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Metacognition, public health compliance, and vaccination willingness

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Metacognition, our ability to reflect on our own beliefs, manifests itself in the confidence we have in these beliefs, and helps us guide our behavior in complex and uncertain environments. Here, we provide empirical tests of the importance of metacognition during the pandemic. Bayesian and frequentist analyses demonstrate that citizens with higher metacognitive sensitivity—where confidence differentiates correct from incorrect COVID-19 beliefs—reported higher willingness to vaccinate against COVID-19, and higher compliance with recommended public health measures. Notably, this benefit of accurate introspection held controlling for the accuracy of COVID-19 beliefs. By demonstrating how vaccination willingness and compliance may relate to insight into the varying accuracy of beliefs, rather than only the accuracy of the beliefs themselves, this research highlights the critical role of metacognitive ability in times of crisis. However, we do not find sufficient evidence to conclude that citizens with higher metacognitive sensitivity were more likely to comply with recommended public health measures when controlling for the absolute level of the confidence citizens had in their COVID-19 beliefs.

COVID-19 | misinformation | metacognition | vaccination | compliance

The COVID-19 pandemic is accompanied by what has come to be known as the infodemic, an unprecedented surge of information that is characterized by both its scale, and its high proportion of misinformation (1). COVID-19 misinformation may entail originally true information that is spun or decontextualized rendering it misleading, but also fabricated information that is entirely false (2). Recently, evidence has accumulated that susceptibility to COVID-19 misinformation—believing FALSE statements to be TRUE—negatively predicts compliance with public health measures (3–5). Here, we propose, however, that in the noisy information environment of the infodemic where external feedback on the accuracy of own beliefs is unreliable, citizens' metacognitive insight into the varying accuracy of their beliefs is relevant for explaining compliance with public health measures. There is considerable research on how human metacognition, our ability to reflect upon, and evaluate own beliefs, enables us to avoid making decisions based on unreliable evidence in the absence of external feedback (6–8). Metacognitive reflection expresses itself in confidence, an awareness of the validity and fallibility of our beliefs, which can be used as an internal control signal to guide behavior (9–11). Ideally, then, citizens' confidence should have high sensitivity in that it distinguishes correct from incorrect beliefs. Sensitivity is high for a person who has high confidence in beliefs that are correct, and low confidence in beliefs that are incorrect. This would be the case for a person who has high confidence in the belief that, say, physical distancing prevents infection with the virus, and low confidence in the belief that 5G masts foster infection. Importantly, to the extent that citizens use the confidence they have in their beliefs to guide their behavior, the relationship between metacognitive confidence (and, by extension also sensitivity) and subsequent behavior should hold above and beyond (controlling for) the accuracy of the beliefs themselves. The present study, therefore, explores the role of individual metacognition during the COVID-19 pandemic.

Prior research has shown that representations of confidence helps us control and guide our behavior (12), such as during belief-formation (13), belief revision (14), self-regulated learning (15), evidence accumulation (9), learning from mistakes (16), or information search and processing (7, 10). Furthermore, cognitive and neuroscientific research has shown that individuals vary in their ability to correctly map confidence to the accuracy of their object-level beliefs (17, 18). This metacognitive ability may transfer to real-world behavior. For example, participants with higher metacognitive sensitivity in distinguishing legitimate and phishing emails as determined in a lab task were less likely to have malicious files on their home computers (19), students with higher metacognitive accuracy tend to achieve higher academic success (20), and metacognitive insight translates cognitive and functional skills into real-world contexts in patients with schizophrenia (21). Neurocognitive

Significance

Metacognition, the ability to reflect upon, and evaluate our own beliefs, can help us avoid making decisions based on unreliable evidence. Here, we provide empirical tests of the importance of human metacognition during the COVID-19 pandemic. Results demonstrate the predictive power of metacognitive sensitivity—our insight into the accuracy and fallibility of own COVID-19 beliefs—for reported compliance with recommended public health measures and vaccination willingness, above and beyond the accuracy of these beliefs. However, results provide only mixed evidence for the predictivity of metacognitive insight, controlling for the absolute confidence citizens had in their COVID-19 beliefs. This research highlights how behavior during the pandemic may relate to metacognitive self-reflection, not only to critical evaluation of external information.

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studies found that lacking sensitivity of metacognitive confidence, in contrast, may drive negative behavioral outcomes. These studies showed that following high-confidence decisions, subsequent neural information processing is biased such that it reduces the integration of disconfirmatory evidence (22). In sum, existing evidence suggests that people use fluctuations in confidence to guide future behavior, and that variation in the introspective ability to correctly map confidence to object-level accuracy (i.e., metacognitive sensitivity) may be mirrored in variation in real-world behavior. We therefore expect that metacognitive sensitivity of the confidence citizens have in their COVID-19 beliefs predicts adoption of recommended public health measures as well as their willingness to get vaccinated.

Since the onset of the pandemic, researchers have collected considerable evidence about the factors that explain the adoption of recommended public health measures, and vaccination willingness, including health literacy and accurate object-level knowledge (23–27), and belief in COVID-19 misinformation and conspiracy theories (3, 4, 28). Hence, while it is now established that own beliefs shape behavior during the pandemic, the extent to which this relationship is modulated by the metacognitive ability to realize which beliefs are correct and which ones incorrect, remains unknown.

Here, we investigate whether insight into the validity and fallibility of own beliefs can explain self-reported behavior and vaccination willingness during the pandemic, above and beyond the accuracy of the beliefs themselves. That is, we investigate whether higher metacognitive sensitivity predicts higher compliance, and higher vaccination willingness at one particular level of accuracy of COVID-19 beliefs. The present research harnessed methods from Signal Detection Theory (SDT) on both the object-level, and the metacognitive level (29, 30). This provides us with the unique benefit to assess metacognitive ability objectively, rather than relying on self-reports. Furthermore, SDT allows us to assess how well an individuals' metacognitive confidence distinguishes between correct and incorrect beliefs (metacognitive sensitivity; *meta-d'*), independently of how well their beliefs distinguish between correct information and misinformation (object-level sensitivity; *d'*). In two studies using national German samples, we predict compliance with recommended public health measures (e.g., wearing face masks, keeping physical distance; study 1), and vaccination willingness (study 2) from the accuracy of object-level COVID-19 beliefs (*d'*), and metacognitive awareness of the varying accuracy of these beliefs (*meta-d'*), while controlling for demographical variables (gender, age, education, political attitude). The present research, therefore, explores the questions: Are citizens with higher insight into the validity of their beliefs about COVID-19 more likely to comply with recommended public health measures compared to citizens with poorer self-assessment? Are citizens with higher insight more willing to get vaccinated? And, importantly: Does that hold irrespective of the differences in the accuracy of their beliefs?

