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Willingness to vaccinate against SARS-CoV-2: The role of reasoning biases and conspiracist ideation

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ABSTRACT

Backgr1ound: Widespread vaccine hesitancy and refusal complicate containment of the SARS-CoV-2 pandemic. Extant research indicates that biased reasoning and conspiracist ideation discourage vaccination. However, causal pathways from these constructs to vaccine hesitancy and refusal remain underspecified, impeding efforts to intervene and increase vaccine uptake.
Method: 554 participants who denied prior SARS-CoV-2 vaccination completed self-report measures of SARS-CoV-2 vaccine intentions, conspiracist ideation, and constructs from the Health Belief Model of medical decision-making (such as perceived vaccine dangerousness) along with tasks measuring reasoning biases (such as those concerning data gathering behavior). Cutting-edge machine learning algorithms (Greedy Fast Causal Inference) and psychometric network analysis were used to elucidate causal pathways to (and from) vaccine intentions.
Results: Results indicated that a bias toward reduced data gathering during reasoning may cause paranoia, increasing the perceived dangerousness of vaccines and thereby reducing willingness to vaccinate. Existing interventions that target data gathering and paranoia therefore hold promise for encouraging vaccination. Additionally, reduced willingness to vaccinate was identified as a likely cause of belief in conspiracy theories, subverting the common assumption that the opposite causal relation exists. Finally, perceived severity of SARS-CoV-2 infection and perceived vaccine dangerousness (but not effectiveness) were potential direct causes of willingness to vaccinate, providing partial support for the Health Belief Model's applicability to SARS-CoV-2 vaccine decisions.
Conclusions: These insights significantly advance our understanding of the underpinnings of vaccine intentions and should scaffold efforts to prepare more effective interventions on hesitancy for deployment during future pandemics.

1. Introduction

> Mr. Gibbs was convinced that there were a number of medical men…who wanted nothing to be said upon the subject [of the harms associated with smallpox vaccination], and it was therefore his mission to compel them to speak out.
>
> —*The Leeds Mercury (December 3, 1867) describing the commentary of Mr. Gibbs, honorary secretary to the Anti-Vaccination League, Leeds, England*

As the epigraph implies, unwillingness to vaccinate was an obstacle to controlling infectious disease long before the SARS-CoV-2 pandemic [21,49,60]. However, this challenge has taken on new urgency as significant numbers of adults hesitate or refuse to vaccinate themselves [9,29] and/or their children [33,59] against SARS-CoV-2, creating an ongoing risk of vaccine-preventable morbidity and mortality made particularly salient by the progressively increasing virulence of emerging SARS-CoV-2 variants [13].

Conspiracist ideation, which proliferates during societal crises (including disease outbreaks; [55], may have contributed to this public health crisis. The association between conspiracist ideation and vaccine hesitancy is longstanding (as implied by the epigraph above), reliable [3,45,51], and strong relative to other correlates of hesitancy [23]. Exposure to conspiracy theories weakens vaccine intentions [8,26], and potential mediators of this effect—such as perceived disease risk and vaccine dangerousness [26,45]—are plausible mechanisms by which conspiracy theories might discourage vaccination: the Health Belief Model (a prominent theory

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of medical decisions) posits that both these constructs (along with perceived vaccine effectiveness and disease severity) influence vaccination decisions [25].

The putative causal relation between conspiracist ideation and vaccine intentions implies that causes of such ideation, including paranoia and locus of control, should indirectly impact intentions. Paranoia may cause belief in conspiracy theories by encouraging fear of external agents and the belief that intentions (rather than coincidences) are primary causes of world events [10], explaining its association with SARS-CoV-2 conspiracist ideation [17]. Threats to internal locus of control may cause belief in conspiracy theories by increasing illusory pattern perception, which may explain increased endorsement of such theories following natural disasters [54], such as pandemics.

Reasoning biases may also facilitate conspiracist ideation. Conspiracist ideation is correlated with several biases, including the tendency to gather less data prior to decision-making ("jumping to conclusions"; [44,47] and the tendency toward lowered decision thresholds ("liberal acceptance"; [28], both of which are thought to cause epistemically-suspect beliefs (see: [6]. Manipulating particular reasoning biases, such as the tendency to perceive patterns in data when none are present ("illusory pattern perception"), increases conspiracist ideation [62]. Reasoning biases may cause conspiracist ideation because they influence individuals' likelihood of endorsing epistemically-suspect alternatives to official accounts, and motivate them to search for these accounts by encouraging paranoid thinking styles and distrust of information authorities, including scientists (see: [41]).

Determining whether the aforementioned factors indirectly impact vaccine intentions could support more effective intervention on vaccine uptake. Many of these factors (e.g., paranoia, reasoning biases) are modifiable [19]; Steffen [35] and are therefore potential novel targets for interventions aiming to increase vaccine uptake. Novel interventions that encourage vaccination would be invaluable because commonly-used strategies are frequently ineffective [42] or backfire. For instance, correcting myths that vaccines cause disease can increase hesitancy [40]. Interventions that reduce belief in conspiracy theories may have the additional beneficial effects of discouraging violence [38] and encouraging prosocial behavior [27,53].

1.1. The present study

With this literature in mind, the present study tested the pre-registered hypothesis that belief in conspiracy theories reduces willingness to vaccinate against SARS-CoV-2, and that this effect is (at least partially) transmitted via constructs highlighted in the Health Belief Model. Pre-registered hypotheses regarding the interrelations among reasoning biases (see **SI Section S8**) were also tested. Primary tests of these hypotheses were conducted using causal discovery analysis, which leverages machine-learning algorithms to identify potential causal pathways in observational datasets [48]. This cutting-edge method was used alongside more traditional techniques, such as psychometric network analysis, which offers a more relaxed approach to identifying potential causal effects and provides additional information about their valence and relative magnitude, to identify likely determinants (reasoning biases, personality traits, etc.) of belief in SARS-CoV-2 related conspiracy theories and vaccine intentions. Testing these hypotheses was expected to shed light on the mechanisms underlying willingness to vaccinate and their relationship to belief in conspiracy theories, laying foundations for more effective interventions that could be deployed to combat pandemics in the post-truth era (see: [31]).

2. Method

2.1. Participants and recruitment

Data were collected April 1–8, 2021. Participation was restricted to Prolific users ages 18+ who lived in the United States, had access to a computer, and reported being unvaccinated against SARS-CoV-2 in a screening survey. The final sample (after excluding low-quality responses) included 554 participants (demographics, information on drop-out, see **SI Section S1**).

