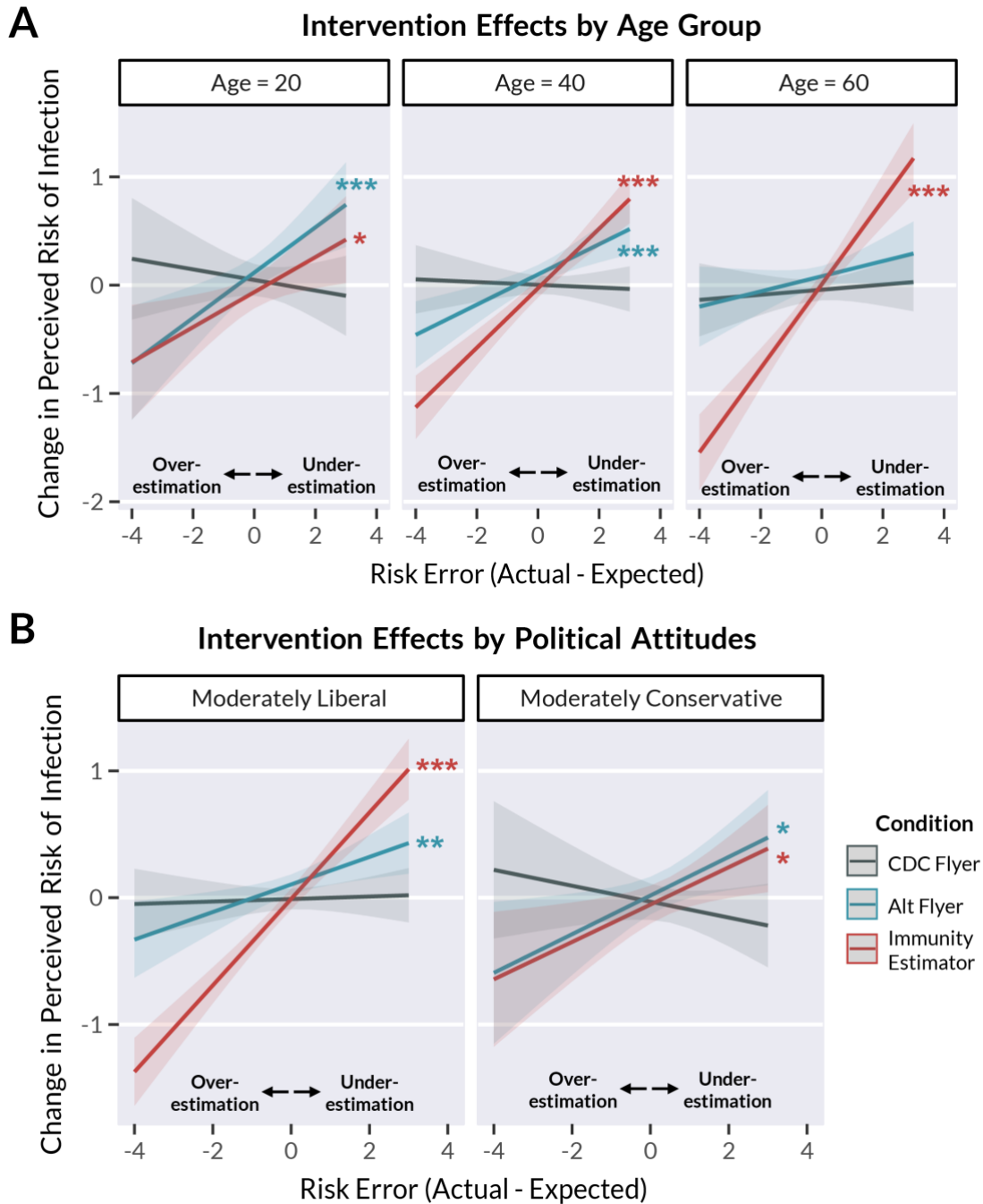
Figure 3. Correction of risk misestimation by age and political attitudes. Shaded bands indicate 95% confidence intervals around lines. A) For younger adults (ages 18-39) and middle-aged adults (ages 40-59), both the Immunity Estimator and Alt-Flyer conditions were effective at correcting risk misestimation. For older adults (ages 60+), only the Immunity Estimator condition was effective. In the statistical model, age was included as a continuous variable; lines depict model-derived slope estimates for 20, 40, and 60 year-old individuals, controlling for political attitudes. B) Liberal and conservative participants alike showed changes in perceived risk in response to both the Immunity Estimator and Alt-Flyer conditions, but effects were weaker for conservatives. In the statistical model, political attitudes were modelled with a

continuous variable; lines depict model-derived slope estimates for moderately-liberal (2/5) and moderately-conservative (4/5) participants, controlling for age. Shaded bands indicate 95% confidence intervals. Plots depict unstandardized variables. Note that here we plot slope estimates without individual points to improve comparison of slopes across conditions; plots with raw data are included in the Supplementary Information (Figure S3). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

1 **Intentions, Knowledge, and Beliefs**

2   Next, we investigated whether the interventions changed intentions, beliefs, or

3 knowledge regarding COVID-19 vaccines. For each measure, we conducted one-sample t-tests

4 on the overall change scores (post-intervention–pre-intervention). We also used ANOVA to

5 compare change scores across conditions; with the exception of interest in learning about

6 COIVD-19 risks, there were no significant differences among conditions. Descriptive statistics

7 and ANOVA results are reported in the Supplementary Information (Table S5, *Beliefs, Attitudes,*

8 *and Knowledge about COVID-19 Booster Vaccines*).

9   Among the subset of participants who were eligible but had not yet received an updated

10 COVID-19 vaccine (n=387), 34.6% already intended to receive the dose at baseline. Post-

11 intervention, there was a small increase in vaccination intentions (3.1% increase; $t_{(386)}$=3.25,

12 p=0.001, Cohen's d=0.17, 95% CI [0.06, 0.27]). This subset of participants also reported

13 increased knowledge of eligibility criteria ($t_{(377)}$=3.61, p=0.0004, Cohen's d=0.19, 95% CI [0.08,

14 0.29]).

15   Among all participants, we observed increased awareness of the updated vaccine

16 ($t_{(881)}$=2.50, p=0.013, Cohen's d=0.08, 95% CI [0.02, 0.15]), but no changes in perceived vaccine

17 safety ($t_{(881)}$=1.65, p=0.100, Cohen's d=0.06, 95% CI [-0.01, 0.12]) or effectiveness ($t_{(881)}$=1.45,

18 p=0.146, Cohen's d=0.05, 95% CI [-0.02, 0.11]). These effects did not differ across conditions,

19 suggesting that providing information about waning immunity did not decrease confidence in

1   vaccine safety or effectiveness. Participants also reported decreased interest in learning about

2   COVID-19 risks ($t_{(881)}$=−3.48, p=0.0005, Cohen's d=−0.12, 95% CI [−0.18, −0.05]); comparing

3   conditions revealed that this effect was driven by the CDC-Flyer ($F_{(2,879)}$=3.01, p=0.050,

4   η^2=0.01).

Session 2: Follow-Up Survey

6   After two months, we recontacted participants who (at baseline) were eligible but had not

7   yet received an updated vaccine; 291 participants returned (Immunity Estimator n=98, CDC-

8   Flyer n=99, Alt-Flyer n=94). We aimed to investigate vaccine uptake and test whether perceived

9   risk remained realigned with actual risk.

Updated Booster Vaccine Uptake

11   During the two months after Session 1, updated COVID-19 vaccine coverage among

12   adults in the U.S. increased by 0.9%[1]. We tested whether the proportion of participants who

13   received an updated vaccine was greater than this national increase. During the study period

14   between February–April 2023, in the Immunity Estimator condition, 7.1% (95% CI: 2–12%) of

15   participants received an updated COVID-19 vaccine, significantly more than the national

16   increase ($t_{(97)}$=2.4, p=0.019, Cohen's d=0.24, 95% CI [0.04, 0.44]). Similarly, in the Alt-Flyer

17   condition, 7.4% (95% CI: 2–13%) of participants received a vaccine ($t_{(93)}$=2.4, p=0.018, Cohen's

18   d=0.25, 95% CI [0.04, 0.46]). In the CDC-Flyer condition, 3.0% (95% CI: 0–6%) of participants

19   received a vaccine; this increase did not significantly differ from the national benchmark

20   ($t_{(98)}$=1.2, p=0.222, Cohen's d=0.12, 95% CI [−0.07, 0.32]). Overall, rates of updated vaccine

21   uptake during the post-intervention period in the Immunity Estimator and Alt-Flyer conditions—

22   the two interventions that informed about waning immunity—were approximately 8x greater

23   (95% CI: 2–14x) than the rate among all U.S. adults.

