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Effective strategies for rebutting science denialism in public discussions

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Science deniers question scientific milestones and spread misinformation, contradicting decades of scientific endeavour. Advocates for science need effective rebuttal strategies and are concerned about backfire effects in public debates. We conducted six experiments to assess how to mitigate the influence of a denier on the audience. An internal meta-analysis across all the experiments revealed that not responding to science deniers has a negative effect on attitudes towards behaviours favoured by science (for example, vaccination) and intentions to perform these behaviours. Providing the facts about the topic or uncovering the rhetorical techniques typical for denialism had positive effects. We found no evidence that complex combinations of topic and technique rebuttals are more effective than single strategies, nor that rebutting science denialism in public discussions backfires, not even in vulnerable groups (for example, US conservatives). As science deniers use the same rhetoric across domains, uncovering their rhetorical techniques is an effective and economic addition to the advocates' toolbox.

Vaccines are safe and effective[1]. Humans cause global warming[2]. Evolution theory explains the diversity and change of life[3]. Although the majority of people take these robust results of scientific inquiry for granted, science deniers publicly oppose these results and spread misinformation. This evidently biases public opinion[4,5] and affects important decisions[6]. Historically, science denialism has persuaded people to turn down life-saving HIV/AIDS treatments[7] or preventive measures such as vaccinations[8], leading to distorted attitudes and years of severe illness and death.

Science denialism must not be confused with scepticism[9–11]. Scepticism towards scientific propositions is a crucial element of science itself. In fact, it functions as a driving force of scientific debates and increases the quality of new propositions via mechanisms such as peer review and the replication of experimental research[12]. The common ground of this functional scepticism is the scientific ethos that scientists use data to update their prior beliefs regardless of the outcome. However, in contrast to functional scepticism, science deniers accept evidence only if it confirms their prior beliefs—that usually contradict the scientific consensus[13]. This dysfunctional scepticism is driven by how the denier would like things to be rather than what he has evidence for, making science denialism a motivated rejection of science[14,15].

The scientific community ignored the question of how to effectively counter arguments of science denialism for too long[16,17] and now recognizes the urgent need for science advocates to publicly engage in debunking misinformation[18]. Advocates for science are spokespeople who follow scientific consensus and argue for the evidence-based position[19], for example in the media. Researchers have now increased their efforts to focus on how advocates for science can inoculate individuals against misinformation before they encounter it[20,21] and how misinformation can be corrected once individuals believe it[22,23]. A third option is to counter arguments of denial at the very moment that they reach an audience; that is, rebutting deniers in public discussions[24]. We will focus on this third option.

Public discussions, for example on social media or as televised debates, are popular and persuasive[25]. Moreover, they allow scientists to leave their ivory tower and contribute to opinion making. This seems increasingly important in an era where false news stories about science spread faster than true ones[26]. However, public discussions also entail risks for the discussants. Bad performance can, in the worst case, serve the opponent's cause[27]. Moreover, backfire effects in attempts to debunk misconceptions[23,28,29] lead us to question whether publicly rebutting misinformation is useful and successful. These backfire effects are most likely to be found among audiences whose prior beliefs or political ideologies are threatened by the advocate[28,30]. For example, attempts to correct misconceptions about vaccination in an audience with low confidence in the safety of vaccination[28] can ironically reinforce the misconception. The same effect occurred among US conservatives (who strongly object to governmental regulation regarding climate change) when there were attempts to debunk misinformation about climate change[30]; that is, when they received information that eventually might lead to regulation. This fear of governmental regulation has also been discussed as a cause for US conservatives distrusting scientists on the topic of vaccination[14]. These risks make it difficult for science advocates to decide whether they should participate in a public discussion at all[19], potentially leading to the absence of advocates for science from a discussion (henceforth referred to as 'advocate absent').