2.2. Data quality measures

Several steps were taken to ensure high data quality, including checks on attention/effort and survey completion speed (see **SI Section S1**).

2.3. Open science practices

The hypotheses and analysis plan for this study was pre-registered (https://osf.io/v6ej2). Anonymized data are available at: https://osf.io/z9cf6/.

2.4. Protocol

This study was approved by the University of Minnesota Institutional Review Board and informed consent was obtained accordingly. The screening survey included demographic questions and the Belief in Conspiracy Theories Inventory (BCTI; [50]. We invited all eligible participants with sufficient data quality to the main study, despite our pre-registered stratified sampling plan, to ensure sufficient statistical power. The main study included self-report measures of vaccine intentions, Health Belief Model constructs (e.g., perceived vaccine dangerousness), belief in SARS-CoV-2 vaccine-related conspiracy theories, paranoia, locus of control, and epistemic trust in scientists. It also included task-based measures of reasoning biases. Tasks and measures were completed in randomized order. Participants received $9 remuneration.

2.5. Measures

Participants completed the measures listed below. All measures had good-to-excellent internal consistencies, as evaluated using Omega Total [32]; see: **SI Section S2**). For a summary of evidence regarding validity of the self-report measures below, see **SI Sections S2 and S3.** For full versions of measures developed for this study, see **SI Section S3**.

2.5.1. Self-report measures

SARS-CoV-2 Vaccine Intentions were measured using a five-item scale developed for the present study (a sixth item was excluded, see: **SI Section S3**). Respondents rate each item (example: "I am confident that getting the [Pfizer/Moderna] vaccine this week would be the right thing to do") on a 7-point scale (1="completely disagree, 7="completely agree"). Scores range from 5 to 35. Participants also rated willingness to vaccinate their children (if they had them), for exploratory purposes (see **SI Section S7**). Prior to rating the items, participants were randomly assigned to read the Emergency Use Authorization (EUA) fact sheet for either the Pfizer or Moderna vaccine against SARS-CoV-2 (for comparison of intentions on this basis, see: **SI Section S8**). Thus, the present study measured willingness to receive a specific SARS-CoV-2 vaccine authorized by the US Food and Drug Administration (FDA).

Perceived Vaccine Dangerousness was measured using a seven-item scale developed for the present study. Respondents rate each item (example: "Vaccines cause people to develop allergies") on a seven-point scale (1="completely disagree, 7="completely agree"). Scores range from 7 to 49.

Perceived Vaccine Effectiveness [43] was measured by having respondents rate four items (example: "vaccines are one of the most effective medical treatments") on a seven-point scale (1="strongly disagree", 7="strongly agree"). Scores range from 4 to 28.

Perceived Severity of SARS-CoV-2 Infection was measured using an eight-item scale developed for this study. Respondents rate the likelihood that a person inflected with SARS-CoV-2 will experience various outcomes (examples: "be hospitalized" and "die") on a seven-point scale (1="Extremely Unlikely", 7="Extremely Likely"). Scores range from 1 to 56.

Belief in SARS-CoV-2 vaccine conspiracy theories was measured using a six-item scale developed for the present study. For each item, respondents rate the accuracy of a different SARS-CoV-2 vaccine related conspiracy theory (example: "The [SARS-CoV-2] vaccine contains a microchip that will be used in a global tracking system") on a nine-point scale (1="Completely False", 9="Completely True"). Scores range from 1 to 54.

Generalized Conspiracist Ideation was measured using the Belief in Conspiracy Theories Inventory (BCTI; [50]. Respondents rate 14 items (example: "The Apollo moon landings never happened and were staged in a Hollywood film studio") on a nine-point scale (1="Completely False", 9="Completely True"). One BCTI item was excluded because it dealt with UK government distribution of drugs to racial/ethnic minorities and was deemed less relevant to our US-based participants. Ratings were averaged to produce a total score; scores ranged from 1 to 9.

Paranoia was measured using the Revised Green et al. Paranoid Thoughts Scale's (R-GPTS; [16]) persecutory ideation subscale (the GPTS-B). Respondents rate the ten subscale items (example: "I was sure someone wanted to hurt me") on a five-point scale (0="Not at all", 4="Totally"). Scores range from 0 to 40.

Epistemic Trust in Scientists was measured using the Muenster Epistemic Trustworthiness Inventory (METI; [22]). Respondents rated how well 14 opposing adjective pairs describe scientists, as a group, using a seven-point scale (example: I consider scientists to be: 1="Competent", 4="In the middle", 7="Incompetent"). Adjective pairs were designed to address perceptions (of the expert's integrity, benevolence, and expertise) that may impact decisions to place epistemic trust in and defer to the expert. Scores range from 14 to 98.

Locus of Control was measured using Levenson's Locus of Control scale [30]. Respondents rate 24 items on a six-point scale (1="Strongly Disagree", 6="Strongly Agree"). The measure has three subscales: internal and external locus of control, and control by chance. Scores on each subscale range from 8 to 48.

2.5.2. Task-based measures of reasoning biases

Data Gathering was measured using the Box Task (Steffen [36]). The goal of the Box Task is to determine whether an array of (12) closed boxes is primarily black or yellow inside. In each task trial, respondents can either report their determination or gather more data by opening a random box. Prior to opening a box, participants indicated (on an 11-point scale: 1="100% sure black", 11="100% sure yellow") whether they believed the open boxes in the resulting display would be primarily black or yellow. The sequence of colors revealed was randomized, but used the same color ratio (5[black]:4[yellow]) as that employed in two previous studies (Steffen [36,37]). Respondents are told that there is a maximum number of boxes they can open before reporting their decision (in this case, nine), but not the exact limit. After a determination is made, respondents report their post-decision confidence on a seven-point scale (1="I was guessing", 7="Certain I was right"). The key metric derived from this task was the number of data points requested before a decision was made ("draws to decision").

Decision Thresholds [34] were measured via a multiple-choice painting title quiz. Respondents rated the plausibility of each title (on a 0–100 scale; higher rating=more plausible), then could decide whether one title was correct. The key metric derived from the task was the average plausibility rating for titles that the participant decided were correct.