Results

Study 1: Metacognitive Insight as a Predictor of Compliance with Recommended Health Measures.

Accuracy of beliefs and metacognitive accuracy. Descriptive statistics of the main measures used in this study are given in Table 1. Fig. 1 displays the accuracy of COVID-19 beliefs in the German population and suggests that, by and large, German citizens were well informed about COVID. Specifically, citizens were 2.7 to 12.5 times more likely to indicate that a false statement is false (rather than true), and 2.8 to 22 times more likely to indicate that a true statement is true (rather than false).

Does accuracy of COVID-beliefs relate to compliance with public health measures? We first investigated the zero-order relationship of whether the accuracy of COVID-19 beliefs (d') relates to compliance with public health measures in our sample. In line with previous results (3–5), this was indeed the case, for both a simple compliance score (sum of health preventative behaviors adopted per participant (5); $r(576) = 0.14$, $P < 0.001$, and a frequency-weighted compliance score (weighted mean of all measures adopted, weighted by the frequency with which they were performed; see Methods), $r(576) = 0.09$, $P = 0.03$; suggesting that citizens with more accurate COVID-19 beliefs were more likely to comply with recommended health measures.

Table 1. Means, SDs, and correlations of the main variables used in study 1

Variable	*M*	*SD*	1	2	3	4	5	6
1. Compliance, simple	0.44	0.24						
2. Compliance, frequency-weighted	0.50	0.49	0.66**					
			[0.61, 0.71]					
3. Political attitude	4.66	1.50	−0.04	−0.01				
			[−0.12, 0.04]	[−0.09, 0.08]				
4. Accuracy of beliefs (d')	1.95	0.74	0.14**	0.9*	−0.07			
			[0.06, 0.22]	[0.01, 0.17]	[−0.15, 0.02]			
5. Confidence	0.86	0.10	0.13**	0.10*	−0.04	0.34**		
			[0.05, 0.21]	[0.02, 0.18]	[−0.12, 0.05]	[0.26, 0.40]		
6. Metacognitive sensitivity (meta-d')	1.73	1.15	0.16**	0.12**	−0.04	0.51**	0.81**	
			[0.08, 0.24]	[0.04, 0.20]	[−0.12, 0.05]	[0.45, 0.57]	[0.78, 0.84]	
7. Metacognitive efficiency (Mratio)	0.93	0.70	0.10**	0.10*	−0.04	−0.15**	0.59**	0.58**
			[0.02, 0.18]	[0.02, 0.18]	[−0.13, 0.05]	[−0.23, 0.−07]	[0.54, 0.64]	[0.53, 0.63]

Note: M and SD are used to represent mean and standard deviation, respectively. Values in square brackets indicate the 95% CI for each correlation. * indicates $P < 0.05$. ** indicates $P < 0.01$.

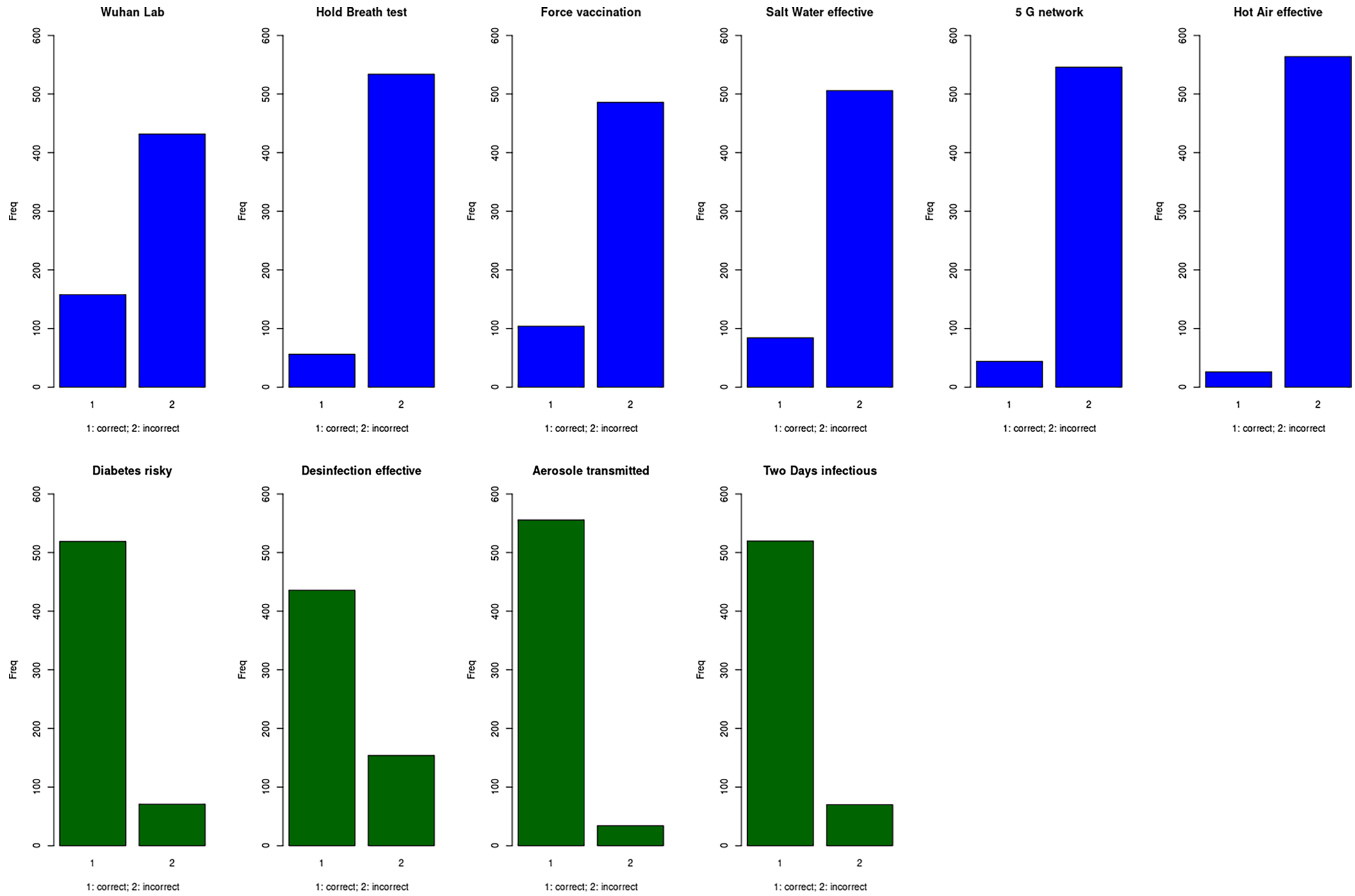

Fig. 1. Answers to the COVID-19 beliefs, separately for false statements (blue, top row) and true statements (green, bottom row). Answers indicate whether participants believed the statement to be correct or incorrect.