Beyond the question of whether to attend the discussion at all, advocates for science around the globe lack empirical advice on how to respond to a science denier in a public discussion[17,31]. Persuasion psychology highlights three components that can determine whether persuasive attempts will be successful: characteristics of the receiver (for example, need for cognition[32], persuasion knowledge[33]), characteristics of the sender (for example, credibility[34], likeability[35]) and message content and structure (for example, type of evidence[36], message sidedness[37]). This study assesses which types of message content are effective for advocates when responding to science deniers in public discussions. Rebuttal messages can have two different goals. An advocate can aim to overwhelm the opposing position by providing support only for her own view or she can aim to refute the opposing position by attacking its plausibility and

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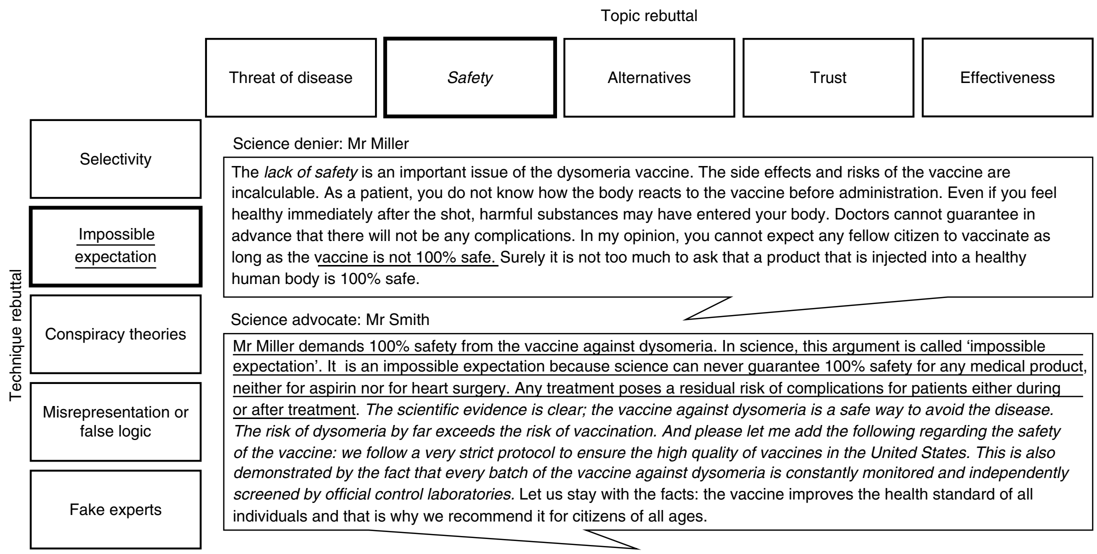

Fig. 1 | 5 × 5 matrix of rebutting science denialism in public discussions about vaccination. The abundance of arguments against vaccination is reduced to five recurring core topics (columns) and five typical strategies of science denialism (rows)[24,31]. The displayed dialogue represents a combination of technique and topic rebuttal as used in Experiment 4 and provides an example of the highlighted categories (safety, impossible expectations). Italics indicate the topic and underlined text indicates the technique of science denialism. The content is adapted to climate change in Experiment 5 and displayed in Supplementary Fig. 1.

explaining why it is wrong[37,38]. As there is theoretical support for both types of rebuttal messages, it is now necessary to introduce practical strategies regarding how to overwhelm or refute an opposing message in public debates about science[31].

Advocates for science can respond to misinformation by supporting the scientific standpoint with scientific facts, that is, topic rebuttal (Fig. 1). For example, when a denier argues that vaccines should be 100% safe, the advocate can provide evidence of the excellent safety record. Thus, topic rebuttal provides guidance on how to overwhelm the denier's opposition. Such a mere provision of facts has been criticized as insufficient to reduce the influence of misinformation because, inter alia, it lacks the important explanation of why the misinformation is wrong[22].

Advice from the World Health Organization's Regional Office for Europe (WHO/Euro) regarding how to handle science deniers in public antivaccination debates[24,31] introduces a second strategy: technique rebuttal (uncovering the techniques of science denial). Previous research identified the major techniques of science denialism (overview in Fig. 1) that are widely used across several domains of science denialism to make the appearance of a strong argument where there is none[13,21]. Unmasking these techniques will educate the audience about why arguments of denial are appealing but incorrect[13,24,39]. For example, when a denier argues that vaccines should be 100% safe, the advocate can uncover the technique of impossible expectations—because no medical product can ever guarantee 100% safety. The assumptions regarding the benefits of technique rebuttal are also in line with research about resistance to persuasion, which shows that individuals can better cope with persuasive attempts when they are aware of the techniques used on them[33]. Thus, technique rebuttal provides a strategy for refuting a denier's position in public discussions about science. Figure 1 provides an example of topics and techniques frequently used in the area of vaccination; Supplementary Fig. 1 adapts the example to climate change.