1   Next, we tested whether recent vaccine uptake differed across conditions, controlling for

2   other variables that we expected would predict vaccination. Using generalized linear regression,

3   we predicted recent *vaccine uptake* (1=received dose, 0=did not receive dose) from the variables

4   *condition* (Immunity Estimator, Alt-Flyer, CDC-Flyer), *prior intentions* reported immediately

5   post-intervention (1=planned to receive dose, 0=unsure/did not plan to receive dose), *risk error*

6   (continuous variable), and all interaction terms. We also included covariates for *age* and *political*

7   *attitudes* (continuous variables).

8   There was a main effect of prior intentions; participants who previously planned to get a

9   booster vaccine were more likely to do so (β=0.18, 95% CI [0.05, 0.31], t=2.65, p=0.008). There

10   was also an interaction between condition and prior intentions ($\chi^2_{(2, N=291)}$=7.10, p=0.029).

11   Among participants who had intended to get a booster vaccine, uptake was highest in the

12   Immunity Estimator condition (14% acted on their intentions). This effect was driven by the

13   contrast between the Immunity Estimator and Alt-Flyer conditions (Immunity Estimator > Alt-

14   Flyer: β=0.48, 95% CI [0.01, 0.96], t=2.0, p=0.047; Immunity Estimator > CDC-Flyer: β=0.29,

15   95% CI [−0.79, 0.22], t=1.13, p=0.260; Alt-Flyer > CDC-Flyer: β=−0.19, 95% CI [−0.70, 0.31],

16   t=0.75, p=0.454). Among participants who had reported *not* intending to get a vaccine, uptake

17   was higher in the Alt-Flyer condition. This effect was driven by the contrast between the Alt-

18   Flyer and CDC-Flyer conditions (Alt-Flyer > CDC-Flyer: β=0.39, 95% CI [0.03, 0.75], t=2.16,

19   p=0.031; Alt-Flyer > Immunity Estimator: β=0.30, 95% CI [−0.07, 0.67], t=1.61, p=0.108;

20   CDC-Flyer > Immunity Estimator: β=−0.09, 95% CI [−0.45, 0.27], t=−0.49, p=0.625). There

21   were no other significant effects. All parameter estimates are reported in Table S6.

22   Overall, during the two months post-intervention, vaccine uptake in the Immunity

23   Estimator and Alt-Flyer conditions was substantially greater than the rate among all U.S. adults

1   during the same time period. Participants in the Immunity Estimator condition who reported

2   intending to get a vaccine dose post-intervention were most likely to act on their intentions.

3   ***Risk Perception Two Months Later***

4   Lastly, we assessed perceived risk two months after intervention. Using linear regression,

5   we predicted *perceived risk* (average of perceived risk of infection/severe illness) from the

6   variables *condition*, *actual risk* (inverse of protection category scores), *risk error* (baseline risk

7   misestimation), and all relevant interaction terms. We expected that the interventions, particularly

8   the Immunity Estimator, would lead to enduring alignment between perceived and actual risk.

9   Overall, actual risk continued to predict perceived risk in Session 2 (β=0.68, 95% CI

10   [0.54, 0.82], t=9.57, p<0.0001). The strength of this association differed across conditions

11   (Figure 4B); there was an interaction between condition and actual risk ($F_{(2,282)}$=5.79, p=0.003,

12   η^2_p=0.04). Perceived-actual risk alignment was stronger in the Immunity Estimator condition

13   relative to the CDC-Flyer (β=0.58, 95% CI [0.24, 0.91], t=3.40, p=0.0008); other contrasts were

14   not significant (Alt-Flyer > CDC-Flyer: β=0.30, 95% CI [−0.05, 0.65], t=1.67, p=0.096,

15   Immunity Estimator > Alt-Flyer: β=0.28, 95% CI [−0.06, 0.62], t=1.60, p=0.110). Risk error also

16   predicted perceived risk, indicating that baseline misestimation was not fully corrected (β=−0.93,

17   95% CI [−0.1.08, −0.79], t=−13.04, p<0.0001). There was no main effect of condition

18   ($F_{(2,282)}$=0.42, p=0.656, η^2_p=0.003), nor an interaction between condition and risk error

1      $(F_{(2,282)}=2.24, p=0.108, \eta^2_p=0.02)$. Overall, perceived risk remained aligned with actual risk two

2   months post-intervention, especially in the Immunity Estimator condition.
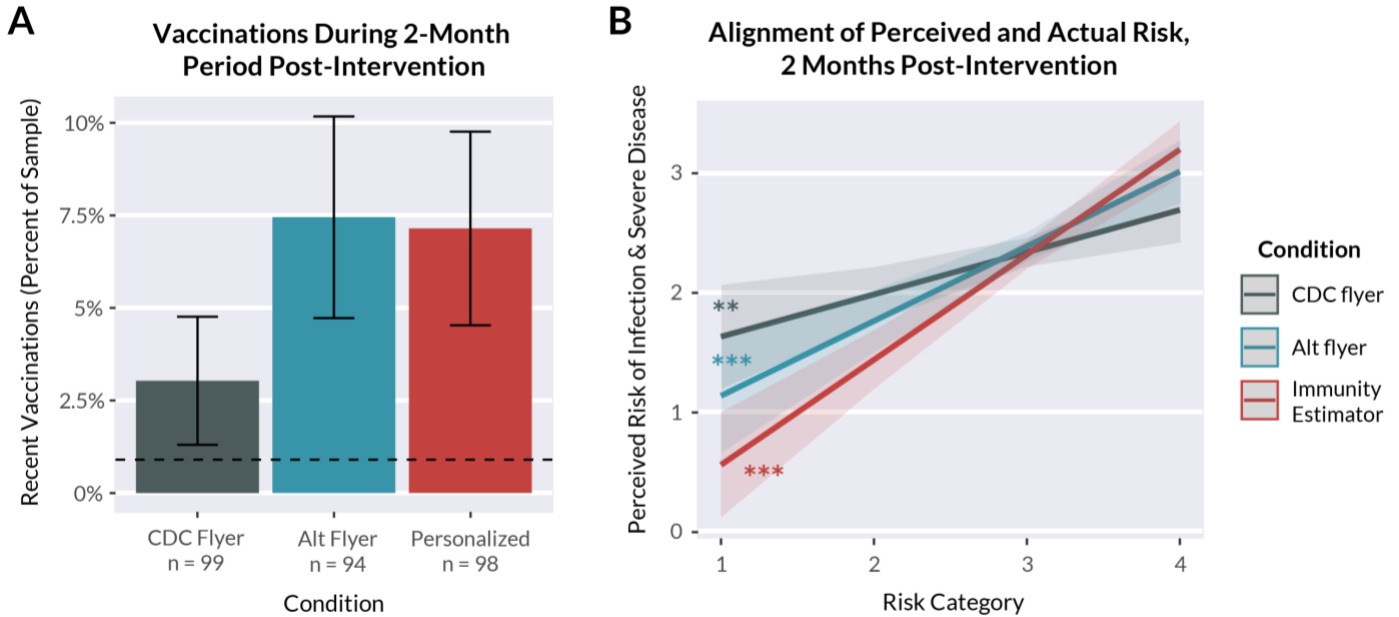

Figure 4. Follow-up survey results (291 participants who had not received a booster vaccine at Time 1). A) Comparing the proportion of participants who recently received a booster vaccine across the three intervention conditions. Dotted black line marks 0.9%, the increase in booster vaccine coverage among adults in the United States during the same 2-month period [1]. Proportions for each condition were compared with this national benchmark. Error bars indicate SEM. B) Comparing the association between perceived and actual risk across conditions. Two months post-intervention, perceived risk was positively correlated with actual risk in all conditions, with the strongest alignment in the Immunity Estimator condition. Lines depict estimated slopes for each condition, derived from a linear regression model controlling for baseline risk misestimation. Shaded bands indicate 95% confidence intervals. Plots depict unstandardized variables. Note that here we plot slope estimates without individual points to improve comparison of slopes across conditions; plots including raw data from all participants are included in the Supplementary Information (Figure S4). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
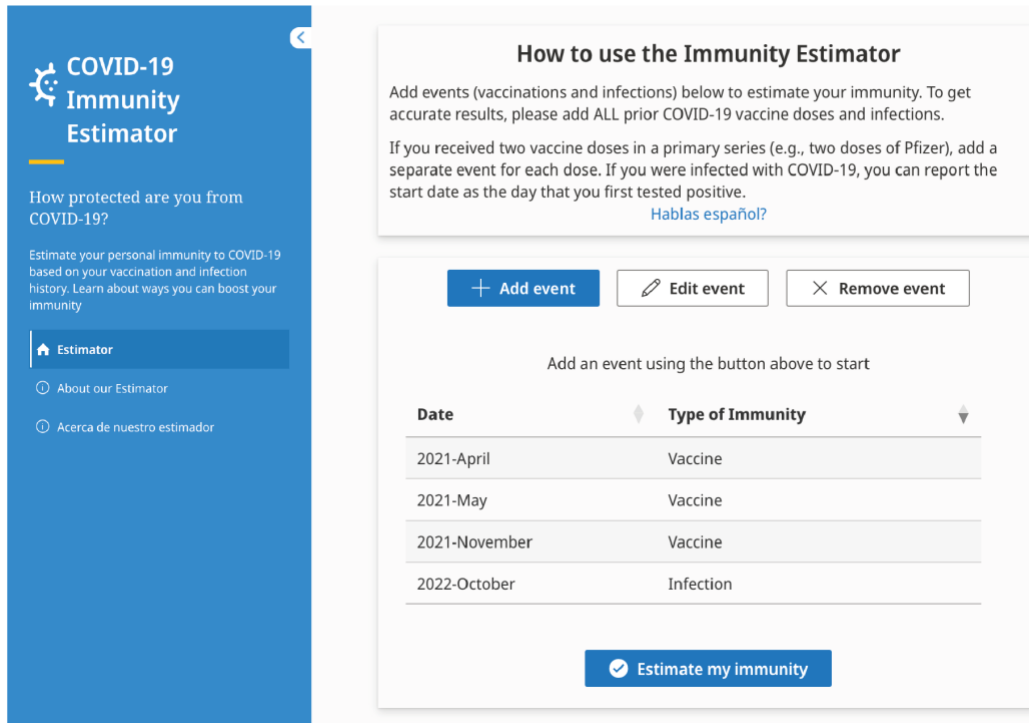
Figure 5. Overview of the COVID-19 Immunity Estimator website used in Study 2. Users added "events" (prior COVID-19 infections or vaccine doses) to a table, reporting the event type, month, and date. After entering all events, participants viewed a feedback page (Figure S5). The website included both English and Spanish language versions.