Illusory Pattern Perception was measured using the Snowy Pictures Task [62]. Respondents view 24 pictures with visual noise (from: [58] and indicate whether they contain a difficult-to-perceive object (half do, half do not). They rate their post-decision confidence on a seven-point scale (1="I was guessing", "7=Certain I'm right"). False alarm rates ("detection" of an object where none was present) were the key metric derived from the task.

Denominator Neglect [47]. Respondents imagine trying to draw a red ball from one of two urns. They indicate their preferred urn on a seven-point scale (1="Definitely Urn A", 7="Definitely Urn B"). Ratings are made for seven sets of urns. Urn A always had one red and nine black balls. Urn B always had 100 total balls. Between seven and thirteen were red. Thus, in three cases Urn B had more red balls (a higher numerator) but offered poorer odds of winning than Urn A. As in previous work [47], denominator neglect was calculated by averaging participants' preference ratings across these three cases. Scores range from 1 to 7.

2.6. Analyses

Boostrapped mediation models (**SI Section S8**) were analyzed as preliminary tests of the hypothesis that Health Belief Model constructs mediate the relation between conspiracist ideation and vaccine intentions.

2.6.1. Causal discovery analysis

Causal discovery analyses, an emerging class of machine-learning algorithms which examine relations between variables (e.g., patterns of partial correlation) to determine the relative plausibility of potential causal relations (Fig. 1), were the primary test of study hypotheses. These analyses have been successfully used to recover complex causal pathways, such as those involved in the pathophysiology of Alzheimer's disease [48], from observational data.

The present study employed the Greedy Fast Causal Inference (GFCI) algorithm to infer empirically plausible causal relations between SARS-CoV-2 vaccine intentions, belief in SARS-CoV-2 conspiracy theories, and other relevant individual-difference variables (e.g., reasoning biases). The GFCI algorithm searches the space of penalized likelihood scores of all possible acyclic causal relations among the measured variables to produce a preliminary assessment of likely causal pathways. This preliminary result is then iteratively refined by ruling out causal models that imply patterns of conditional independence inconsistent with the data. The output of this procedure is a partial ancestral graph (PAG), with the edge type (Table 1) varying depending on the set of directed edges that were present across all remaining plausible causal models (e.g., a directed edge [→] is present if, and only if, all models not containing that edge were removed during the steps outlined above). A particular strength of the GFCI model is its ability to identify situations where unmeasured variables confound the relation between two measured variables, making it particularly well-suited to analyses of data from human research studies (where practical concerns, such as time limitations, constrain measurement of all relevant variables).

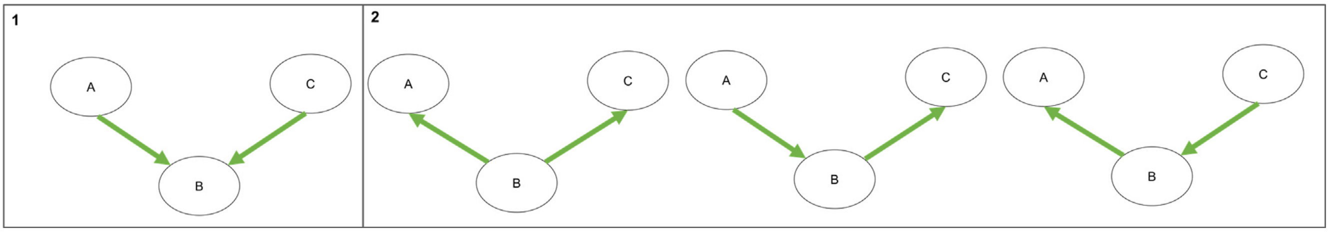
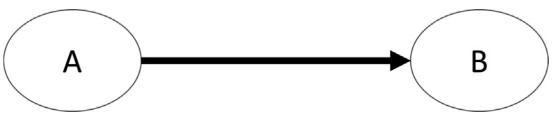
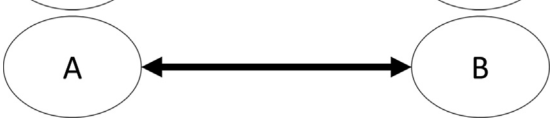
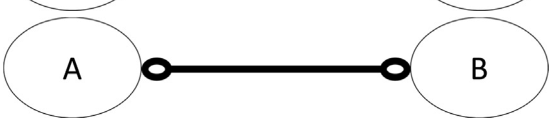


Fig. 1. Patterns of conditional relations convey information about causal orientations. The absence of an arrow denotes the absence of a causal relation. Green arrows denote causal relations between variables (see Table 1). **Panel 1:** A "collider" graph (A and C directly cause B, no edge between A and C). A is unconditionally independent of C, and A is dependent on C conditional on B. **Panel 2:** However, in all other possible relations between A, B, and C (where no edge is present between A and C), a different pattern of conditional relations emerges: A is unconditionally dependent on C, and A is independent of C conditional on B. Given the differential pattern of conditional relations between the graphs in **Panel 1** and **Panel 2**, examining conditional relations can support inference about whether a collider or some other causal process generated the observed data. Greedy Fast Causal Inference uses cases like that illustrated above to determine the direction of causal edges and to rule in/out latent confounds of the relations between variables. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Edge types in a partial ancestral graph convey information about potential causal relations.

Edge Type	Information Conveyed
	A is a direct or indirect cause of B. A and B are potentially confounded. B is not a cause of A.
	Either A is a cause of B or there is an unmeasured confounder of A and B, or both.B is not a cause of A.
	There is an unmeasured confounder (L) of A and B. There may be measured variables along the causal pathway from L to A or B.
	Exactly one of the following holds: 1. A is a cause of B 2. B is a cause of A 3. There is an unmeasured confounder of A and B 4. Both 1 and 3 5. Both 2 and 3

Note. In addition to the above, if an edge is **bold** (thickened), then the relation is definitely direct. Else, it is possibly indirect. If an edge is green, there is no latent confounder of the relation; if it is blue, there may be a latent confounder.

To better ensure graph stability, the GFCI algorithm was repeated on 10,000 jackknifed re-samples of the study data. These re-samples were created by randomly deleting 10% of cases from the study dataset. The original dataset was included as an additional re-sample. Results were aggregated into a single, consensus PAG by depicting the edge type (including: "no edge") and orientation most commonly present in the PAGs created from the jackknifed re-samples. The full FCI rule set was employed. Default values for remaining parameters were used. For example, the penalty discount (c) used for generating the initial likelihood scores (BIC) was set to 1, the alpha value used in conjunction with Fisher's *z* tests to determine conditional independence and refine the preliminary results was set to 0.010, and one-edge faithfulness was not assumed. Because causal discovery algorithms recover causal pathways more effectively when they are provided with prior knowledge [48], the algorithm was given a set of forbidden edges: 1) age and sex could not be caused by any other variable, and 2) vaccine-related variables, such as belief in SARS-CoV-2 conspiracy theories, could not cause locus of control, as this was deemed implausible.