Technique and topic rebuttal are not mutually exclusive; combining arguments yields a third possibility for responding to science deniers. In fact, the WHO/Euro approach[24,31] claims that combining topic and technique rebuttal will make advocates for science most effective in mitigating the influence of a denier. Established dual-process theories of persuasion (elaboration likelihood model[40]; heuristic–systematic model[35]) suggest two potential reasons for why combining several arguments should be superior in limiting the denier's influence on the audience. According to these models, persuasion is more likely when high-quality messages are provided, so long as the receiver has high motivation to process the information. Given only limited motivation or ability, peripheral cues will guide persuasion (cues that point to the validity of arguments, such as the mere length of the argument). Thus, a combination of several arguments might be more effective than single strategies, either because the combination increases the quality of the argument (central route) and/or because it contains more arguments and is longer (peripheral route)[41]. Despite the theoretical benefits of the combination, the WHO/Euro guidance document also acknowledges the practical complexity of delivering a rebuttal message that covers both dimensions in a public debate[24,31]. Hence, it is important for advocates to know whether training in and use of the most complex strategy is justified by evidence or whether the less complex single strategies are sufficient to strengthen the evidence-based voice for science.

To provide empirical tests of the single and combined effectiveness of the strategies in the specific context of public discussions about science denialism, we: examined whether a science denier influences the audience differently when followed by an advocate for science who uses either topic or technique rebuttal; assessed whether the combination of the rebuttal strategies is more effective than the single strategies; and analysed the potential damage when the advocate is absent and there is no reaction to the denial at all. Finally, we explored potential damage and backfire effects as a function of prior beliefs and political ideology.

In six online experiments ($N = 1,773$), we collected data on the attitude towards a behaviour favoured by science (Experiments 1–4 and 6: vaccination; Experiment 5: taking action against climate change) and the intention to perform this behaviour before and after participants listened to or read a debate with a science denier. The selection of primary outcomes was based on previous research showing that the attitude towards a behaviour and the intention to perform the behaviour are major predictors of actual behaviour[42]. Furthermore, attitude change and resistance to change is the