1   **Study 2 Results**

2   Following Study 1, we scaled our Immunity Estimator intervention to a free and

3   accessible public website, *covid19immunity.com* (Figure 5, Figure S5). In 09/2023, updated

4   COVID-19 vaccines were released. In 12/2023, we recruited an online sample (stratified by age,

5   sex, and race to approximate the demographics of the U.S.) of 606 participants to complete

6   surveys before and after interacting with the Immunity Estimator website. After exclusions (see

7   Methods), the sample included survey data from 553 participants and matching Immunity

8   Estimator website data from 290 participants. Descriptive statistics are provided in Table S7.

9   **Intentions, Knowledge, and Beliefs**

10   To assess the effects of the Immunity Estimator website on beliefs and intentions, we

11   calculated change scores (post-intervention–pre-intervention). Among participants who had not

12   yet received an updated COVID-19 vaccine, the intervention significantly increased intentions to

13   get an updated vaccine ($t_{(370)}$=3.84, p=0.0001, d=0.20, 95% CI [0.10, 0.30]). Among all

14   participants, the intervention increased perceived risk of infection ($t_{(552)}$=6.78, p<0.0001, d=0.29,

15   95% CI [0.20, 0.37]), perceived knowledge about the updated COVID-19 vaccines ($t_{(552)}$=5.81,

16   p<0.0001, d=0.25, 95% CI [0.16, 0.33]), perceived vaccine effectiveness ($t_{(552)}$=4.09, p<0.0001,

17   d=0.17, 95% CI [0.09, 0.26]), and perceived vaccine safety ($t_{(552)}$=2.51, p=0.012, d=0.11, 95% CI

18   [0.02, 0.19]). The intervention did not change interest in learning about COVID-19 risks

19   ($t_{(552)}$=−0.92, p=0.356, d=−0.04, 95% CI [−0.12, 0.04]) or perceived risk of severe illness

20   ($t_{(552)}$=−0.98, p=0.325, d=0.04, 95% CI [−0.04, 0.13]).

21   **Correcting Risk Misestimation**

22   Next, we tested whether the Immunity Estimator website corrected risk misestimation. As

23   in Study 1, in Study 2 we calculated a *risk error* score for each participant (Methods, *Measures*),

1   comparing baseline perceived risk with inversed immunity scores to identify the direction and

2   magnitude of risk misestimation. Using linear regression, we predicted *change in perceived risk*

3   *of infection* from *risk error*, *vaccination status* (0 doses vs. 1+ doses), and the interaction term.

4   We also included age and political ideology as covariates.

5   Replicating our prior findings, risk error predicted change in perceived risk of infection

6   (β=0.48, 95% CI [0.66, 0.30], t=5.19, p<0.0001) (Figure 6A). Participants who underestimated

7   risk reported increased perceived risk, whereas those who overestimated risk reported decreased

8   perceived risk. In addition, there were main effects of vaccination status (β=−0.26, 95% CI

9   [−0.45, −0.08], t=−2.78, p=0.006) and age (β=−0.11, 95% CI [−0.22, −0.01], t=−2.78, p=0.034),

10   such that vaccinated individuals and younger adults reported greater increases in perceived risk.

11   There were no other significant effects; all parameter estimates are reported in Table S8. We also

12   tested a separate model with *change in perceived risk of severe illness* as the dependent variable.

13   Again, risk error was robustly associated with change in perceived risk (β=0.40, 95% CI [0.20,

14   0.60], t=3.90, p=0.0001) (Figure 6B). There were no other significant effects; all parameter
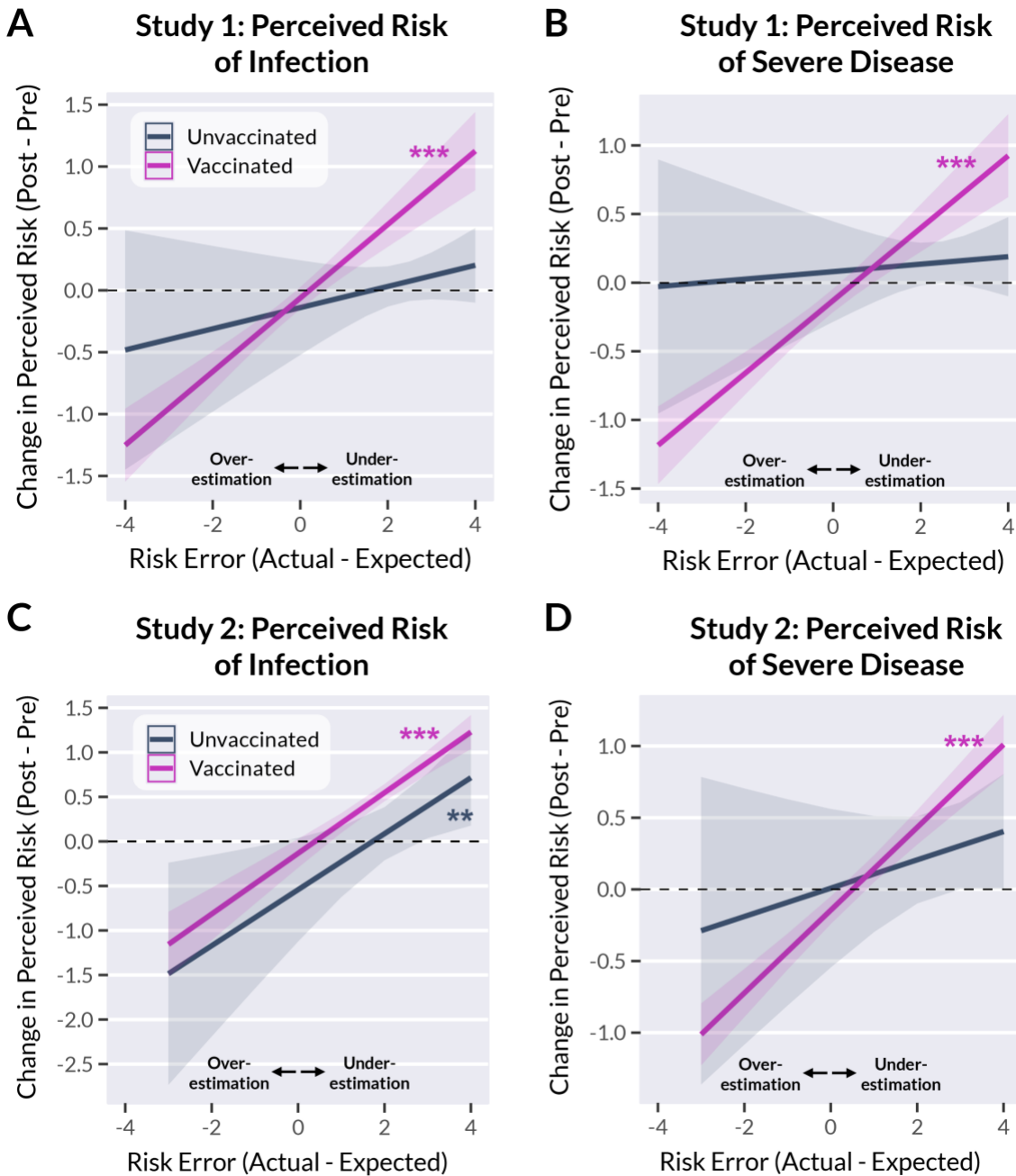
15   estimates are reported in Table S9.