To provide information about the size of potential causal effects identified by GFCI, structural equation models featuring the edges GFCI suggested were fit to the data (using lavaan; [46]. Standardized structure coefficients were then added to the PAG. In cases where the voting ensemble preferred one edge orientation ($\rightarrow$) to its opposite ($\leftarrow$) by a slim margin (<10%), or when an edge orientation did not match that suggested by prior literature, Vuong's test [57] was used to compare the model suggested by GFCI to that with the edge in question reversed. Significant results indicate support for GFCI's conclusion about the edge orientation over the alternative.

2.6.2. Psychometric network analysis

As a complement to this casual discovery analysis, a psychometric network analysis was conducted. This analysis affords a more relaxed approach to identifying potential causal relations between SARS-CoV-2 vaccine intentions, belief in SARS-CoV-2 conspiracy theories, reasoning biases, and other relevant individual-difference variables. It also conveys information about the valence and relative magnitude of these relations.

Network edges were calculated using partial correlations and regularized with the least absolute shrinkage and selection operator (LASSO; [52]). As recommended by Foygel, Barber, and Drton [14], the LASSO tuning parameter (λ) was selected to minimize the Extended Bayesian Information Criterion (EBIC; [7]). The EBIC hyper-parameter (γ) was set to 0.5 to prioritize avoidance of Type I errors [15]. Network graphs were visualized using *qgraph* version *1.6.9* [12].

Network accuracy and stability were examined using bootstrapping. Node centrality and predictability, and associated bootstrapped difference tests, were conducted for exploratory purposes. For more information, see **SI Section S6.**

2.6.3. Outliers and missing data

Outliers were detected using the method of Hubert and Van Der Veeken [24], as pre-registered. Detected outliers were winsorized [18]. For additional information, see **SI Section S4.** Participants with missing data were included in path analyses given that the selected parameter estimation method (FIML) handles these data effectively. All other analyses were conducted after excluding participants with missing data list-wise.

2.6.4. Demographic covariates

Small differences were observed on SARS-CoV-2 vaccine intentions as a function of demographic variables. For example, older individuals were less willing to vaccinate against SARS-CoV-2, rho(552)=-0.17, *p*<.001, as were women (*M*=25.13, *SD*=9.48 vs. men: *M*=27.00, *SD*=8.40). For this reason, age and sex are included as covariates in all analyses (other than zero-order correlations).

3. Results

3.1. Evaluation of novel measures

Support for the validity of the novel measures created to assess SARS-CoV-2 vaccine intentions and conspiracist ideation was found. SARS-CoV-2 vaccine intentions were associated with past influenza vaccination behavior, as expected (**SI Section S3**). The measure of SARS-CoV-2 specific conspiracy theories correlated as expected with a generalized measure of conspiracist beliefs (the BCTI), rho(552)=0.59, *p*<.001. After these initial checks, the measure of SARS-CoV-2 vaccine intentions was subjected to additional scrutiny. Mokken and Principle Component Analyses were used to assess unidimensionality. Item Response Theory was used to investigate whether the measure was reliable and discriminating across the usual range of vaccine intentions in the general population.

PCA and Mokken analyses suggested that only the first five items of the measure loaded strongly on one dimension and exhibited strong scaling properties. The sixth item was therefore excluded. Remaining items were highly discriminative of participants' willingness to vaccinate. Item difficulties suggested that individuals providing the highest item ratings are likely slightly above the population mean willingness to vaccinate, while those providing the lowest ratings are likely > 1 *SD* below this mean. The measure provided sufficiently reliable and informative estimates of vaccine intentions for individuals approximately one standard deviation above to two standard deviations below the population mean on this trait. Thus, the final five-item measure was deemed sufficient for investigating SARS-CoV-2 vaccine intentions. For additional information on these analyses, see **SI Section S3**.

3.2. Descriptive statistics

The mean level of adults' vaccine intentions (26.11) indicated that unvaccinated adults, on average, are relatively willing to vaccinate. The distribution of adults' vaccine intentions was left-skewed, with fewer individuals being increasingly unwilling to vaccinate. Mean willingness to vaccinate one's children (19.37) was significantly lower than that for adults, *t*(147.78)=6.22, *p*<.001, 95%CI=[4.60 8.87], perhaps reflecting the lack of FDA endorsement of SARS-CoV-2 vaccines for children when data were collected. Mean levels of SARS-CoV-2 conspiracist ideation (13.54) indicated that, on average, participants did not strongly believe these theories. The score distribution was right-skewed, with fewer people endorsing stronger belief. Average endorsement of generalized conspiracy theories (on the BCTI) was 3.76, which is comparable to previous studies (example: in [20] it was 3.56), suggesting that our selection of unvaccinated participants did not result in a sample that endorsed conspiracist ideation to a degree that is not representative of the general population. For additional descriptive statistics, see **SI Section S2**.

3.3. Zero-order correlations between study variables

Non-parametric correlations (Spearman's rho) were used to account for non-normality. Confidence intervals were calculated using R's *spearmanCI* package, version 1.0. Notably, SARS-CoV-2 vaccine intentions were correlated with belief in SARS-CoV-2 vaccine conspiracy theories (rho(552)=−0.61, *p*<.001, 95%CI=[−0.67–0.55]) and with constructs from the Health Belief Model, including the perceived severity of SARS-CoV-2 infection (rho(552)=0.23, *p*<.001 , 95%CI=[0.14 0.31]), as well as general perceptions of vaccine dangerousness (rho(552)=-0.61, *p*<.001, 95%CI=[−0.66 −0.55]), but not effectiveness (rho(552)=0.06, *p*=.183, 95%CI=[−0.03 0.14]). These results are broadly consistent with Hypothesis 1′s assertion that conspiracist ideation and Health Belief Model constructs impact SARS-CoV-2 vaccine intentions.