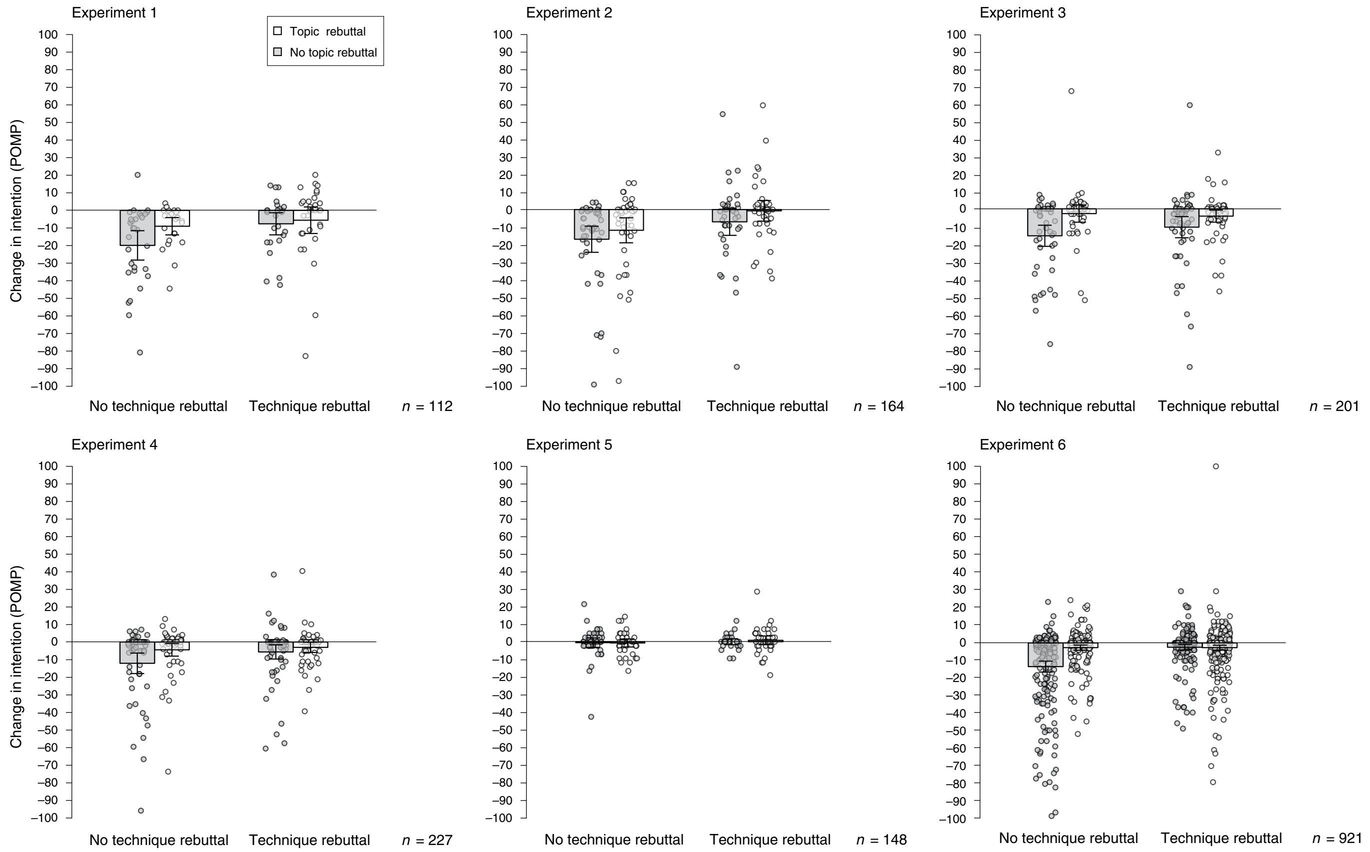

Fig. 2 | Effects of denial and rebuttals on intention to perform a behaviour favoured by science. The *y* axes represent mean changes in intention to perform the behaviour (POMP values) and the *x* axes represent experimental conditions. The negative influence of the denier on the intention to perform the behaviour was weaker when rebuttal was used (except in Experiment 5). Applying topic or technique rebuttal, or a combination thereof, can decrease the influence of science denialism. Error bars represent 95% CIs. Dots indicate individual changes in the intentions of individual participants. Four conditions were tested: advocate absent, topic rebuttal, technique rebuttal and the combination of topic and technique rebuttal; these are shown from left to right on each graph.

primary focus of research on persuasion[43], which delivers the theoretical underpinnings of this work[33]. In Experiments 2–6 we explored potential moderators regarding the effectiveness of denialism and rebuttal strategies (Experiments 2–4 and 6: individuals' general confidence in the safety and effectiveness of vaccination; Experiments 4 and 6: US residents' political ideology on a conservatism–liberalism spectrum). This allowed the exploration of whether rebuttals that threaten an audience's prior beliefs about a scientific measure or those that threaten an audience's political ideology are more likely to backfire.