Figure 6. Correction of risk misestimation in Study 2. Replicating findings from the Immunity Estimator condition in Study 1 (reproduced in panels A and B), participants who used the Immunity Estimator website reported changes in perceived risk of infection (C) and severe illness (D) that scaled with the direction and magnitude of feedback (risk error, x-axis). Lines depict estimates slopes from a multiple linear regression model. Shaded bands indicate 95% confidence intervals. Dotted horizontal line marks zero change in perceived risk. Plots depict unstandardized variables. Note that here we plot slope estimates without individual points to improve comparison of slopes across conditions; plots with raw data are included in the Supplementary Information (Figure S6). ** *p* < .01, *** *p* < .001

1   **Discussion**

2   Protection against many viral infections, including COVID-19, weakens as time passes

3   after an infection and/or vaccine dose[3,4,7,9]. Understanding waning immunity is crucial for health

4   behavior; those who overestimate immunity may (i) neglect to stay up-to-date on vaccinations;

5   (ii) not take an antigen test when experiencing symptoms; or (iii) engage in behaviors that

6   increase exposure risk. In Study 1, we showed that our *Immunity Estimator* intervention—which

7   provided personalized feedback about estimated protection against COVID-19 infection and

8   severe illness—effectively corrected both underestimation and overestimation of COVID-19

9   risk. Two months later, corrections to risk perception endured, and the increase in booster

10   vaccine uptake was substantially higher than the national increase. Crucially, this approach was

11   more effective than other informational interventions (a CDC-produced flyer about COVID-19

12   vaccines, or a modified flyer informing about waning immunity), especially for older adults. In

13   Study 2, we developed a public website for the Immunity Estimator intervention and replicated

14   our findings. The Immunity Estimator intervention corrected risk misestimation and increased

15   vaccination intentions, perceived vaccine safety and effectiveness, and awareness of updated

16   vaccines. Overall, we found that providing personalized information about protection against

17   COVID-19 corrected risk misestimation and motivated vaccination.

18   **Correcting Risk Misestimation**

19   In Study 1, baseline beliefs about risk (of infection and severe illness) were not aligned

20   with our immunity estimates. This misalignment coheres with our prior findings that perceived

21   risk of virus exposure is inaccurate[39], and many individuals who are not up-to-date on vaccines

22   erroneously believe they still have strong protection due to prior infection and/or vaccination[19].

Prior studies have investigated risk perception during the COVID-19 pandemic[32,39,40,45], but have not sought to change risk perception by communicating information about waning immunity.

In the Immunity Estimator condition, we provided personalized feedback about estimated protection against viral infection and severe illness, based on one's history of infections and/or vaccinations. We paired these immunity estimates with personalized guidance about booster vaccines and eligibility criteria. The intervention effectively recalibrated perceived risk: participants who had *underestimated* risk reported *increased* perceived risk, whereas those who had *overestimated* risk reported *decreased* perceived risk. Bidirectionally correcting risk perception is important; risk underestimation may increase viral transmission, but risk overestimation can harm mental health[46,60]. Unilaterally encouraging risk aversion can increase anxiety without furthering public health goals[47].

Two months later, perceived risk remained aligned with actual risk. Although participants were not able to review their immunity feedback during the two-month delay, the intervention may have motivated broader information seeking about COVID-19 risk and immunity; in prior work, we showed that post-intervention information seeking supported durable effects[55]. In Study 2, we robustly replicated the effect of the Immunity Estimator intervention correcting risk perception. These findings parallel other studies on learning from feedback, which have shown that *prediction error* (i.e., surprise elicited by feedback that challenges one's prior beliefs) drives belief updating depending on the direction and magnitude of the error[39,58,59,61].

We compared the Immunity Estimator condition with two other informational interventions. We aimed to test whether the Immunity Estimator intervention was more effective than existing, simpler communication strategies. In the CDC-Flyer condition, we showed participants a CDC-produced informational flyer that promoted the updated COVID-19 vaccines.

In the Alt-Flyer condition, we modified the CDC-Flyer to add information about waning

immunity, testing whether a minor change to existing materials would be sufficient to correct

beliefs. Although the specific information provided (and the likely cognitive mechanisms)

differed across conditions, we aimed to demonstrate that the Immunity Estimator intervention

was more effective than the *existing standard of treatment* (analogous to comparing a new

antidepressant with psychotherapy). We found that the Alt-Flyer was modestly effective, but the

CDC-Flyer was not effective at correcting risk misestimation. These results demonstrated that

the Immunity Estimator intervention was more effective than existing approaches, justifying

large-scale implementation. The effectiveness and durability of the Immunity Estimator

intervention—which clearly conveyed "gist" by illustrating levels of protection with a meter

graphic—aligns with predictions from Fuzzy-Trace Theory[52–54], which proposes that gist-like,

categorical thinking about risk drives health behavior more than verbatim information (such as

the details included in the two Flyer conditions).

Vaccine Beliefs, Intentions, and Uptake

We also investigated vaccine-related beliefs, intentions, and uptake. In Study 1, across all

three intervention conditions, participants reported modest increases in vaccination intentions,

perceived knowledge about COVID-19 vaccines, and awareness of eligibility criteria. Beliefs

about the safety and effectiveness of the vaccines did not change, nor did beliefs differ across the

three intervention conditions. Two months post-intervention, the rate of booster vaccination in

the Immunity Estimator and Alt-Flyer conditions was 8x higher (95% CI: 2–14x) than the

nationwide increase among U.S. adults during the same time period. Participants in the Immunity

Estimator condition were most likely to act on their stated intentions to receive a booster dose.

1   In Study 2, participants who used our Immunity Estimator tool to receive personalized

2   feedback again reported increased vaccination intentions, as well as increases in perceived

3   awareness, safety, and effectiveness of the updated vaccines. Importantly, these findings

4   demonstrate that providing information about waning immunity—with a quick and accessible

5   online tool—motivates vaccine uptake without undermining confidence in the safety or

6   effectiveness of vaccines.

7   Our findings relate to prior evidence that personalizing communications[20] and

8   emphasizing self-relevance (e.g., "a vaccine is reserved for *you*")[27] can motivate vaccination.

9   Other studies have tailored vaccine messaging for specific demographics and patient populations,

10   but with limited effectiveness[62–64]. Personalized approaches to vaccine communication could

11   enhance message effectiveness, particularly for underserved populations[65,66]. Our findings

12   expand on the existing literature on COVID-19 vaccination interventions in several

13   ways[20,21,24,30]. We investigated updated COVID-19 vaccines, which are associated with

14   particularly low uptake and unique challenges[19], and implicated immunity beliefs as a key

15   intervention target. Targeting immunity beliefs may also be effective for increasing routine

16   vaccination for other illnesses, such as influenza.

17   **Individual Differences: Political Ideology and Age**

18   Several demographic variables moderated our effects. Our interventions were less

19   effective for unvaccinated participants and those who identified as politically conservative.

20   These findings align with prior evidence that political partisanship is related to risk perception,

21   beliefs about COVID-19, and vaccine uptake[40–43,67–69]. Importantly, however, the Immunity

22   Estimator and Alt-Flyer conditions still corrected risk misestimation among moderately

23   conservative participants. These results align with our prior findings that although conservatives

were less likely to engage with COVID-19 risk information, those who did engage with our

intervention responded similarly to liberals[45].

Intervention effects also differed by age. Younger and middle-aged adults responded to

both the Immunity Estimator and Alt-Flyer conditions, whereas only the Immunity Estimator

condition was effective for older adults. This finding conceptually replicates our prior work, in

which we demonstrated that a personalized intervention (imagining a scenario that involves

yourself and close others) was the most effective strategy for changing risk perception among

older adults[55]. Communicating risk to older adults is particularly important because older adults

are at considerably higher risk of severe illness and death due to many viruses, including

COVID-19 [16] and influenza[70].

Limitations and Future Directions

The present study is subject to several limitations. In Study 1, we used quota sampling to

stratify our sample by age and sex; in Study 2, we instead stratified our sample to approximate

the demographic makeup of the United States. However, we lack the statistical power to

investigate race or ethnicity as moderators in either study. Future studies that oversample

underrepresented groups are needed to investigate other factors that may influence beliefs about

immunity and vaccines[71].

Our immunity estimates are also imperfect. Our estimates were informed by diverse

evidence from studies of antibody levels and vaccine effectiveness, but prior studies have yielded

different estimates for the rate at which immunity wanes[3–5,8,12–15,17,72,73]. Protection also depends

on viral evolution and reformulation of vaccines. Furthermore, as stated to our participants, our

immunity estimates did not account for personal risk factors like age and pre-existing conditions,

which influence the risk of severe illness.