Metacognition as a predictor of compliance. We investigated whether metacognitive accuracy predicts compliance (frequency-weighted), controlling for object-level accuracy of beliefs (d'), political attitude, and sociodemographics, using Bayesian and frequentist regressions (Fig. 2).

The best model selected entailed age + *meta-d',* indicating that compliance was best predicted by age and metacognitive sensitivity. This model had a Bayes Factor (BF) of BF10 = 339, indicating that the data were approximately 339 times more likely under this model compared to under the intercept-only model, amounting to extreme evidence in favor of the model. Furthermore, this model was over twice as good as the best model without metacognitive variables (comprising only age, BF = 131). These results proved robust to using the simple compliance score, with the best model selected from the Bayesian regression entailing only *meta-d'* (BF10 = 10.2).

For the frequentist regression, we predicted the compliance score from a baseline model (accuracy of beliefs: *d'* + political attitude + demographics), and subsequently entered the metacognitive accuracy variables in two additional models, sensitivity (*meta-d'*), or efficiency (*Mratio*). Results are largely in line with the Bayesian regression and corroborated the importance of metacognitive accuracy, with the only difference that a model consisting of age + d' + *Mratio* (rather than age + *meta-d'*) proved to be the better model. Age proved the best predictor of the list of sociodemographics, and revealed that older citizens were more likely to comply with recommended health behaviors.

Using Bayesian model averaging, we also quantified posterior inclusion probabilities per predictor, averaged across all potential models. Fig. 3 shows that the strongest model-averaged evidence was obtained for age, followed by metacognitive sensitivity (*meta-d'*), accuracy of beliefs (*d'*), and demographical variables. In particular, the median model (comprising only predictors with a model-averaged posterior inclusion probability > 0.5) entailed only age.

We conducted a large number of additional tests. First, we conducted an alternative computation of *meta-d'* that uses maximum likelihood estimation (30), using the code provided under https://www.columbia.edu/~bsm2105/type2sdt/ (with corrections applied to zero-cell counts). Results were robust to this alternative measure of *meta-d',* including the best models selected in Bayesian regression (simple compliance score: *meta-d',* BF10 = 10.4; frequency-weighted compliance score: age + *meta-d'*; BF10 = 2,244), as well as Bayesian Model Averaging (BMA) (*SI Appendix, Supplementary Material* 2. *Additional Analysis*).

Second, we conducted all analyses controlling for absolute levels of confidence (*SI Appendix, Supplementary Material* 1.2). Results were mixed: The single-best model selected by Bayesian regression entailed metacognitive sensitivity (*age* + *meta-d';* BF10 = 338), as did all analyses involving maximum-likelihood estimation of meta-d', that is, the Bayesian single-best model (*age* + +*meta-d';* BF10 = 2,243), BMA, and frequentist regression However, we did not find support for a predictivity of meta-d' (computed using the Bayesian approach) controlling for confidence in the frequentist regression, and BMA. It needs to be noted, however, that due to the large correlation between meta-d' and confidence in this study (r = 0.81), multicollinearity might affect the reliability of these regression models. And indeed, with a Condition Number

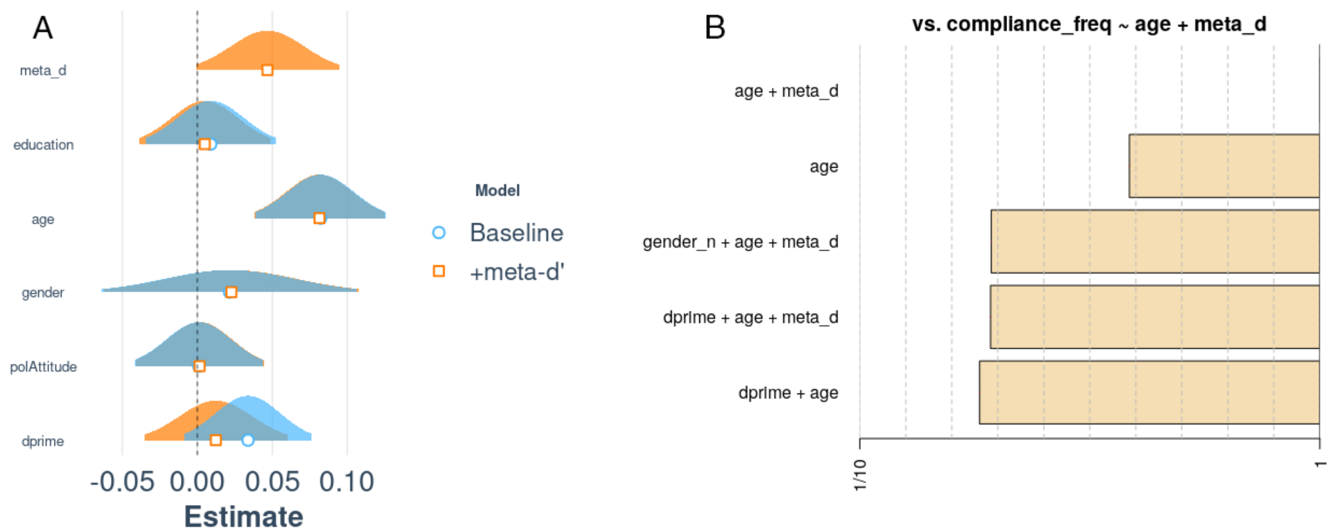

Fig. 2. Results of multiple regression models predicting the frequency-weighted compliance score. (*A*) Frequentist regression. Size of the distribution indicates 95% CI. Education and gender (1 = male, 2 = female) are dummy-coded. (*B*) Bayesian regression. Bars compare the single-best model (age + *meta-d'*) against the four next-best models.

of >60—where condition numbers between 10 and 30 indicate the presence of, and values >30 indicate strong multicollinearity (31)—these models appear to be strongly affected by multicollinearity, and variance decomposition proportions of 0.64 and 0.94 locate confidence and meta-d' as affected parameters (31, 32). To mitigate the effects of multicollinearity, we conducted least absolute shrinkage and selection operator regression (33). Results largely corroborated the single-best model selected by Bayesian regression in that age and metacognitive sensitivity (*meta-d'*) were significant predictors, together with belief accuracy (*d'*) (*SI Appendix*, *Supplementary Material* 3).