In all the experiments, participants first received an interview with a science denier. Participants were then randomly assigned to the following design, determining the rebuttal condition: 2 (topic rebuttal versus no topic rebuttal; between subjects) × 2 (technique rebuttal versus no technique rebuttal; between subjects) × 2 (time of measurement: before versus after the debate; within subjects) mixed design. Depending on the condition, a science advocate: was absent from the debate; responded to the denier by using topic rebuttal or technique rebuttal; or responded with a combination of both strategies (Fig. 1 provides an example of the materials used in Experiments 1–4 and 6). The first experiment was conducted among German university students. The experiment addressed vaccination and the debate was presented auditorially as a radio show. Following best practices in research[44], we replicated the results of the first experiment in more heterogeneous samples (Experiments 2 and 3), in a different language and political landscape (US: Experiments 4 and 6), in a different domain (climate change: Experiment 5) and in a different presentation format (written: Experiments 2–6). We preregistered Experiments 2–6 (see Methods). First, we analysed whether the denier influences the audience's attitude towards and intention to perform the respective behaviour. Second, we analysed whether technique or topic rebuttal are effective strategies for reducing the denier's influence and whether the combined strategy is more effective than the single strategies. Finally, we explored whether the influence of denialism and the effectiveness of rebuttal strategies are functions of the audience's prior beliefs or political ideologies.

In the Results, we report an internal random effects meta-analysis including all six experiments[44,45]. Effects in confirmatory analyses are presented as Hedges' adjusted *g* (standardized mean differences) because the scales measuring attitude and intention differ depending on the domain (vaccination versus climate change). In exploratory subgroup analyses, the scales are identical between studies. Therefore, we report these results as absolute mean differences[46]. Attitudes and intentions from the single experiments are reported using the percentage of maximum possible scores of the original scales (POMP[47]), with higher values indicating a more positive attitude and higher intentions. Subgroup analyses on prior beliefs and political ideology are based on median splits for confidence in vaccination and conservatism. The Supplementary Results contain detailed results for each experiment.

Results

The results show that public discussions with a science denier have a damaging effect on the audience, as revealed by negative