1   In Study 1, although the rate of vaccine uptake was greater than the national average,

2   relatively few participants received a booster vaccine within the two months post-intervention.

3   Some participants who did not initially report planning to get a booster dose did so after the

4   intervention (particularly in the Alt-Flyer condition). These participants may have been unsure or

5   erroneously believed they were ineligible; we lack sufficient statistical power to analyze these

6   uncommon response options. Further research is needed to replicate our vaccine uptake findings

7   in a longitudinal sample that is adequately powered to detect small effects. Lastly, beliefs about

8   immunity may also influence other behavioral intentions, such as willingness to take a COVID-

9   19 test, wear a mask, or avoid situations with high exposure risk. For instance, prior studies have

10   linked perceived risk to many preventative health behaviors during the COVID-19 pandemic[33–

11   36,42]. Future studies could explore whether beliefs about immunity predict other health behaviors.

12   **Conclusion**

13   Here, we demonstrated that a new intervention—an "immunity estimator" tool that

14   provides personalized information about protection against viral infection and severe illness—

15   effectively changed risk perception and motivated booster vaccine uptake. This intervention

16   corrected risk underestimation and overestimation, immediately and two months later. Likewise,

17   our personalized Immunity Estimator intervention increased vaccination intentions immediately

18   post-intervention, as well as vaccine uptake during the two-month period post-intervention. This

19   personalized approach to risk communication was particularly effective for older adults, who are

20   at greater risk of severe illness. We then converted our intervention to an accessible public

21   website and replicated our findings. Importantly, existing promotional materials for vaccines

22   failed to correct misconceptions about immunity or increase vaccination. Overall, we

23   demonstrate that personalized guidance about immunity can change health beliefs and behaviors.

1   We implicate immunity beliefs as a promising target for interventions to increase routine

2   vaccinations, such as for COVID-19 and influenza.

1   **Materials & Methods**

2   **Study 1: Participants**

3   We recruited 900 participants from Prolific, an online platform for paid study

4   participants. The study was described as a "survey about COVID-19 experiences." Data

5   collection took place between 2/10/23 and 2/13/23.

6   We used quota sampling to recruit equal numbers of younger adults (ages 18-39), middle-

7   aged adults (ages 40-59), and older adults (ages 60+). In order to participate, users needed to be

8   fluent in English and currently residing in the United States. Due to low diversity among older

9   adults in the Prolific participant pool, we did not stratify our sample by race or ethnicity. We

10   excluded 17 participants who failed an attention check during the task. We also excluded one

11   participant who provided inaccurate information (claimed to have received the bivalent booster,

12   but had only received one dose of the Johnson & Johnson vaccine). After exclusions, the final

13   sample included 883 participants. Detailed demographic information is provided in the

14   Supplementary Information (*Supplemental Methods, Participant Demographics*).

15   **Study 1: Procedure**

16   Participants first answered questions about their prior experiences with COVID-19

17   infections and vaccines, as well as their beliefs and attitudes pertaining to COVID-19 risk and

18   vaccines. We then randomly assigned participants to one of three intervention conditions:

19   *Immunity Estimator*, *CDC-Flyer*, or *Alt-Flyer*. After completing one of these three interventions,

20   participants completed a post-intervention questionnaire that reiterated some of the pre-

21   intervention questions (to assess changes in beliefs), in addition to demographics questions.

22   In total, the task took approximately 5 minutes. Participants were compensated with

23       $1.40. All participants provided informed consent by clicking a button on a digital form before

1   beginning the task. The study was approved by the Duke University Institutional Review Board

2   and the Georgia Institute of Technology Institutional Review Board.

3   ***Pre-Intervention Questionnaire***

4   We first asked participants to provide information about their prior experiences with

5   COVID-19 infections and vaccinations. Participants reported the number of prior COVID-19

6   infections (diagnosed with a rapid test or PCR test, with or without symptoms), then reported

7   when each infection occurred (date of first positive test). Next, participants reported the number

8   of prior COVID-19 vaccine doses; if a participant had completed a two-part primary vaccination

9   series, they were instructed to count this as two doses. For each prior vaccine dose, participants

10   reported the date the vaccine was received and the brand (Pfizer, Moderna, Johnson & Johnson /

11   Janssen, AstraZeneca, or Novavax) of each vaccine dose.

12   Based on each participant's vaccine history, we identified whether or not each participant

13   had likely received an updated bivalent booster vaccine. Updated booster vaccines were made

14   available across the United States on September 2nd, 2022, replacing the previous monovalent

15   booster vaccines; after this date, all booster doses administered in the U.S. should have used the

16   updated formula. However, exceptions are possible (e.g., if the participant received an updated

17   booster dose earlier as part of a clinical trial, or if a participant received a vaccine dose outside of

18   the United States). We provided this information to participants and asked them to verify whether

19   or not they had received an updated booster vaccine. At this point, participants were also allowed

20   to review their vaccine history and return to the previous page to correct any input errors.

21   Participants then completed a questionnaire about perceived risk and COVID-related

22   beliefs and attitudes. Participants first rated their perceived risk of getting infected with COVID-

23   19 (if exposed to the virus) and perceived risk of getting severely ill with COVID-19 (if

1   infected), as well as their interest in learning more about COVID-19 risks. Next, participants

2   answered several questions about the updated booster vaccines. Participants rated the extent of

3   their prior knowledge about the updated vaccines, whether or not they believed they were

4   eligible to receive an updated vaccine, perceived safety and effectiveness of the updated

5   vaccines, and intentions to get a dose of the updated vaccine (if they had not yet done so).

6   Further information about these questions and response options is provided in the Supplementary

7   Information.

8   ***Immunity Estimator Intervention***

9   **Immunity Estimation.** The Immunity Estimator condition provided personalized

10   information about an individual's protection against COVID-19 infection and severe illness,

11   along with vaccination guidance. We first informed participants, "Next, we will show you some

12   personalized information about your current protection against COVID-19. Our

13   recommendations for you are tailored to your personal history with COVID-19 vaccines and

14   infections. Note that the risk of getting very sick or dying due to COVID-19 is greater if you are

15   above age 50, are overweight or obese, have a weakened immune system, or have underlying

16   health conditions (including diabetes, cancer, heart conditions, or lung conditions)."

17   To provide personalized guidance, we calculated an *immunity score* for each participant.

18   In brief, these immunity scores were determined by each individual's history of COVID-19

19   infections and vaccines, accounting for the number and recency of immune-modifying events.

20   Detailed information about the calculation of immunity scores is reported in the Supplementary

21   Information (*Supplemental Methods*). Due to feasibility issues and privacy concerns, we did not

22   ask participants to report their medical histories to account for other risk factors, such as pre-

23   existing conditions.

1   Participants were not directly shown their immunity scores. Instead, we used the

2   immunity scores to classify participants into five levels of protection. Participants with 0 points

3   (i.e., unvaccinated and with no confirmed COVID-19 infections) were classified as "No

4   Protection." Participants with 1-2 points were classified as "Weak Protection"; we estimated that

5   these participants had weak protection against infection, but moderate protection against severe

6   illness. Participants with 3-6 points were classified as "Moderate Protection" (weak protection

7   against infection, moderately strong protection against severe illness). Participants with 7-10

8   points were classified as "Moderately Strong Protection" (moderate protection against infection,

9   strong protection against severe illness). Participants with 11+ points were classified as "Strong

10   Protection" (strong protection against infection, strong protection against severe illness).

11   **Feedback Page**. Participants viewed a personalized feedback page (participants were not

12   permitted to proceed until at least five seconds had elapsed). At the top of the feedback page, we

13   displayed a meter graphic indicating the participant's protection level, as described above. Below

14   the meter, we provided more information about waning immunity and vaccine eligibility. The

15   full text of the feedback is provided in the Supplementary Information (*Supplemental Methods,*

16   *Immunity Estimator Text*). In brief, the feedback message was tailored to each participant,

17   including general information about waning immunity, personalized guidance about protection

18   and current vaccine eligibility guidelines, and a statement about how vaccines safely boost

19   protection (as opposed to acquiring natural immunity through infections, which are associated

20   with greater health risks).

21   ***Informational Flyer Interventions***

22   We compared the Immunity Estimator intervention with two other interventions that

23   provided similar information without personalization. The CDC-Flyer was an active control

1   condition; we presented a digital copy of a publicly available, CDC-approved informational flyer

2   that was intended to motivate uptake of updated booster vaccines (e.g., in clinics and

3   pharmacies). The Alt-Flyer was a modified version of the CDC-Flyer; we added text about

4   waning immunity to emphasize that protection must be restored and maintained over time. In

5   both conditions, participants were required to view the flyer for at least five seconds before they

6   were permitted to proceed with the task.