Third, considering the low trial number in study 1, we conducted a simple analysis that does not rely on parametric Signal Detection Theoretic measures of metacognitive sensitivity, but rather compares the predictivity of confidence given correct vs. incorrect object-level beliefs. The theoretical reasoning is that if is metacognitive sensitivity (but not overall confidence) that drives compliance, confidence given correct beliefs should positively predict compliance, while confidence given incorrect responses should show no, or even a negative relationship. Results uniformly supported this reasoning, both using binary correlations, multiple regressions in the preregistered regression model, as well as Bayesian model averaging (*SI Appendix*, *Supplementary Material* 4).

Together, these results suggest that citizens with more accurate metacognition—where confidence matches the accuracy of the underlying belief—were more likely to comply with recommended public health measures. Notably, this benefit of higher introspective ability in the varying accuracy of own beliefs held controlling for the accuracy of these beliefs. However, results were mixed when controlling for absolute levels of confidence. Hence, these results do not lend sufficient evidence to conclusively support an incremental predictivity of metacognitive sensitivity above and beyond the confidence citizens had in their COVID-19 beliefs.

In the present study, metacognitive ability was estimated with a sample of only 10 COVID-19 beliefs, potentially reducing the reliability of individual-level estimates of metacognitive sensitivity (*meta-d'*). Study 2 therefore aimed to replicate and extend the present results in a higher powered study involving over three

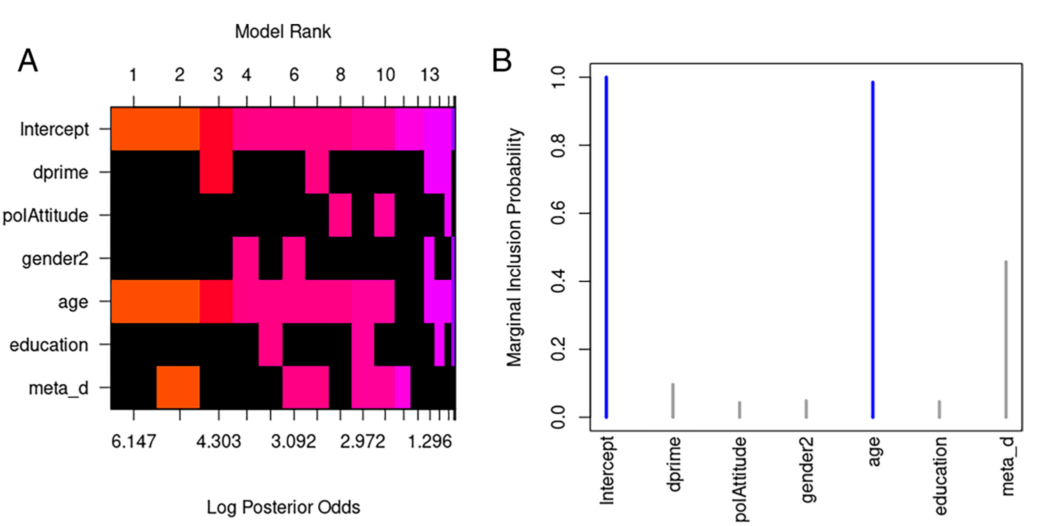

Fig. 3. Model-averaged results predicting frequency-weighted compliance. The figure displays the model-averaged posterior probability of all possible models (*A*), together with the marginal inclusion probability per predictor (*B*), and shows that the best model-averaged evidence is obtained for age, followed by metacognitive sensitivity (*meta-d'*).

times the number of belief-items (n = 33), and almost twice the sample size (N = 1.093).

Study 2: Metacognitive Insight as a Predictor of Vaccination Willingness. Study 2 assessed the relevance of metacognitive sensitivity for what constitutes an increasingly important aspect to combat the pandemic during its later stages: willingness to get vaccinated. A number of studies have uncovered public vaccine hesitancy (28, 34), and some social groups hold increasingly skeptical views on vaccination, thereby driving public polarization over vaccinations (35). It is therefore essential to understand the cognitive mechanisms related to reduced vaccination willingness. Prior research demonstrated that exposure to misinformation reduces vaccination willingness (28), while individuals holding more accurate vaccination beliefs have higher levels of vaccination willingness (26). Here, we tested the relevance of metacognitive insight into the varying accuracy of these COVID-19 beliefs for vaccination willingness.

Accuracy of beliefs and metacognitive accuracy. Descriptive statistics of the main measures used in study 2 are given in Table 2. Results on the absolute level of accuracy of COVID-19 beliefs (d'), as well as its relationship with willingness to vaccinate, largely corroborated study 1 results. In particular, with a d' of 1.72, German citizens were well informed about COVID-19, and this object-level accuracy (d') was substantially related to willingness to vaccinate, r(1043) = 0.46, $P < 0.001$. With an average of Mratio=0.65, however, metacognitive efficiency was considerably worse than optimal (Mratio = 1.0), suggesting that citizens tended to be meta-cognitively confused about the accuracy of their COVID-19 beliefs.

Metacognition as a predictor of vaccination willingness. We investigated whether metacognitive sensitivity (*meta-d'*) predicted vaccination willingness, controlling for object-level accuracy of beliefs (*d'*), and demographical variables. Results largely corroborated study 1 results. For the Bayesian regression, the best model selected entailed *d'* + gender + *meta-d'*. With a Bayes Factor of >1.000, the data provide extreme evidence in favor of this model. Furthermore, as Fig. 4 shows, the best model (*d'* + gender + *meta-d'*) was over twice as good as the best model that did not include metacognitive sensitivity (*d'* + gender). For the frequentist regression, we predicted vaccination willingness from a baseline model (accuracy of beliefs: *d'*, political attitude, demographics), and subsequently entered the metacognitive accuracy variables in two additional models, sensitivity (*meta-d'*), or efficiency (*Mratio*). Both models predicted willingness to vaccinate better than the baseline model (*SI Appendix, Supplementary Material 3. Main Analysis*).

Furthermore, we conducted the alternative computation of *meta-d'* using maximum likelihood estimation using the same methods as in study 1. Results were robust to this alternative measure of meta-d' (*SI Appendix, Supplementary Material 4. Additional Analysis*). In particular, the best model selected in the Bayesian regression entailed *d'* + gender + *meta-d'* (BF10 > 1,000).

Bayesian model averaging. Model-averaged results are displayed in Fig. 5 that orders models according to the log posterior odds compared to the intercept-only model. Model-averaged results corroborated results from the Bayesian single-best, as well as frequentist regression model. In particular, the median model (the model comprising only predictors with model-averaged posterior inclusion probabilities > 0.5) entailed gender + accuracy of beliefs (*d'*) + metacognitive sensitivity (*meta-d'*).