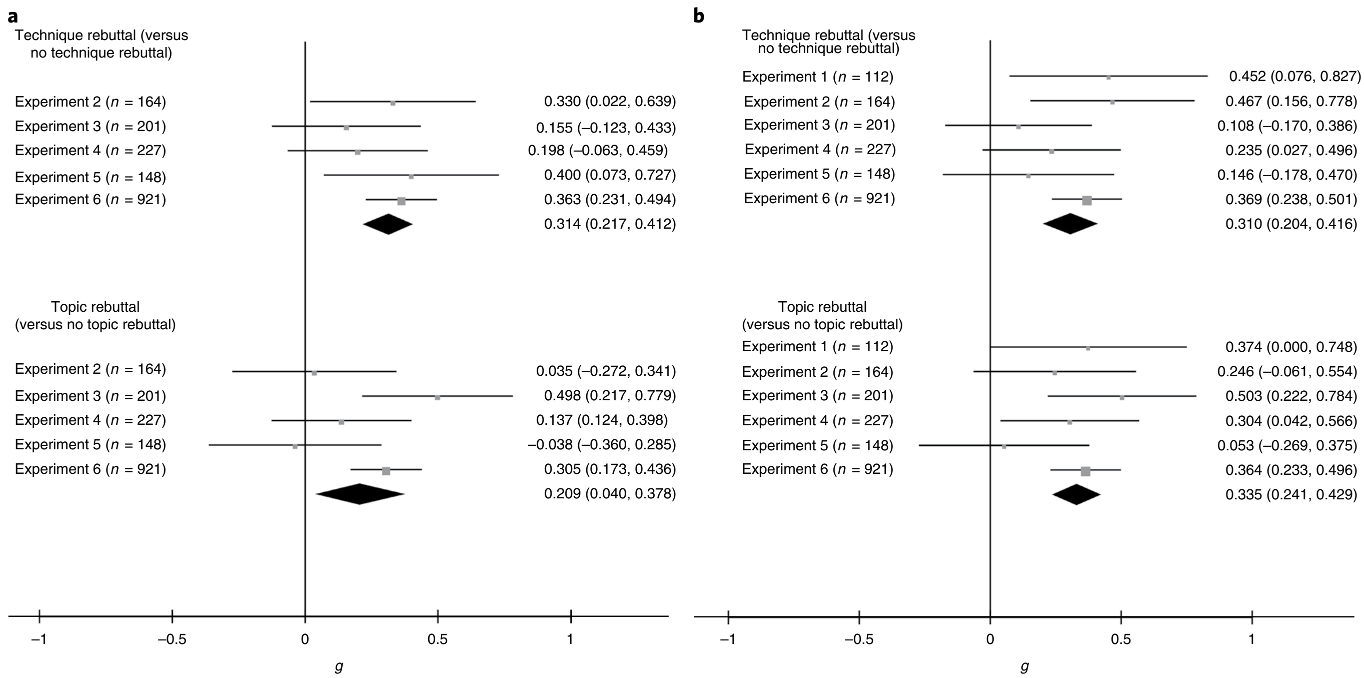

Fig. 3 | Technique rebuttal and topic rebuttal mitigate the influence of the science denier. a,**b**, Internal meta-analyses of changes in attitude (Experiments 2–6; $N=1{,}661$; **a**) and changes in intention (Experiments 1–6; $N=1{,}773$; **b**) using random effects models. The *y* axes represent experiments and the *x* axes represent *g* (derived from comparisons of means of changes in attitude and intention from topic rebuttal versus no topic rebuttal (main effect of topic rebuttal) and technique rebuttal versus no technique rebuttal (main effect of technique rebuttal)). The sizes of the squares are proportional to the precision of the estimates. Error bars show 95% CIs. Diamonds show summary effects; the lateral points of each diamond indicate the 95% CI values for these estimates. The numbers in brackets show the values of the CIs. Heterogeneity of the presented results: ratio of between-studies variance to total variance (I^2) = 0% (between-studies variance $T^2=0$) (**a**) and $I^2=11\%$ ($T^2<0.01$) (**b**) for technique rebuttal; and $I^2=57\%$ ($T^2=0.02$) (**a**) and $I^2=0\%$ ($T^2=0$) (**b**) for topic rebuttal.

changes in attitudes (Supplementary Fig. 2) and intentions (Fig. 2): pre- and post-measures showed that the attitude towards a behaviour favoured by science and the intention to perform this behaviour were reduced by reading or listening to a discussion with a science denier (attitude: $g=-0.32$, 95% confidence interval (CI): −0.46, −0.17; intention: $g=-0.21$, 95% CI: −0.35, −0.08). When no advocate for science was present, the denier had the strongest effects compared with conditions where an advocate was present (attitude: $g=0.49$, 95% CI: 0.37, 0.60; intention: $g=0.57$, 95% CI: 0.46, 0.68). The climate change experiment replicated the pattern of results of all previous experiments regarding attitude change (see Supplementary Fig. 2); that is, the denier caused a decreased attitude towards acting against climate change. However, there was no evidence for a damaging effect of the denier on the intention to act against climate change (see Fig. 2).

Uncovering the techniques of science denial had a mitigating effect on the influence of the denier (Fig. 3); that is, the influence of the denier was decreased by technique rebuttal (attitude: $g=0.31$, 95% CI: 0.22, 0.41; intention: $g=0.31$, 95% CI: 0.20, 0.42). In line with previous findings[21], these results empirically support the assumption that revealing denial techniques can decrease their influence[13,24,39]. The same pattern was obtained for presenting the facts in the discussion (Fig. 3): there was no evidence that topic rebuttal led to a backfire effect; instead, topic rebuttal reduced the denier's influence on individuals' intention ($g=0.33$, 95% CI: 0.24, 0.43) and attitude (attitude: $g=0.21$, 95% CI: 0.04, 0.38).

Contrary to the assumptions of the dual-process models of persuasion[35,40], the direct comparison of the single strategies and the combined strategy reveals no evidence of an additive benefit of the combination. Attitudes and intentions were similarly affected as in the technique or topic rebuttal conditions (attitude: $g=0.14$, 95% CI: −0.04, 0.32; intention: $g=0.09$, 95% CI: −0.02, 0.20; Fig. 4). There is also no evidence for a benefit of the combination when interaction effects are analysed (see Supplementary Table 1 for meta-analyses of the respective simple main effects). Thus, using either of the less complex single rebuttal strategies is sufficient to decrease the science denier's influence.

Exploratory subgroup analyses support the notion of motivated rejection of science among certain audiences[14,15], as a priori beliefs and political ideology moderated the effect of the science denier. The influence of the denier on an individual's attitude was higher among individuals with low a priori confidence in vaccination compared to individual's with high confidence (Fig. 5d); the same effect occurred for intention (Fig. 5a). Likewise, the influence of the denier on an individual's attitude (Fig. 6d) and intention (Fig. 6a) was stronger for conservatives than for liberals.