Belief in SARS-CoV-2 vaccine conspiracy theories was associated with several reasoning biases, including increased denominator neglect (rho(552)=0.21, *p*<.001, 95%CI=[0.12 0.29]), higher rates of illusory pattern perception (rho(552)=0.11, *p*=.013, 95%CI =[0.02 0.19]), and (marginally) less data gathering (rho(552)=−0.09, *p*=.042, 95%CI=[−0.17 0.00]). These results are compatible with possibility that reasoning biases might contribute to belief in conspiracy theories.

For the full set of zero-order correlations between study variables, see **SI Section S5**.

3.4. Causal discovery analyses

The consensus PAG generated via causal discovery analysis is depicted in Fig. 2. A structural equation model featuring the relations suggested by this PAG was an adequate fit to the data, RMSEA=0.07, CFI=0.87, SRMR=0.07. Vuong's test supported this model over alternative models with the edges between the following variables reversed: vaccine conspiracist ideation and vaccine intentions (z=1.55, *p*=.061), trust in scientists and vaccine intentions (z=2.34, *p*=.010), and vaccine conspiracist ideation and perceived vaccine dangerousness (z=2.07, *p*=.019), suggesting that GFCI's edge orientations were more likely correct than their reversed counterparts. This result is notable given that the examined edges' orientation in the PAG differed from that expected from prior literature (see Discussion section).

The PAG generated by GFCI was only partially consistent with the hypothesis that conspiracist ideation causes vaccine intentions via Health Belief Model constructs. In this PAG, perceived disease severity and vaccine dangerousness (but not effectiveness) directly caused vaccine intentions, supporting the existence of the latter leg ("path b") of the hypothesized indirect effect. However, perceived disease severity (indirectly, via vaccine intentions) and vaccine dangerousness (directly, and/or indirectly via vaccine intentions) were identified in the PAG as causes of belief in SARS-CoV-2 conspiracy theories, implying that they are not, as predicted, caused by this belief. Moreover, the PAG indicated that belief in SARS-CoV-2 conspiracy theories was (directly) caused by vaccine intentions, but not vice-versa, as hypothesized.

Because belief in SARS-CoV-2 conspiracy theories did not function as hypothesized, the PAG was inspected for potential causal pathways leading from reasoning biases to vaccine intentions through other variables. Two such pathways were identified. Low-

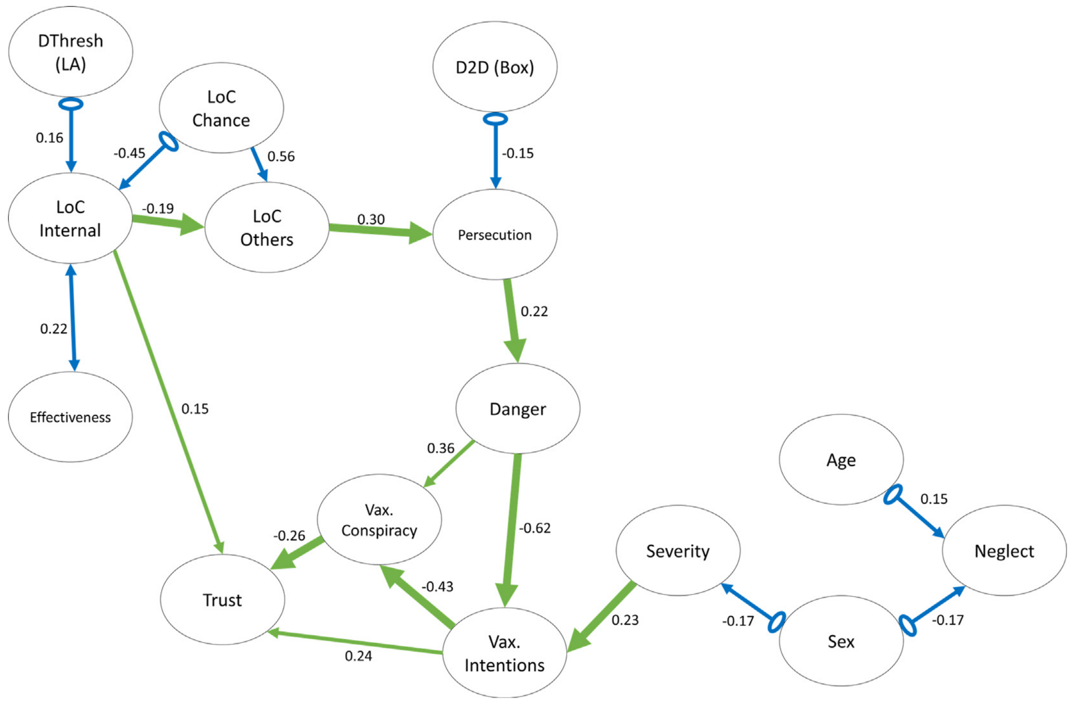


Fig. 2. Directed Acyclic Graph suggested by the Greedy Fast Causal Inference (GFCI) causal discovery algorithm. See Table 1 for a description of possible edge types. Variables are not depicted if GFCI could not determine a potential causal relation between them and another variable included in the analysis. Numbers adjacent to edges are standardized parameter estimates from a structural equation model of the causal structure suggested by GFCI. Neglect=Denominator Neglect. Trust=Epistemic Trust in Scientists. Vax.=Vaccine. LoC=Locus of Control. D2D=Draws to Decision. DThresh=Decision Threshold. Sex is coded as the effect of being male (vs. female).

ered decision thresholds and reduced data gathering were both causal ancestors of persecutory ideation, which caused perceptions of vaccine dangerousness and, in turn, vaccine intentions. Thus, even if belief in conspiracy theories does not cause vaccine intentions, reasoning biases associated with this belief may modulate intentions via their effects on paranoia. However, it should be noted that GFCI indicated that the role of these reasoning biases as a causal ancestor of paranoia (and, in turn vaccine intentions and conspiracist ideation) may be due to an unmeasured confounder. This possibility should be investigated in future research, especially as it is consistent with theoretical frameworks describing the relation between reduced data gathering and more extreme (delusional) forms of paranoia [6].

On a more exploratory basis, the relations between epistemic trust in scientists, conspiracist ideation, and willingness to vaccinate was inspected. The PAG indicated that belief in SARS-CoV-2 conspiracy theories (directly) and vaccine intentions (directly, or indirectly, via belief in SARS-CoV-2 conspiracy theories) caused epistemic trust in scientists, implying that trust in scientists is (perhaps counterintuitively) not a direct cause of vaccine intentions.