7   We predicted that the Immunity Estimator condition would be the most effective at

8   correcting risk misestimation. We expected modest benefits from the Alt-Flyer, which provided

9   information about waning immunity but did not offer personalized guidance. In contrast, we

10   expected that the CDC-Flyer would not effectively correct risk misestimation, because existing

11   promotional materials did not address waning immunity.

12   ***Post-Intervention Questionnaire***

13   After completing one of the three interventions described above (Immunity Estimator,

14   CDC-Flyer, or Alt-Flyer), participants completed a post-intervention questionnaire. As in the pre-

15   intervention questionnaire, we assessed perceived risk of COVID-19 infection and severe illness,

16   interest in learning about COVID-19 risk, knowledge about the updated booster vaccine and

17   one's eligibility to receive it, perceived safety and effectiveness of the updated booster vaccine,

18   and intentions to get an updated booster vaccine. We also measured COVID-skepticism with two

19   items previously used in other studies of COVID-19 attitudes and vaccine hesitancy [74]. For

20   participants who were eligible to receive an updated booster dose, we also provided a link to a

21   government appointment-finder tool for COVID-19 vaccines. Lastly, participants completed a

22   demographics survey.

23

Follow-Up Survey

Two months after the initial study, we recontacted participants who had been eligible to receive an updated booster vaccine but had not yet done so (at the time of the initial study). Of the 384 participants who were recontacted, 291 (76%) completed the follow-up survey. Data collection took place between 4/11/23 and 4/18/23.

In the follow-up survey, we asked participants to report any recent infections or vaccine doses that had occurred in the past two months. Participants then responded to the same set of survey questions that had previously been included in the post-intervention questionnaire (see above). For participants who had not received a COVID-19 vaccine in the past two months, we asked about intentions to get an updated booster vaccine. Those who reported planning to get an updated booster were then prompted to specify when they planned to get the dose (within the next week, in 2-4 weeks, in 4-8 weeks, in 2-6 months, in 6-12 months, or more than a year from now). Lastly, participants rated their agreement (5-point Likert scale ranging from *1=Strongly Disagree* to *5=Strongly Agree*) with two statements that probed beliefs about whether or not COVID-19 vaccines were beneficial personally ("COVID-19 vaccines are beneficial for me as an individual") or societally ("COVID-19 vaccines are beneficial for people in general.")

Study 2: Participants

We recruited a sample of 606 participants from Prolific that was stratified by age, sex, and race variables to approximate the demographics of the United States. Data collection took place between 12/15/23 and 12/18/23. Notably, COVID-19 vaccines were updated again between Study 1 and Study 2; the latest formula was made available on 9/14/23. Participants were paid $1 to complete a task that took up to 5 minutes. All participants provided informed consent by clicking a button on a digital form before beginning the task. The study was approved by the

1   Duke University Institutional Review Board and the Georgia Institute of Technology Institutional

2   Review Board.

3   We excluded 19 participants who failed an attention check, 17 participants who did not

4   click the link to view the Immunity Estimator tool, and 17 participants who remained on the

5   Immunity Estimator website for less than 10 seconds. Analysis of survey questions (e.g.,

6   perceived safety and effectiveness of COVID-19 vaccines) included the remaining 553

7   participants. Analysis of risk misestimation included data from 290 of these participants who

8   successfully submitted data on the Immunity Estimator website with a matching ID variable.

9   While interacting with the Immunity Estimator website, 25 participants (8.0% of the sample)

10   edited their infection and vaccine history to add or correct events, creating multiple entries in the

11   database. To retrieve the final records, we retained the last submission from each participant and

12   excluded any prior submissions. Detailed information about participant demographics is reported

13   in the Supplementary Information (*Supplemental Methods, Participant Demographics*).

14   **Study 2: Procedure**

15   Before interacting with the Immunity Estimator website (https://covid19immunity.com/),

16   participants completed a questionnaire about COVID-19-related beliefs and attitudes. We first

17   informed participants that COVID-19 vaccines had been recently updated to increase protection

18   against new variants of the virus. Participants were asked to report whether they had received a

19   dose of a COVID-19 vaccine on or after 9/14/23, and if so, which brand they had received.

20   As in Study 1, participants then rated the perceived risk of getting infected with COVID-

21   19 (if exposed to the virus) and perceived risk of getting severely ill with COVID-19 (if

22   infected). Participants also rated their interest in learning more about COVID-19 risks, prior

23   knowledge about the updated vaccines (2023-2024 updated bivalent formula), perceived

1   eligibility to receive an updated vaccine, perceived safety and effectiveness of the updated

2   vaccines, recent vaccine uptake, and intentions to receive a dose of the updated vaccine (if they

3   had not yet done so). Further information about these questions and response options is provided

4   in the Supplementary Information.

5   Participants were then instructed to click a link that directed them to our public Immunity

6   Estimator website. Within the survey, we tracked clicks on the link and timed the duration of

7   interaction before participants proceeded with the survey. Participants were free to read and

8   interact with the Immunity Estimator website in the same way that other unpaid users would

9   interact with the website. When participants submitted vaccine and infection history via the

10   Immunity Estimator tool, we saved these responses and used URL parameters to link website

11   data with survey data. After interacting the Immunity Estimator website, participants returned to

12   the survey and responded to the same questions about COVID-19-related beliefs and attitudes.

13   ***Immunity Estimator Website***

14   The Immunity Estimator website provided a user-friendly interface for inputting one's

15   vaccine and infection history and receiving personalized guidance about protection and vaccines

16   (Figure S5). In brief, users were prompted to add "events" to a table, specifying the month and

17   year of all prior COVID-19 vaccines and infections. Users were able to add, delete, and edit

18   events as needed. Upon completing their personal history, users clicked a button labelled

19   "Estimate my immunity" to calculate and reveal feedback. The website then displayed a

20   feedback page that included two protection meter graphics (reflecting protection against

21   infection and severe illness, respectively), general information about waning immunity,

22   personalized guidance about immunity and vaccine eligibility, and a statement about how

23   COVID-19 vaccines safely strengthen immunity (even for individuals who acquired natural

1   immunity through infection). The full text of the feedback page is provided in the Supplementary

2   Information (*Supplemental Methods, Immunity Estimator Text*).

3   On a separate page titled "About our Estimator", we provided additional information

4   about how we estimated protection, other factors that influence protection and risk (e.g., age and

5   comorbidities), and our institutional affiliations and funding sources. We also provided a link to

6   the CDC's webpage on COVID-19 vaccine guidance (https://www.cdc.gov/coronavirus/2019-

7   ncov/vaccines/stay-up-to-date.html).

8   ***Immunity Score Calculation***

9   Immunity scores were estimated using a similar method as in Study 1. However, we

10   adjusted the calculation of these scores to reflect new empirical evidence regarding immunity

11   against SARS-CoV-2. In Study 2, users received separate scores for protection against infection

12   and severe illness. Immunity scores were intended to account for multiple factors that influence

13   protection against SARS-CoV-2: differing rates of waning for protection against infection vs.

14   severe illness, the number of prior immune-modifying events, synergistic effects of hybrid

15   immunity, benefits of recent infections or vaccinations, and exposure to variants of SARS-CoV-2

16   that were circulating at the time that the study was conducted. As in the preliminary version of

17   the tool tested in Study 1, users were not shown their precise immunity scores, only the

18   protection meters and summary text. Detailed information about the calculation of immunity

19   scores is reported in the Supplementary Information (*Supplemental Methods, Calculation of*

20   *Immunity Scores*).

21   **Statistical Analysis**

22   Data were preprocessed and analyzed with R (v4.3.2), implemented in R Studio

23   (v2023.12.1). All follow-up tests for significant interaction terms were corrected with Tukey's

1   HSD to account for multiple comparisons. All statistical models reported in the main text and

2   Supplementary Information use z-scored continuous variables to enable reporting of standardized

3   effect sizes. However, plots depict unstandardized variables for ease of interpretation. ANOVA

4   models use Type III Sum of Squares to account for interaction effects.

5   To assess risk misestimation, we calculated a *risk error* score for each participant. On the

6   basis of their immunity scores (calculated on the basis of prior infections and vaccines),

7   participants were classified into 5 protection categories (ranging from 1=*no protection* to

8   5=*strong protection*); these categories determined the feedback provided in the Immunity

9   Estimator condition. We reverse-scored participants' protection category scores to get a *risk*

10   *category* measure that was directly comparable to the 5-point scale used for perceived risk

11   ratings. We then calculated *risk error* scores by subtracting each participant's pre-intervention

12   *perceived risk* ratings from their *risk category* scores. A risk error score of zero indicates accurate

13   estimation of risk (i.e., perceived risk is appropriately calibrated to one's actual immunity).