A large number of additional analyses is reported in *SI Appendix, Supplementary Material*, including all analyses controlling for confidence (Bayesian and maximum likelihood estimation of meta-d', Bayesian and frequentist regression, Bayesian model averaging; *SI Appendix, Supplementary Material* 4.2). These results convergingly demonstrate the predictive power of metacognitive sensitivity (*meta-d'*) for vaccination willingness. One exception was the nonparametric approach that was introduced in study 1 to account for its low trial numbers that did not show a predictivity of confidence given correct beliefs when controlling for all preregistered covariates (*SI Appendix, Supplementary Material* 5) which may be due to the high correlation between confidence given correct beliefs and object-level accuracy (*d'*) in study 2; highlighting the higher predictivity of *meta-d'* compared to simple nonparametric approaches when trial numbers are higher.

These results suggest that willingness to vaccinate against COVID-19 is best explained with the overall accuracy of COVID-19 beliefs (*d'*), as well as metacognitive insight into which beliefs, exactly, are correct and which ones incorrect (*meta-d'*).

Discussion

The onset of the COVID-19 pandemic has been accompanied by an infodemic, "an overabundance of information—some accurate and some not—that makes it hard for people to find trustworthy information sources and reliable guidance when they need it" (36). Prior evidence has shown that citizens use varying levels of metacognitive confidence as a signal to guide behavior (6, 7, 9, 10), and that confidence can act as an internal advice-giver when

Table 2. Means, SDs, and correlations of the main variables used in study 2

Variable	*M*	*SD*	1	2	3	4	5
1. Willingness to vaccinate	5.77	1.83					
2. Political attitude	3.77	1.20	−0.13**				
			[−0.19, −0.06]				
3. Accuracy of beliefs (d')	1.72	0.82	0.53**	−0.16**			
			[0.49, 0.58]	[−0.22, −0.09]			
4. Confidence	0.80	0.12	0.24**	−0.06	0.40**		
			[0.18, 0.29]	[−0.13, 0.00]	[0.34, 0.45]		
5. Metacognitive sensitivity (meta-d')	1.08	1.12	0.36**	−0.11**	0.55**	0.75**	
			[0.31, 0.42]	[−0.17, −0.04]	[0.51, 0.59]	[0.72, 0.77]	
6. Metacognitive efficiency (Mratio)	0.65	1.75	−0.03	−0.07*	−0.03	0.24**	0.22**
			[−0.09, 0.03]	[−0.13, −0.00]	[−0.09, 0.04]	[0.18, 0.30]	[0.16, 0.27]

Note: M and SD are used to represent mean and standard deviation, respectively. * indicates $P < 0.05$. ** indicates $P < 0.01$.

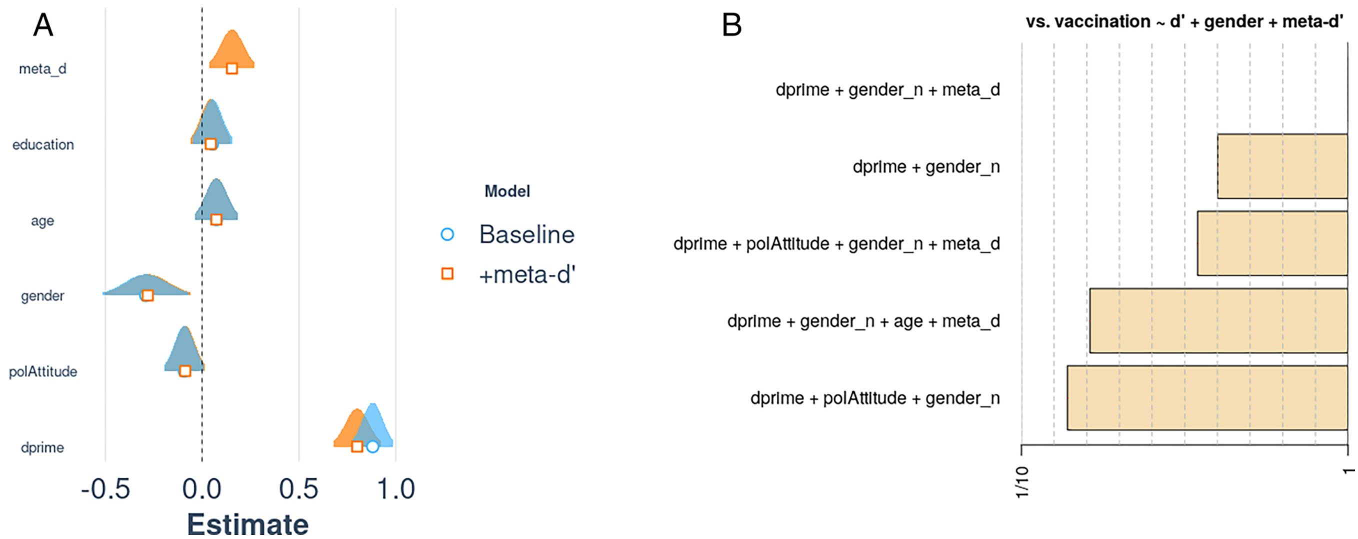

Fig. 4. Results of multiple regression models predicting vaccination willingness. (*A*) Frequentist regression. Size of the distribution indicates 95% CI. Education and gender (1 = male, 2 = female) are dummy-coded. (*B*) Bayesian regression. Bars indicate compare the four best models against the single-best model (*d′* + gender + *meta-d′*).

external advice is unavailable (37). However, little is known about the relevance of metacognition to guide behavior in times of the pandemic—where external guidance can be highly unreliable. The present research was based on the proposition that metacognition can serve the purpose of internal guidance: By helping citizens decide how much weight (confidence) they should assign to a particular belief, confidence can inform subsequent behavior. Two independent national studies among the German population suggested that citizens with more accurate metacognition—where confidence matches the accuracy of the underlying belief—were more likely to self-report compliance with recommended public health measures, and had higher vaccination willingness. Notably, this benefit of higher introspective ability in the varying accuracy of own beliefs held above and beyond (controlling for) the accuracy of these beliefs. This result provides evidence that behavior during the pandemic relates to the accuracy of insight into the varying accuracy of COVID-19 beliefs, rather than only the accuracy of the beliefs themselves. However, results provide insufficient evidence to conclude that metacognitive sensitivity explains compliance, above the beyond the absolute levels of confidence citizens have in their COVID-19 beliefs.