3.5. Exploratory analyses involving psychometric networks

Although these results grant insight into potential causal pathways leading to (and from) vaccine intentions, they are limited in that they provide no information about the valence and relative magnitude of potential causal effects. Moreover, because causal discovery analyses identify potential causal relations using a stringent rule set, they may overlook relations worthy of further investigation. Psychometric network analyses that use partial correlation to draw network edges address these limitations by taking a more relaxed approach to identifying potential causal relations (identifying associations that persist after controlling for multiple possible confounds), and by providing a visualization of potential causal relations' valence and relative magnitudes. Accordingly, for exploratory purposes a partial correlation network was constructed from the same set of variables subjected to causal discovery analysis.

3.5.1. Network estimation

The goldbricker function (*networktools*) suggested that none of the nodes in the resulting network (Fig. 3) were redundant. In the regularized network, vaccine intentions were strongly (negatively) related to perceived dangerousness of vaccines, and were more moderately (positively) associated with perceived severity of SARS-CoV-2 infection. Both these variables were identified as possible causes of intentions in the causal discovery analyses. Vaccine intentions were also strongly (negatively) associated with belief in SARS-CoV-2 conspiracy theories and were more moderately (positively) associated with epistemic trust in scientists. Vaccine intentions were identified as a likely cause of both these variables by GFCI.

Belief in SARS-CoV-2 conspiracy theories was strongly (positively) associated with perceived vaccine dangerousness. In our causal discovery analysis, it was ambiguous whether the relation between these variables was direct, indirect (via vaccine intentions), or both. The presence of this edge in a network controlling for vaccine intentions (and its statistical significance in the structural equation model fit to the PAG produced via causal discovery analysis) provides preliminary support for the presence of a direct relation (in addition to the indirect one) between perceived dangerousness and SARS-CoV-2 conspiracist ideation. Belief in SARS-CoV-2 conspiracy theories was more moderately (and negatively) associated with epistemic trust in scientists, potentially because belief in these theories discourages this form of trust (as indicated in the causal discovery analysis). Belief in SARS-CoV-2 conspiracy theories was also (positively) associated with several reasoning biases, including illusory pattern perception and denominator neglect. While these biases were not identified as possible causes

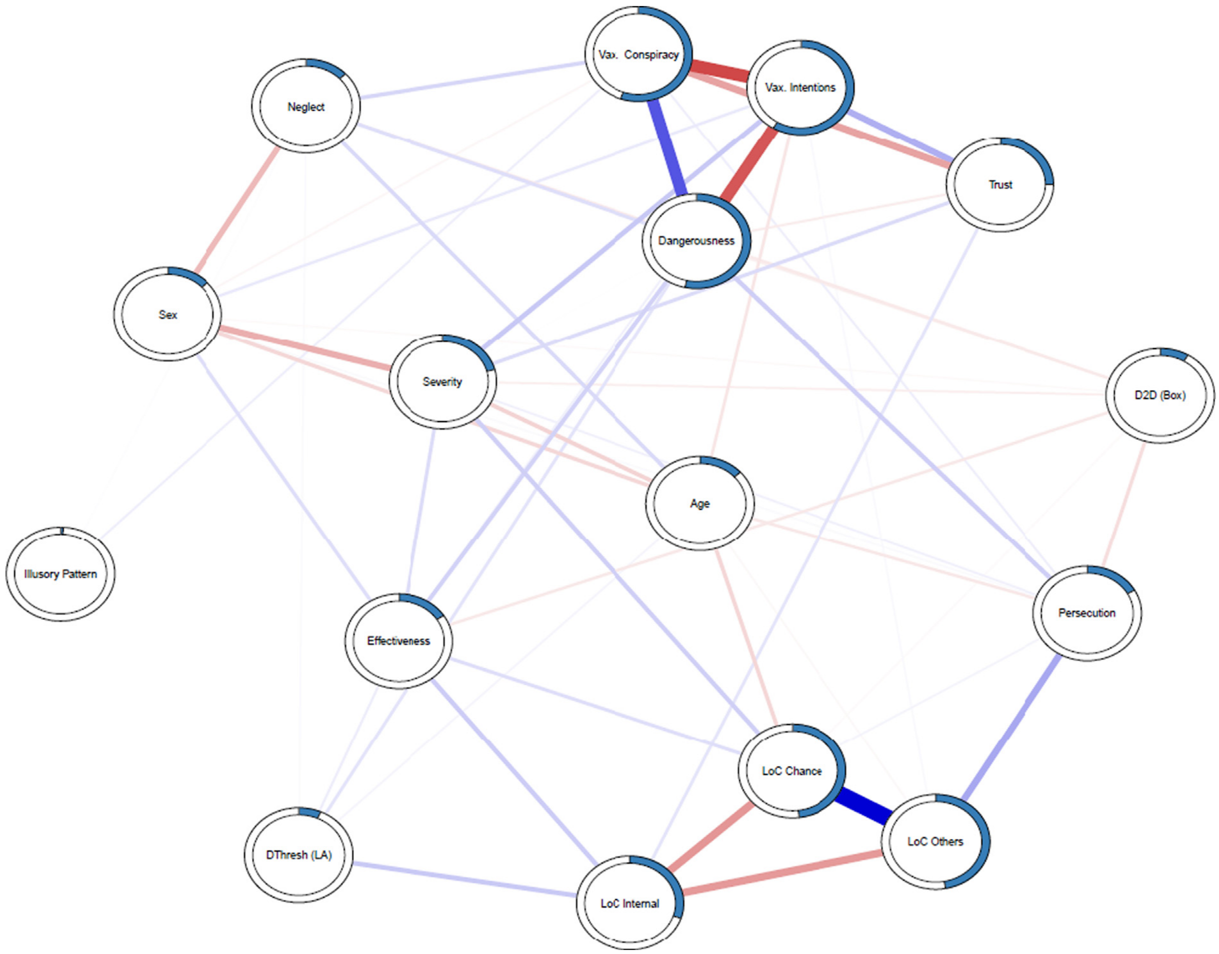


Fig. 3. Regularized partial correlation network. Annulus surrounding each node denotes predictability (more filled=more predictable). Red=negative association. Blue=positive association. Neglect=Denominator Neglect. Trust=Epistemic Trust in Scientists. Vax.=Vaccine. LoC=Locus of Control. D2D=Draws to Decision. DThresh=Decision Threshold. Sex is coded as the effect of being male (vs. female). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of conspiracist ideation by GFCI, previous literature providing evidence of a causal relation between these variables [47,56,62] suggests that additional exploration of the role of these biases may be warranted. Belief in SARS-COV-2 conspiracy theories was also positively associated with persecutory ideation (which GFCI suggested was causally upstream of belief in conspiracy theories) and negatively associated with epistemic trust in scientists (which GFCI suggested was reduced by belief in SARS-CoV-2 conspiracy theories).