14   Scores that are further from zero in either direction indicate more severe risk misestimation.

15   Negative risk error scores indicate risk underestimation, whereas positive risk error scores

16   indicate risk overestimation. Note that in Study 2, we calculated separate immunity scores and

17   displayed separate feedback meters for protection against infection vs. protection against severe

18   illness; therefore, we calculated separate risk error scores for these two protection types.

19   We measured political attitudes by averaging responses to two questions on the

20   demographics survey; participants rated their social and economic political attitudes on a 5-point

21   scale (1=*very liberal* … 3=*centrist* … 5=*very conservative*). The variable for political attitudes

22   was continuous in statistical models, but visualizations and follow-up tests compare moderately-

23   liberal participants (2/5) and moderately-conservative (4/5) participants. Likewise, age was

1   included in statistical models as a continuous variable, but visualizations and follow-up tests

2   show the effect of age at three levels: younger adults (age=20), middle-aged adults (age=40), and

3   older adults (age=60).

Acknowledgements

We thank Adriana Lucia-Sanz, Marian Dominguez-Mirazo, and Rogelio Rodriguez-Gonzalez for their valuable contributions to the Immunity Estimator website, particularly the development of the Spanish-language version of the website. We also thank Samantha Callahan and Gabi Steinbach for their contributions to website design and Benjamin Lopman for feedback on the manuscript.

Author Note

References

1. Centers for Disease Control and Prevention. COVID-19 Vaccinations in the United States. *Data.CDC.gov* https://data.cdc.gov/Vaccinations/COVID-19-Vaccinations-in-the-United-States-Jurisdi/unsk-b7fc/explore.

2. Centers for Disease Control and Prevention. Weekly Flu Vaccination Dashboard. *Centers for Disease Control and Prevention* https://www.cdc.gov/flu/fluvaxview/dashboard/vaccination-dashboard.html (2024).

3. Levin, E. G. *et al.* Waning Immune Humoral Response to BNT162b2 Covid-19 Vaccine over 6 Months. *N Engl J Med* **385**, e84 (2021).

4. Goldberg, Y. *et al.* Protection and Waning of Natural and Hybrid Immunity to SARS-CoV-2. *New England Journal of Medicine* **386**, 2201–2212 (2022).

5. Chemaitelly, H. *et al.* Duration of immune protection of SARS-CoV-2 natural infection against reinfection. *Journal of Travel Medicine* **29**, taac109 (2022).

6. Dadras, O. *et al.* COVID-19 Vaccines' Protection Over Time and the Need for Booster Doses; a Systematic Review. *Arch Acad Emerg Med* **10**, e53 (2022).

7. Bobrovitz, N. *et al.* Protective effectiveness of previous SARS-CoV-2 infection and hybrid immunity against the omicron variant and severe disease: a systematic review and meta-regression. *The Lancet Infectious Diseases* **23**, 556–567 (2023).

8. Chenchula, S., Karunakaran, P., Sharma, S. & Chavan, M. Current evidence on efficacy of COVID-19 booster dose vaccination against the Omicron variant: A systematic review. *Journal of Medical Virology* **94**, 2969–2976 (2022).

9. Crotty, S. Hybrid immunity. *Science* **372**, 1392–1393 (2021).

10. Stamatatos, L. *et al.* mRNA vaccination boosts cross-variant neutralizing antibodies elicited by SARS-CoV-2 infection. *Science* **372**, 1413–1418 (2021).

11. Reynolds, C. J. *et al.* Prior SARS-CoV-2 infection rescues B and T cell responses to variants after first vaccine dose. *Science* **372**, 1418–1423 (2021).

12. Link-Gelles, R. Effectiveness of Bivalent mRNA Vaccines in Preventing Symptomatic SARS-CoV-2 Infection — Increasing Community Access to Testing Program, United States, September–November 2022. *MMWR Morb Mortal Wkly Rep* **71**, (2022).

13. Surie, D. Early Estimates of Bivalent mRNA Vaccine Effectiveness in Preventing COVID-19–Associated Hospitalization Among Immunocompetent Adults Aged ≥65 Years — IVY Network, 18 States, September 8–November 30, 2022. *MMWR Morb Mortal Wkly Rep* **71**, (2022).

14. Tenforde, M. W. Early Estimates of Bivalent mRNA Vaccine Effectiveness in Preventing COVID-19–Associated Emergency Department or Urgent Care Encounters and Hospitalizations Among Immunocompetent Adults — VISION Network, Nine States, September–November 2022. *MMWR Morb Mortal Wkly Rep* **71**, (2022).

15. Scheaffer, S. M. *et al.* Bivalent SARS-CoV-2 mRNA vaccines increase breadth of neutralization and protect against the BA.5 Omicron variant. 2022.09.12.507614 Preprint at https://doi.org/10.1101/2022.09.12.507614 (2022).

16. Chen, Y. *et al.* Aging in COVID-19: Vulnerability, immunity and intervention. *Ageing Research Reviews* **65**, 101205 (2021).

17. Tan, C. Y. *et al.* Effectiveness of a Fourth Dose of COVID-19 mRNA Vaccine Against Omicron Variant Among Elderly People in Singapore. *Ann Intern Med* **175**, 1622–1623 (2022).

18. CDC. COVID-19 Vaccination. *Centers for Disease Control and Prevention*

    https://www.cdc.gov/coronavirus/2019-ncov/vaccines/stay-up-to-date.html (2022).

19. Sinclair, A. H., Taylor, M. K., Weitz, J. S., Beckett, S. J. & Samanez-Larkin, G. R. Reasons

    for Receiving or Not Receiving Bivalent COVID-19 Booster Vaccinations Among Adults —

    United States, November 1–December 10, 2022. *MMWR Morb Mortal Wkly Rep* **72**, 73–75

    (2023).

20. Batteux, E., Mills, F., Jones, L. F., Symons, C. & Weston, D. The Effectiveness of

    Interventions for Increasing COVID-19 Vaccine Uptake: A Systematic Review. *Vaccines* **10**,

    386 (2022).

21. Böhm, R. *et al.* Crowdsourcing interventions to promote uptake of COVID-19 booster

    vaccines. *eClinicalMedicine* **53**, (2022).

22. Wang, Y. & Liu, Y. Multilevel determinants of COVID-19 vaccination hesitancy in the

    United States: A rapid systematic review. *Preventive Medicine Reports* **25**, 101673 (2022).

23. Evans, W. D. & French, J. Demand Creation for COVID-19 Vaccination: Overcoming

    Vaccine Hesitancy through Social Marketing. *Vaccines* **9**, 319 (2021).

24. Peters, M. D. J. Addressing vaccine hesitancy and resistance for COVID-19 vaccines.

    International Journal of Nursing Studies **131**, 104241 (2022).

25. Omer, S. B. *et al.* Promoting COVID-19 vaccine acceptance: recommendations from the

    Lancet Commission on Vaccine Refusal, Acceptance, and Demand in the USA. *The Lancet*

    398, 2186–2192 (2021).

26. CDC. 12 COVID-19 Vaccination Strategies for Your Community. *Centers for Disease*

    Control and Prevention https://www.cdc.gov/vaccines/covid-19/vaccinate-with-

    confidence/community.html (2022).

27. Dai, H. *et al.* Behavioural nudges increase COVID-19 vaccinations. *Nature* **597**, 404–409 (2021).

28. Rabb, N. *et al.* Evidence from a statewide vaccination RCT shows the limits of nudges. *Nature* **604**, E1–E7 (2022).

29. Patel, M. S. *et al.* Effect of Text Message Reminders and Vaccine Reservations on Adherence to a Health System COVID-19 Vaccination Policy. *JAMA Netw Open* **5**, e2222116 (2022).

30. Sprengholz, P., Henkel, L., Böhm, R. & Betsch, C. Different Interventions for COVID-19 Primary and Booster Vaccination? Effects of Psychological Factors and Health Policies on Vaccine Uptake. *Med Decis Making* **43**, 239–251 (2023).

31. Faksova, K. *et al.* COVID-19 vaccines and adverse events of special interest: A multinational Global Vaccine Data Network (GVDN) cohort study of 99 million vaccinated individuals. *Vaccine* **42**, 2200–2211 (2024).

32. Yıldırım, M. & Güler, A. Factor analysis of the COVID-19 Perceived Risk Scale: A preliminary study. *Death Studies* **0**, 1–8 (2020).

33. Dryhurst, S. *et al.* Risk perceptions of COVID-19 around the world. *Journal of Risk Research* **23**, 994–1006 (2020).

34. Vai, B. *et al.* Risk Perception and Media in Shaping Protective Behaviors: Insights From the Early Phase of COVID-19 Italian Outbreak. *Front. Psychol.* **11**, (2020).

35. Yıldırım, M., Geçer, E. & Akgül, Ö. The impacts of vulnerability, perceived risk, and fear on preventive behaviours against COVID-19. *Psychology, Health & Medicine* **26**, 35–43 (2020).