Our beliefs naturally vary in accuracy. In line with prior research demonstrating the impact of COVID-19-related misinformation on vaccination willingness (28), we found that citizens with more accurate COVID-19 beliefs were more likely to comply with public health measures, and showed higher vaccination willingness. A key result from the present study, however, is that realizing which beliefs exactly are right or wrong increases vaccination willingness, above and beyond the benefit of holding more accurate beliefs overall. This result highlights the crucial function of metacognitive self-reflection as allowing us to distance ourselves from our object-level beliefs, and to assign due weight to them (38). Notably, given a behavior-guiding function of confidence, an importance of metacognitive accuracy is to be expected with almost analytical necessity: When beliefs are weighted by accurate confidence, low-confidence beliefs that are likely to be inaccurate (such as believing in global efforts to enforce mandatory vaccinations) are down-weighted and less likely to inform vaccination intentions. In contrast, high-confidence beliefs that are likely to be accurate (such as believing in the genetic safety of mRNA vaccines) are up-weighted and more likely to inform vaccination intentions.

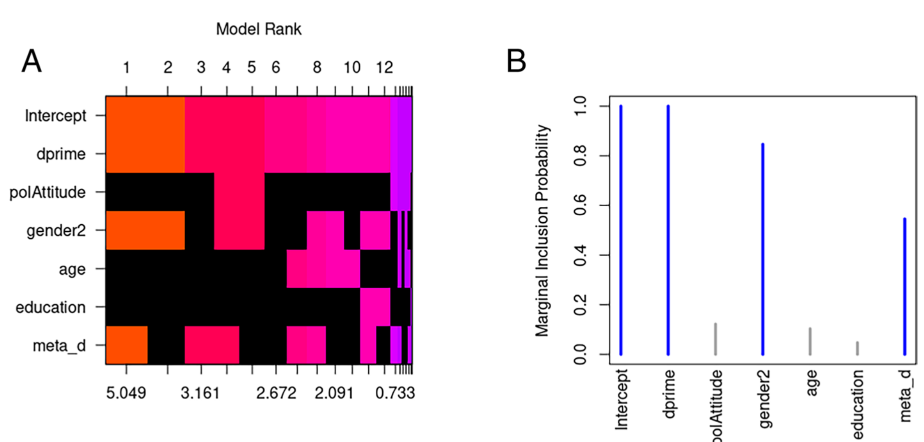

Fig. 5. Model-averaged results predicting vaccination willingness. The figure displays the model-averaged posterior probability of all possible models (*A*), together with the marginal inclusion probability per predictor (*B*). Predictors with model-averaged posterior inclusion probability > 0.5 entail accuracy of COVID-19 beliefs (*d′*) + gender + metacognitive sensitivity (*meta-d′*).

Although the present results convergingly show that metacognitive sensitivity predicted self-reported behavior and vaccination intentions controlling for the accuracy of COVID-19 beliefs, metacognitive sensitivity did not reliably predict compliance with recommended public health measures, controlling for the absolute confidence citizens had in these beliefs in study 1. Methodologically, this could be due to an insufficient number of belief items used to reliably measure metacognitive sensitivity in this study. In line with this conjecture, first, the single-best regression model selected by Bayesian regression entailed meta-d' and age—but not confidence— speaking for the predictivity of metacognitive sensitivity. Furthermore, additional analyses employing a simple nonparametric approach revealed a positive relationship between compliance and confidence given correct COVID-19 beliefs, but not confidence given incorrect beliefs; suggesting that it is confidence in correct beliefs that drives compliance, rather than simply confidence in one's beliefs in general, irrespective of the beliefs' validity. And second, metacognitive sensitivity did deliver incremental predictivity in our second study using over three times the number of belief items, and almost twice the sample size. Furthermore, it needs to be noted that all analyses where metacognitive sensitivity (meta-d') and absolute levels of confidence were included in one regression model suffered from multicollinearity, particularly so in study 1, due to the substantial bivariate correlation between metacognitive sensitivity and confidence, which may reduce the precision of the estimated parameters, and increase the risk of false rejections (39). Hence, results that indicate a lack of predictivity of meta-d' while controlling for confidence could be misleading. While collinearity will reduce the likelihood of finding incremental predictivity of meta-d', however, these arguments obviously do not rule out that metacognitive sensitivity is indeed confounded with absolute levels of confidence, and that this confound is more difficult to disentangle when trial numbers are low (as in present study 1). The dissociation between study 1 and study 2 results might also have theoretical reasons in that metacognitive sensitivity could indeed be less relevant to explain self-report behavior in relation to public health measures than in relation to vaccination. Potentially, this could be due to partially contradicting and inconsistent recommendations of some behavioral measures (such as wearing masks; ref. 40), whereas vaccinations, once available, where broadly recommended as safe and effective in Germany.

German citizens were well informed about COVID-19 overall. This result is in line with prior research demonstrating overall high levels of public knowledge about COVID-19 (41–43). The present results, therefore, deliver an explanation for the somewhat puzzling observation that we can see considerable variation in vaccination willingness (44), despite high absolute levels of public knowledge about COVID-19: because vaccination willingness also relates to varying awareness of the accuracy of these beliefs.

The infodemic is hence worrisome not only because exposure to misinformation reduces the accuracy of object-level beliefs (28, 45). Rather, the infodemic is worrisome because it produces informational noise that may reduce the reliability of evidence. When citizens form confidence judgments by accumulating low-reliability evidence, this necessarily decreases metacognitive efficiency, that is, the sensitivity with which confidence distinguishes between true and false beliefs (11). In line with a mechanism whereby the reliability of evidence determines the accuracy of confidence judgments, it was found that citizens' metacognitive efficiency is lower for the politicized science of climate change that confronts citizens with a high proportion of misinformation, compared to nonpoliticized science (46). According to our results, skewed individual-level confidence may then exert behavioral consequences with real-world, collective implications, such as the decision of whether or not to get vaccinated during a global pandemic.

The sharp increase in online misinformation since the onset of the pandemic is considered a threat to public health (47). Although the present research does not provide consistent evidence to conclude that metacognitive sensitivity explains compliance with public health measures, above and beyond the confidence citizens have in their COVID-19 beliefs, results do suggest that citizens with more accurate awareness of the accuracy of their beliefs were more likely to report compliance with recommended public health measures, and had higher vaccination willingness. Notably, this introspective ability into the accuracy of own COVID-19 beliefs was predictive above and beyond the accuracy of these beliefs themselves. The present research, therefore, highlights how behavior during the pandemic may relate to how we validate our own beliefs, rather than only external information.