There is also evidence that technique rebuttal and topic rebuttal are especially valuable for mitigating the denier's influence in these vulnerable subgroups. The moderator analyses presented in Fig. 6 reveal that technique rebuttal reduces the influence of the denier for liberal and conservative participants, but the effect was especially strong for conservative participants (Fig. 6b,e; attitude as a function of political ideology: χ^2 (degrees of freedom = 1) = 7.11, $P=0.008$, $I^2=85.9\%$; intention: $\chi^2(1)=5.36$, $P=0.020$, $I^2=81.4\%$). The same effect partially occurs for prior beliefs (Fig. 5). The effect of technique rebuttal on the intention to get vaccinated was stronger for participants with low confidence in vaccines than for participants with high confidence (Fig. 5b; $\chi^2(1)=4.98$, $P=0.030$, $I^2=79.9\%$). However, evidence of this effect was absent for the attitude of individuals towards vaccination. (Fig. 5e; $\chi^2(1)=2.90$, $P=0.090$, $I^2=65.6\%$).

For topic rebuttal, the same pattern occurred. Topic rebuttal reduced the impact of the denier on liberal and conservative participants' attitudes and intentions, yet the effect was stronger for conservative participants (Fig. 6c,f; attitude as a function of being

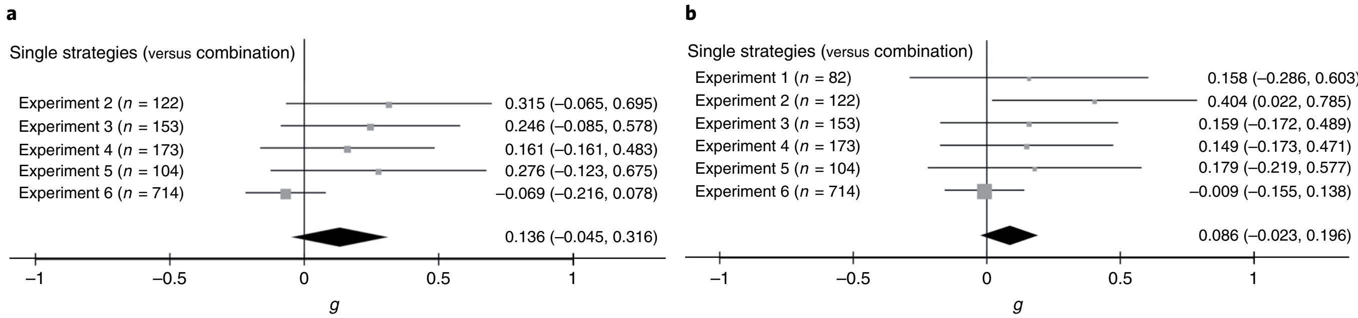

Fig. 4 | No evidence that the combination of topic and technique rebuttal is more effective than the single strategies. a,**b**, Internal meta-analyses of changes in attitude (Experiments 2–6; $N=1{,}266$; **a**) and changes in intention (Experiments 1–6; $N=1{,}348$; **b**) using random effects models. The *y* axes represent experiments and the *x* axes represent *g* (derived from comparisons of means of changes in attitude and intention from single strategies versus the combination of strategies). The sizes of the squares are proportional to the precision of the estimates. Error bars show 95% CIs. The diamonds show summary effects; the lateral points of each diamond indicate 95% CI values for these estimates. The numbers in brackets show the values of the CIs. Heterogeneity of the presented results: $I^2=46\%$ ($T^2=0.02$) (**a**) and $I^2=0\%$ ($T^2=0$) (**b**).

liberal versus conservative: $\chi^2(1)=10.45$, $P=0.001$, $I^2=90.4\%$; intention: $\chi^2(1)=8.88$, $P=0.003$, $I^2=88.7\%$). Again, for prior beliefs we found such a moderating effect only for the intention to vaccinate (Fig. 5c; $\chi^2(1)=4.70$, $P=0.030$, $I^2=78.7\%$); the attitude of participants with high or low confidence was equally affected by topic rebuttal (Fig. 5f; $\chi^2(1)=2.09$, $P=0.150$, $I^2=52.1\%$). It is important to note that the moderating effects of conservatism are limited to US conservatism and evidence of moderating effects is absent in the German samples of Experiments 3 and 5 (see Supplementary Tables 2 and 3 for meta-analyses including German samples).