3.5.2. Network Inference

In addition to providing information about the absolute strength and valence of relations identified by GFCI, network analysis provides information about the relative strength of potentially causal effects. There were several significant differences among edge weights in the network (Fig. S5: top). Notably, the negative edges connecting vaccine intentions to belief in SARS-CoV-2 conspiracy theories and perceived vaccine dangerousness were stronger than every other negative edge in the network. This result indicates that among the causal effects suggested by GFCI, the effect of perceived dangerousness on vaccine intentions and the effect of vaccine intentions on belief in SARS-CoV-2 conspiracy theories are likely to be the strongest (most negative). Other edges stronger than most others in the network included those connecting belief in SARS-CoV-2 conspiracy theories to epistemic trust in scientists and perceived vaccine dangerousness, as well as the edge connecting vaccine intentions to epistemic trust in scientists. GFCI suggested that all of these edges were reflective of causal relations.

For information about the one-step expected influence and predictability of nodes in the network, as well as overall network accuracy and stability (which was quite good), see **SI Section S6**.

4. Discussion

The present study extends previous research on willingness to vaccinate against SARS-CoV-2 by using machine learning algorithms and psychometric network analysis to elucidate relations between reasoning biases, conspiracist ideation, and vaccine intentions. Causal discovery analyses suggested that SARS-CoV-2 vaccine intentions and perceived vaccine dangerousness caused belief in SARS-CoV-2 vaccine conspiracy theories (but not vice-versa). This suggestion is inconsistent with our pre-registered hypothesis that there would be an indirect effect of these beliefs on vaccine intentions via constructs highlighted in the Health Belief Model. Stronger support was observed for the specific prediction that Health Belief Model constructs influence adults' intentions to vaccinate themselves (and their children, **SI Section S8**). Two constructs from this model – perceived disease severity and perceived vaccine dangerousness – were implicated as direct causes of SARS-CoV-2 vaccine intentions. Finally, reasoning biases, such as the tendencies to gather less data and adopt lower decision thresholds, were identified as causal ancestors of conspiracist ideation and vaccine intentions, expanding our knowledge of the cognitive underpinnings of these processes.

The lack of support for our hypothesis that conspiracist ideation indirectly causes vaccine intentions is surprising given previous experimental [8,26] and observational [45] studies consistent with this hypothesis. This discrepancy may stem from our use of GFCI to uncover potential causal pathways. GFCI assumes that causal graphs are acyclic, and may therefore fail to capture complex causal patterns, such as reciprocal causation. With this in mind, GFCI's suggestion that the causal relation between conspiracist ideation and vaccine intentions is opposite that suggested by previous literature can be interpreted as evidence that this relation is, in fact, bidirectional. Future research could test this conclusion by examining the dynamic interplay between conspiracist ideation and vaccine intentions across multiple measurement occasions. Regardless of the outcome of this future work, the present study's suggestion that reduced willingness to vaccinate causes belief in conspiracy theories (perhaps as a confirmatory strategy, see: [3] lends new urgency to efforts to address vaccine hesitancy and refusal because belief in conspiracy theories is associated with undesirable outcomes, including reduced engagement in prosocial behavior [53] and decreased epistemic trust in scientists (Fig. 2), which may hinder efforts to combat infectious disease outbreaks [39].

Although the present study found no evidence for the hypothesized indirect effect of conspiracist ideation, significant support was found for the notion that the hypothesized mediators influence vaccine intentions. Two constructs from the Health Belief Model, perceived vaccine dangerousness and perceived severity of SARS-CoV-2 infection, were implicated as direct causes of willingness to vaccinate against SARS-CoV-2. However, a third construct from this model, perceived vaccine effectiveness, was not identified as a cause of vaccine intentions. Indeed, in our psychometric network, perceived effectiveness was only associated with vaccine intentions indirectly, via perceived disease severity and vaccine dangerousness, and perceived effectiveness did not correlate with intentions at zero-order. Given that manipulating perceived effectiveness impacts willingness to vaccinate (e.g., against HPV; [5], this null result may be a Type II error (particularly given that the majority of individuals scored within a three-point range on our measure of effectiveness). Accordingly, future research should clarify whether there is a causal relation between perceived vaccine effectiveness and SARS-CoV-2 vaccine intentions, and whether any such relation is direct or, as suggested by our network analysis, indirect (via perceived vaccine dangerousness and/or disease severity).

The results of the present study were clearer concerning the potential for reasoning biases to influence vaccine intentions and conspiracist ideation. In our network analysis, denominator neglect and illusory pattern perception were directly associated with belief in SARS-CoV-2 conspiracy theories, in accordance with previous research on generalized conspiracist ideation [47,62]. Although neither of these biases was identified as a cause of conspiracist ideation in the present study, two other reasoning biases (lowered decision thresholds and the tendency to gather less data prior to decision making) were identified as potential causal ancestors of belief in SARS-CoV-2 related conspiracy theories, building on previous research showing an association between these variables [28]. Both of these reasoning biases were involved in causal pathways that increased paranoia and the perceived dangerousness of vaccines, thereby reducing vaccine intentions and encouraging conspiracist ideation. Given this potential pathway, future research should investigate whether existing intervention that target these biases and/or paranoia, such as SlowMo and Metacognitive Training [19,35], might be adapted to encourage vaccination and reduce conspiracist ideation. The possibility that these interventions might have these effects is particularly exciting given that existing interventions on vaccine intentions are frequently ineffective [42] or backfire [40].

The results of the present study also clearly implicate locus of control in conspiracist ideation and reduced willingness to vaccinate. Causal discovery analyses indicated that locus of control (by others) indirectly encourages vaccine-related conspiracist ideation via its influence on persecutory ideation, and, in turn, perceived vaccine dangerousness and vaccine intentions. Network analyses implied that these effects are strong relative to other influences on conspiracist ideation and vaccine intentions. By identifying this causal pathway from locus of control to conspiracist ideation, this study extends past research showing that threats to personal control motivate generalized conspiracist ideation [55,62].