Materials and Methods

Transparency and Openness. Our main hypothesis (that metacognitive accuracy predicts compliance with recommended health behaviors, above and beyond susceptibility to COVID-19 misinformation) was preregistered under https://aspredicted.org/blind.php?x=MXS_WMO. Additional analyses are indicated as exploratory. Analysis plan for study 2 was preregistered under: https://aspredicted.org/blind.php?x=ZRH_PGM. All data and the analysis code (in R) are openly available under https://osf.io/axj83/. Participants provided informed consent. Methods were accepted by the ethical review board of the Leibnitz Institut für Wissensmedien, Tübingen, Germany. Data for study 1 were collected in December 2020, during the second wave of the pandemic in Germany. Data for study 2 were collected in early June, 2021.

Participants. In study 1 (compliance), a total of N = 590 German citizens took part. The sample constituted a nationally balanced quota sample of German citizens, balanced for gender (female: n = 304, 51%), age (categorical, comprising 5 categories: 18–24 y, 25–34 y, 35–44 y, 45–54 years, and above 55 y; for the analysis age categories were entered as continuous variable) and geographical distribution, and was sampled by the polling company YouGov. For the questions about political attitude and education a "prefer not to say" option was provided (this was a prerequisite for the ethical approval). N = 61 participants chose not to answer one or both of the questions and were excluded from the analysis in which we controlled for political attitude and education. Furthermore, n = 19 participants were excluded based on the exclusion criteria for Mratio (see Analysis section). The final sample therefore comprised N = 510 participants.

In study 2 (vaccination willingness), a total of N = 1.093 German citizens took part. Participants had the option to withdraw their data at the end of the study. This was done in accordance with the guidelines of the ethical review board. A total of n = 26 participates who did not consent were excluded. The sample constituted a nationally balanced quota sample of German citizens, balanced for gender (female: n = 521, 49%), age (mean = 45.98, range =18-74), and geographical distribution, and was sampled by the polling company respondi. For the questions about political attitude and education a "prefer not to say" option was provided (this was a prerequisite from the ethical review). A further n = 167 participants chose not to answer one or both of the questions on political attitude or education and were therefore excluded from the analysis in which we controlled for political attitude and education. Furthermore, n = 22 participants were excluded based on the exclusion criteria for Mratio (see *Analysis* section). The final sample therefore comprised N = 878 participants.

Procedure. The survey of study 1 was conducted in the following order: demographics; media usage (results not reported here); COVID-19 beliefs, together with item-specific confidence items; Compliance with public health guidance; debriefing.

The survey of study 2 was conducted in the following order: Media consumption and emotions about COVID (results not reported here); COVID-19 beliefs, together with item-specific confidence items; vaccination willingness; beliefs about media (results not reported here); demographics; and debriefing.

Measures

Study 1. ***Political attitude.*** Participants indicated "When talking about politics, one often hears the concepts "left" and "right". We would like to know from you where you would place yourself" on a 9-point scale (1: left--9: right; prefer not so say).

COVID-19 beliefs. Participants verified 10 statements about the virus, six of which were FALSE, and four of which were TRUE. The list of statements comprised two true and six false statements from previous research (5), as well as two additional true statements. For each statement, participants indicated: "Is this statement correct or incorrect?" (correct/incorrect). The FALSE statements were: The coronavirus was bioengineered in a military lab in Wuhan; Being able to hold your breath for 10 seconds or more without coughing or discomfort is a good self-check test for whether you have the coronavirus; The coronavirus is part of a global effort to enforce mandatory vaccination; Gargling salt water or lemon juice reduces the risk of infection from the coronavirus; The new 5G network may be making us more susceptible to the virus; Breathing in hot air through your mouth and nose (e.g., from a hair dryer) kills the coronavirus as it can only live in cool places. The TRUE statements were: People with diabetes are at a higher risk of complications from coronavirus infection; using hand sanitizer with at least 60% alcohol is effective in reducing risk of infection from coronavirus; people may be infectious 2 d prior to showing symptoms.

Metacognitive confidence in COVID-19 beliefs. In study 1 and study 2, participants provided an item-specific confidence judgment by indicating, after each statement: "How certain are you that your assessment is correct?" on a 6-point scale ranging from 50 to 100%, where all points were labeled with respective numerical values, and the end points of the scale had additional verbal labels ("50%: I guessed"; "100%; I am certain").

Compliance with public health guidance. For a total of 11 public health guidance measures taken from prior research (5), participants indicated the frequency with which they had adopted the measure in the last month (7-point scale: much rarer, rarer, equally often, more frequently, much more frequently; I did not take this measure). That is, our measure of compliance assessed how much citizens adapted their behavior in response to the pandemic, rather than the extent to which the behavior was part of their normal routine irrespective of the pandemic. The health guidance measures were: hand-washing; using hand disinfectant; wearing a face mask; using public transport; eating out; touch own face; go grocery shopping; eat at home; working from home; visit public gatherings (e.g., parties, family celebrations); and stock additional food.

To quantify participants' compliance with public health guidance, we computed two compliance scores, a frequency-weighted score and a simple score. The frequency-weighted compliance score was computed as the weighted mean of all measures adopted, weighted by their frequency. The simple compliance score was computed by summing up the number of health preventative behaviors adopted by each participant, irrespective of the frequency with which they were performed (5). In both cases, higher scores represent higher compliance.

Study 2.

Political attitude. Participants indicated "how would you describe your political attitude?" on a 7-point scale (1: left--7: right; prefer not to say).

COVID-19 beliefs. Participants verified a total of n=33 statements about COVID-19 (48), 17 of which were FALSE, and 16 of which were TRUE. For each statement, participants indicated: "Please indicate whether this statement is correct or incorrect" (correct/incorrect).

The TRUE statements were: COVID-19 is a multisystemic disease in which symptoms and long-term effects/complications can also occur outside the respiratory tract; washing hands with soap kills the coronavirus just as well as disinfectants do; surgical masks and FFP2 masks can affect breathing and the exercise tolerance of the heart and lungs even in healthy people; so far, there is no evidence that mRNA vaccines against coronavirus manipulate human genes; infected people produce aerosols when they breathe, speak, or sing, which remain in the air for a long time and transmit the coronavirus; since the beginning of the corona pandemic, fewer people than usual have been coming to the clinics with signs of a heart attack or stroke; The Japanese Ministry of Health announced that a new coronavirus variant has been discovered in Japan, which differs from the variants in Great Britain and South Africa; a thermal scanner cannot determine whether a person is infected with COVID-19; Corona rapid tests are not as accurate as PCR tests; companies had already started with the production of vaccines although the approval procedure had not yet been completed; those who are offered vaccination against COVID-19 by the state will not be able to choose the vaccine; it is only after the second corona vaccination that the full protection is achieved for the vaccines approved in Germany (Biontech, Moderna, AstraZeneca); people with diabetes have a higher risk of complications due to infection with the coronavirus; the use of disinfectants/sanitizers is an effective way to reduce the risk of infection with the coronavirus; the virus is mainly transmitted via small respiratory drops; and the period of infectivity can begin up to two and a half days before the first symptoms appear.