36. Xie, K., Liang, B., Dulebenets, M. A. & Mei, Y. The Impact of Risk Perception on Social Distancing during the COVID-19 Pandemic in China. *International Journal of Environmental Research and Public Health* **17**, 6256 (2020).

37. Faasse, K. & Newby, J. Public Perceptions of COVID-19 in Australia: Perceived Risk, Knowledge, Health-Protective Behaviors, and Vaccine Intentions. *Front Psychol* **11**, 551004 (2020).

38. Sánchez-Cañizares, S. M., Cabeza-Ramírez, L. J., Muñoz-Fernández, G. & Fuentes-García, F. J. Impact of the perceived risk from Covid-19 on intention to travel. *Current Issues in Tourism* **24**, 970–984 (2021).

39. Sinclair, A. H., Hakimi, S., Stanley, M. L., Adcock, R. A. & Samanez-Larkin, G. R. Pairing facts with imagined consequences improves pandemic-related risk perception. *PNAS* **118**, e2100970118 (2021).

40. Barrios, J. M. & Hochberg, Y. *Risk Perception Through the Lens of Politics in the Time of the COVID-19 Pandemic*. http://www.nber.org/papers/w27008 (2020) doi:10.3386/w27008.

41. Ye, X. Exploring the relationship between political partisanship and COVID-19 vaccination rate. *Journal of Public Health* fdab364 (2021) doi:10.1093/pubmed/fdab364.

42. Bruine de Bruin, W., Saw, H.-W. & Goldman, D. P. Political polarization in US residents' COVID-19 risk perceptions, policy preferences, and protective behaviors. *J Risk Uncertain* **61**, 177–194 (2020).

43. Pennycook, G., McPhetres, J., Bago, B. & Rand, D. G. Beliefs About COVID-19 in Canada, the United Kingdom, and the United States: A Novel Test of Political Polarization and Motivated Reasoning. *Pers Soc Psychol Bull* **48**, 750–765 (2022).

44. Iachini, T. *et al.* Social Distance during the COVID-19 Pandemic Reflects Perceived Rather Than Actual Risk. *International Journal of Environmental Research and Public Health* **18**, 5504 (2021).

45. Sinclair, A. H. *et al.* Communicating COVID-19 exposure risk with an interactive website counteracts risk misestimation. *PLOS ONE* **18**, e0290708 (2023).

46. Choi, K. R., Heilemann, M. V., Fauer, A. & Mead, M. A Second Pandemic: Mental Health Spillover From the Novel Coronavirus (COVID-19). *J Am Psychiatr Nurses Assoc* **26**, 340–343 (2020).

47. Dorison, C. A. *et al.* In COVID-19 Health Messaging, Loss Framing Increases Anxiety with Little-to-No Concomitant Benefits: Experimental Evidence from 84 Countries. *Affec Sci* **3**, 577–602 (2022).

48. Fitzpatrick, K. M., Drawve, G. & Harris, C. Facing new fears during the COVID-19 pandemic: The State of America's mental health. *J Anxiety Disord* **75**, 102291 (2020).

49. Ajzen, I. The theory of planned behavior. *Organizational Behavior and Human Decision Processes* **50**, 179–211 (1991).

50. Brewer, N. T., Chapman, G. B., Rothman, A. J., Leask, J. & Kempe, A. Increasing Vaccination: Putting Psychological Science Into Action. *Psychol Sci Public Interest* **18**, 149–207 (2017).

51. Van Bavel, J. J. *et al.* Using social and behavioural science to support COVID-19 pandemic response. *Nature Human Behaviour* **4**, 460–471 (2020).

52. Blalock, S. J. & Reyna, V. F. Using Fuzzy-Trace Theory to Understand and Improve Health Judgments, Decisions, and Behaviors: A Literature Review. *Health Psychol* **35**, 781–792 (2016).

53. Reyna, V. F., Broniatowski, D. A. & Edelson, S. M. Viruses, vaccines, and COVID-19: Explaining and improving risky decision-making. *Journal of Applied Research in Memory and Cognition* **10**, 491–509 (2021).

54. Edelson, S. M., Reyna, V. F., Hayes, B. B. & Garavito, D. M. N. Dual-systems and fuzzy-trace theory predictions of COVID-19 risk taking in young adults. *Decision* **11**, 355–382 (2024).

55. Sinclair, A. H. *et al.* Imagining a personalized scenario selectively increases perceived risk of viral transmission for older adults. *Nat Aging* **1**, 677–683 (2021).

56. Chande, A. *et al.* Real-time, interactive website for US-county-level COVID-19 event risk assessment. *Nature Human Behaviour* **4**, 1313–1319 (2020).

57. Sinclair, A. H. *et al.* Scenario-based messages on social media motivate COVID-19 information seeking. *Journal of Applied Research in Memory and Cognition* **13**, 124–135 (2023).

58. Pine, A., Sadeh, N., Ben-Yakov, A., Dudai, Y. & Mendelsohn, A. Knowledge acquisition is governed by striatal prediction errors. *Nature Communications* **9**, 1–14 (2018).

59. Vlasceanu, M., Morais, M. J. & Coman, A. The Effect of Prediction Error on Belief Update Across the Political Spectrum. *Psychol Sci* **32**, 916–933 (2021).

60. French, M., Mortensen, K. & Timming, A. Psychological Distress and Coronavirus Fears During the Initial Phase of the COVID-19 Pandemic in the United States. *The Journal of Mental Health Policy and Economics* **23**, 93–100 (2020).

61. Sinclair, A. H., Stanley, M. L. & Seli, P. Closed-minded cognition: Right-wing authoritarianism is negatively related to belief updating following prediction error. *Psychonomic Bulletin and Review* 1–14 (2020) doi:10.3758/s13423-020-01767-y.

62. Frascella, B. *et al.* Effectiveness of email-based reminders to increase vaccine uptake: a systematic review. *Vaccine* **38**, 433–443 (2020).

63. Szilagyi, P. G. *et al.* Effect of Personalized Messages Sent by a Health System's Patient

    Portal on Influenza Vaccination Rates: a Randomized Clinical Trial. *J GEN INTERN MED*

    37, 615–623 (2022).

64. Christy, K. R., Minich, M., Tao, R., Riddle, K. & Kim, S. To Tailor or Not to Tailor: An

    Investigation of Narrative Tailoring for Health Communication. *Journal of Health*

    Communication **27**, 152–163 (2022).

65. Karinshak, E., Liu, S. X., Park, J. S. & Hancock, J. T. Working With AI to Persuade:

    Examining a Large Language Model's Ability to Generate Pro-Vaccination Messages. *Proc.*

    ACM Hum.-Comput. Interact. **7**, 116:1-116:29 (2023).

66. Ford, K. L., West, A. B., Bucher, A. & Osborn, C. Y. Personalized Digital Health

    Communications to Increase COVID-19 Vaccination in Underserved Populations: A Double

    Diamond Approach to Behavioral Design. *Frontiers in Digital Health* **4**, (2022).

67. Grossman, G., Kim, S., Rexer, J. M. & Thirumurthy, H. Political partisanship influences

    behavioral responses to governors' recommendations for COVID-19 prevention in the

    United States. *Proceedings of the National Academy of Sciences* **117**, 24144–24153 (2020).

68. Kerr, J., Panagopoulos, C. & van der Linden, S. Political polarization on COVID-19

    pandemic response in the United States. *Personality and Individual Differences* **179**, 110892

    (2021).

69. Weisel, O. Vaccination as a social contract: The case of COVID-19 and US political

    partisanship. *Proceedings of the National Academy of Sciences* **118**, e2026745118 (2021).

70. Monto, A. S. *et al.* Influenza control in the 21st century: Optimizing protection of older

    adults. *Vaccine* **27**, 5043–5053 (2009).

71. Baker, L., Phillips, B., Faherty, L. J., Ringel, J. S. & Kranz, A. M. Racial And Ethnic Disparities In COVID-19 Booster Uptake. *Health Affairs* **41**, 1202–1207 (2022).

72. Jones, J. Infection-induced and hybrid immunity. *ACIP June 21-23, 2023 Presentation Slides* https://www.cdc.gov/vaccines/acip/meetings/slides-2023-06-21-23.html (2023).

73. Rössler, A., Riepler, L., Bante, D., von Laer, D. & Kimpel, J. SARS-CoV-2 Omicron Variant Neutralization in Serum from Vaccinated and Convalescent Persons. *N Engl J Med* **386**, 698–700 (2022).

74. Levin, J. & Bradshaw, M. Determinants of COVID-19 skepticism and SARS-CoV-2 vaccine hesitancy: findings from a national population survey of U.S. adults. *BMC Public Health* **22**, 1047 (2022).

75. Sinclair, A. H. Supplemental materials for: Personalized Feedback about Immunity Corrects Risk Misestimation and Motivates Vaccination. (2023) doi:10.17605/OSF.IO/74SZ9.