In addition to these findings, the present study paves the way for future work through its creation of a multi-item, unidimensional measure of SARS-CoV-2 vaccine intentions with discriminative items that is reliable and highly informative for individuals with latent trait intentions within approximately two standard deviations of the population mean. Beyond its favorable psychometrics, the measure has several other useful properties. It explicitly tells participants to assume that the vaccine will be free and delivered at a time convenient for them, which may reduce variance in intentions due to factors not directly related to the vaccine itself, such as socioeconomic status. Further, the measure asks participants to rate their intentions after reading the Emergency Use Authorization (EUA) fact sheet for a specific SARS-CoV-2 vaccine. This provides a platform for future experimental manipulation (e.g., alterations to the fact sheet could be used to test the impacts of health communication on vaccine intentions) and adaptation to studies examining willingness to vaccinate against other diseases (by inserting the appropriate EUA and making minor wording changes to the measure itself).

By providing researchers with this rigorously evaluated measure (**SI Section S3**), we hope to move the field toward a consensus metric of willingness to vaccinate against SARS-CoV-2 and other highly-infectious microbes. Thus far, most studies on this topic (for example: [9,45] have employed single-item measures of intentions with varying wording and types of rating scales. While this strategy was appropriate given the need for rapid insight into a global pandemic, at this time moving toward a multi-item, consensus measure that has been rigorously evaluated confers multiple advantages, such as allowing for easier comparison of study results as well as potentially affording better coverage of the vaccine intentions construct and better prediction of actual vaccination behavior.

The implications of the present study should be considered in the context of several limitations. First, participants were required to deny receipt of any SARS-CoV-2 vaccine. This criterion excluded approximately 30% of the US population (New York Times Vaccine Tracker) at the time of data collection (early April 2021). Excluded individuals may differ systematically from those allowed to participate (e.g., they may have gotten a vaccine dose due to pre-existing medical condition, higher SES, etc.), potentially in ways that could impact the pattern of causal relations observed here-in. Future research should therefore reexamine these relations in samples recruited closer in time to the release of novel vaccines, when selection effects are less likely to bias study results. A second limitation of the present study is that its analyses employed cross-sectional datasets. Casual discovery analyses may more accurately recover casual relations when temporal information is provided [48]. Moreover, the set of contemporaneous causal relations between variables may differ from that unfolding across time. Future research should address this limitation by using causal discovery analyses to examine the relations between conspiracist ideation, reasoning biases, Health Belief Model constructs, and vaccine intentions in longitudinal datasets. A third limitation of this study is that, in keeping with past work on conspiracy theories, the present study examined domain-general locus of control. Because locus of control varies across domains [1], future work examining whether health-specific locus of control plays a similar role in causal pathways leading to vaccine intentions/behavior is warranted. A fourth limitation is that the present study measured generic, rather than individualized, perceptions of disease severity. Individualized and generic severity perceptions may primarily influence different motivators of vaccination. Generic perceptions may be most relevant to prosocial motivators (see: [4,61], whereas individualized perceptions may be more relevant to other motivators, such as the desire for self-protection. Accordingly, measuring both generic and personalized risk perceptions may help future studies explain even more variation in willingness to vaccinate. A final limitation of the present study is that it examined the causes and correlates of willingness to vaccinate, rather than vaccination behavior. While intentions generally explain a moderate amount of variance in ultimate behaviors (approximately 22%, on average; [2]), future research should examine whether receipt of a SARS-CoV-2 vaccine is subject to the same causal influences as those suggested by the present study of intentions.

5. Conclusion

The longstanding trend of disease outbreaks exacerbated by vaccine hesitancy and refusal [11,49] has continued during the SARS-CoV-2 pandemic. Gaining insight into the causal pathways leading to (and from) willingness to vaccinate should scaffold more effective responses to this ongoing crisis. While this study supports certain conventional views of these pathways – for example, by implicating perceived disease severity and vaccine dangerousness as direct causes of vaccine intentions – it challenges others – by, for instance, indicating that belief in SARS-CoV-2 conspiracy theories and epistemic trust in scientists are caused by reduced willingness to vaccinate (but not vice-versa). The present study also broadens our understanding of these pathways by implicating reasoning biases, such as reduced data gathering, as potentially modifiable targets that are causally upstream of vaccine intentions. These insights provide exciting new directions for future research that could make use of the rigorously evaluated measure of SARS-CoV-2 vaccine intentions developed in the present study.

Author contributions

M.V. Bronstein developed the study design and concept, which S. Vinogradov helped refine. M.V. Bronstein analyzed the data. E. Kummerfeld provided expertise surrounding causal discovery analyses. M.V. Bronstein drafted the manuscript. A. MacDonald and S. Vinogradov provided critical revisions. All authors approved the final manuscript for submission.

General audience summary

Large numbers of people routinely refuse or delay vaccinations for themselves and/or their children, leaving individuals and their communities vulnerable to undesirable outcomes (including death) that could be avoided through vaccination. Previous research shows that individuals who believe conspiracy theories, or who are exposed to them, are more likely to delay vaccination or forgo it entirely. While this research links belief in conspiracy theories to reduced willingness to vaccinate, it is unclear whether and how belief in conspiracy theories reduces willingness to vaccinate against SARS-CoV-2 (also referred to as: "COVID-19"). It is also unclear whether tendencies to reason in particular ways ("reasoning biases"), which are thought to encourage belief in conspiracy theories, influence willingness to vaccinate through their impact on conspiracist ideation. Our study involving 554 participants suggested that reduced willingness to vaccinate against SARS-CoV-2 causes belief in vaccine-related conspiracy theories, which contrasts with previous research suggesting that conspiracist ideation reduces willingness to vaccinate (the opposite causal relation). Our study also suggested that reasoning biases, such as a tendency to gather less data before deciding, may influence willingness to vaccinate indirectly, by encouraging paranoia and thereby increasing the perceived dangerousness of vaccines and reducing willingness to vaccinate. Identifying causes of willingness to vaccinate against SARS-CoV-2 is an important first step toward developing interventions that encourage SARS-CoV-2 vaccination. Knowledge provided by our study will therefore help us respond more effectively to the SARS-CoV-2 pandemic and to future infectious disease outbreaks.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.vaccine.2021.11.079.

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