The FALSE statements were: Wearing a mouth-nose-covering mask can be dangerous, as a health-threatening concentration of CO_2 can accumulate underneath; in a clinic near Munich, a newborn was put a mouth-nose covering on immediately after birth; a World Bank document proves that the quarantine measures will last until 25th March 2025; Markus Söder threatens prison sentences for repeated criticism of the corona measures; regular saunas prevent corona infections, as the virus does not survive 90 degrees Celsius; German doctors are paid extra if they enter COVID-19 as the cause of death in the death certificate; The Bundeswehr sent tanks and other military vehicles to the corona demonstration in Berlin on 29th December 2020; over 80% of people in Germany may already be immune to the coronavirus because of its relationship to other cold coronaviruses; The WHO has confirmed that infected people without symptoms cannot transmit the coronavirus; the new corona vaccines can change the genetic code of unborn children and even cause infertility; flu vaccination increases the risk of contracting COVID-19; 100 grams of alcohol a day disinfects the throat and helps against a corona infection; the coronavirus was produced by biotechnology in a military laboratory in Wuhan; the coronavirus is part of the global plan to make vaccination compulsory; gargling salt water or lemon juice reduces the risk of getting the coronavirus; a good self-test for infection with COVID-19 is to test if you can hold your breath for 10 s without coughing or feeling uncomfortable; and stakeholders like Bill Gates are partly responsible for the emergence of the corona pandemic.

Vaccination willingness. Participants indicated 1. "have you already been vaccinated against COVID-19"? (yes, I received two shots; yes, I received one shot; no, I have not been vaccinated as of yet); 2. "if I had the option now, I would get myself vaccinated against Corona/Covid-19"; 3. "I would advise my friends and family not to get vaccinated" (reverse-coded); and 4. "If they had the option now, I would advise my friends and family to get vaccinated against Corona/Covid-19" on a 7-point scale (1: I don't agree at all; 7: I agree completely). In line with the preregistered study design of the project that study 2 data belonged to (https://

aspredicted.org/POX_YOM), own willingness to vaccinate was set to the highest willingness for participants who had already been vaccinated. Willingness to vaccinate was calculated as the mean of items 2-4. Reliability of the willingness to vaccinate scale was high, alpha = 0.88, 95% CI [87, 89].

Analysis. The analytical strategy, computation of accuracy of COVID-19 beliefs, as well as computation of metacognitive strategy were identical in study 1 and study 2.

Analytical strategy. We conducted Bayesian and frequentist regression. To conduct the Bayesian regression, we used the R-package *BayesFactor,* employing default priors, see *SI Appendix, Supplementary Material* 1. Bayesian regression selects the single-best model that best fits the data from all possible combinations of predictors, while at the same time not incurring in overfitting. That is, Bayesian regression selects the model that optimally balances fit and parsimony. The resulting Bayes Factor quantifies the evidential strength for the model. All Bayes Factors presented here indicate the evidence strength of the model, relative to the intercept-only model (null hypothesis), that is, BF10. For interpretation, we followed the heuristic given in ref. 49 and based on Jeffreys (50), where BFs 1 to 3 are interpreted as anecdotal evidence, 3 to 10 as substantial, 10 to 30 as strong, 30 to 100 as very strong, and BFs > 100 as extreme evidence for H1 (and the same values used as denominators in fractions of 1--1/3, 1/10 etc.-- denote the evidence strength for H0).

In addition to results focusing on the single-best model, we report model-averaged results conducting Bayesian model averaging. Classical regression methods select one set of predictors, and use that model for inference. This approach, however, may be susceptible to arbitrary decisions in model selection, and was criticized for neglecting the uncertainty inherent into the model selection process itself, resulting in parameter estimates that generalize poorly. This caveat is addressed in Bayesian model averaging that summarizes posterior probabilities across all possible models, weighting each model by its posterior probability. Bayesian model averaging has been shown to be more robust against model misspecification, produce more reliable parameter estimates, and lower false-positive rates (51–53). Model averaging was conducted using the R package *BAS* with uniform prior distribution on the models. Uniform priors were chosen in order to assign equal prior probability to each possible model. For model selection, the Bayesian information criterion was used as it is stricter in penalizing model complexity compared to the Akaike information criterion (AIC), hence providing more conservative hypothesis tests. However, analysis were also run with the AIC, delivering largely consistent results.

Accuracy of COVID-19 beliefs. To quantify the accuracy of COVID-19 beliefs, we determined sensitivity *d'* as specified in a SDT framework as Z(HR) – Z(FAR), where HR refers to the hit rate (responding "true" to statements that are true), and FAR refers to the false-alarm rate (responding "true" to statements that are FALSE), and *z* is the inverse of the cumulative normal distribution function.

Metacognitive accuracy. To measure metacognitive accuracy, the extent to which confidence judgments discriminate between correct and incorrect answers, we determined two different measures, metacognitive sensitivity and metacognitive efficiency. Metacognitive sensitivity was measured as *meta-d'* (30), a bias-free measure that controls for metacognitive bias, individuals' general tendency to report high/low values of confidence. Since *meta-d'* and (object-level) *d'* are measured on the same signal/noise ratio scale, *meta-d'* provides the unique advantage of being directly comparable to *d'*. Therefore, metacognitive efficiency can be computed as *Mratio* = *meta-d'*/*d'* (54). When meta-d' = d', participants are metacognitively ideal, and able to use all the information available for the type-1 task (assessment of COVID-19 beliefs) when reporting confidence. When meta-d'<d', participants have lower ability to report confidence judgments than expected based on the type-1 task, that is, confidence judgments are noisier than expected based on the accuracy of beliefs.

To compute *meta-d'*, we employed a Bayesian procedure (29), using the code provided at https://github.com/smfleming/HMeta-d. Belief items and responses were coded as true/false. Corrections to zero-cell counts were not applied as this Bayesian procedure uses a multinomial model of cell counts that naturally handles zeros. During the calculation of Mratio, nstudy1 = 19 participants (3.59%) and nstudy2 = 22 participants (2.44%) needed to be excluded. This was for two reasons: i) *Mratio* values of infinity due to division by zero ($n_{excluded\_study1}$ = 7; 1.32%), ii) *Mratio* values that were calculated based on positive values of *meta-d'* and negative values of *d'* as those result in uninterpretable *Mratio* values ($n_{excluded\_study1}$ = 12; 2.27%; $n_{excluded\_study2}$ =22; 2.44%).

Data, Materials, and Software Availability. Raw data have been deposited in Open Science Framework (https://osf.io/axj83/) (55).

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