Altogether, the results do not support the backfire hypothesis in attempts to rebut science denial in public discussions. Instead, the results suggest that both topic and technique rebuttal as single strategies or as a combined strategy can reduce the impact of a science denier. Moreover, it is especially beneficial to use rebuttal strategies among audiences whose prior beliefs or ideology render them particularly vulnerable to science deniers.

To explore psychological processes that may explain the effectiveness of the rebuttal strategies in the single studies, we measured the perceived persuasiveness of the denier and advocate (Experiment 1), the perceived argument strength of the denier and advocate (Experiments 2 and 5) and participants' persuasion knowledge (Experiment 3). However, none of the mediation analyses revealed evidence of indirect effects of rebuttal on participants' changes in intention and attitude via any of these mediators (see Supplementary Results for the results of single studies).

Sensitivity analyses were conducted for all confirmatory analyses. Controlling analyses for the following did not change the obtained meta-analytic patterns: individual knowledge about the behaviours; the relevance of radio and the internet as information sources, and sociodemographic data (see Supplementary Figs. 3 and 4); changing from random models to fixed models; changing the outcome from standardized mean differences to mean differences; dropping Experiment 5, which differed from all others with respect to domain (climate change); including all participants instead of excluding some according to the prespecified criteria; using estimated means of post-values controlled for pre-values rather than difference scores; and excluding statistical outliers from pre- and post-values based on median absolute deviation[48]. See Supplementary Tables 4 and 5 for data from all adjusted meta-analyses.

Discussion

In the light of these findings we recommend that advocates for science train in topic and technique rebuttal. Both strategies were equally effective in mitigating the influence of science deniers in public debates. Advocates can choose which strategy they prefer, depending on their levels of expertise and confidence. For example, a researcher in vaccinology may feel more confident rebutting misinformation with facts about the safety and effectiveness of vaccines, whereas a communication expert might choose to uncover the rhetorical technique used by the science denier. Thus, advocates for science do not need to premanufacture and practice the combination of both strategies as there was no additional benefit from combining topic and technique rebuttal.

Still, being in a public debate with a science denier requires diligent preparation. It may seem like an endless universe of potential misinformation that is difficult to anticipate. However, analyses revealed that most topic arguments fall into five core categories and that deniers use the same five techniques to make those arguments appealing (Fig. 1; ref. [24]). Hence, if they implement only one strategy (topic or technique rebuttal), advocates need to prepare only five key messages that address the core topics or techniques. It is important to note that we did not test all possible topics and techniques and that the effectiveness of the strategies may vary with specific topics and techniques. Nevertheless, training in technique rebuttal seems especially valuable as the techniques are the same across a broad range of scientific domains[13,24], whereas the topics vary across domains (see Fig. 1 and Supplementary Fig. 1). Therefore, technique rebuttal is the more universal strategy in the fight against misinformation. Applying only one of the strategies may seem less complex; however, doing so successfully during an ongoing discussion will still require sufficient training. In recognition of this fact, the WHO already conducts training workshops to support advocates for vaccination in the European region[49]. Adapting such training to other regions and scientific domains should be considered.

The data presented here have a second important implication. Advocates for science do not need a well-disposed audience to effectively mitigate the influence of science denialism on the public. There is mixed evidence regarding whether presenting the facts is ineffective (or might even backfire) in audiences whose prior beliefs or political ideology are threatened by the correction[20,28,30,50]. We find no evidence of backfire effects when using conventional methods of topic rebuttal (presenting the facts) in the present experiments. Moreover, there was no evidence that the effectiveness of this strategy was reduced by political ideology (Experiments 4 and 6) or prior beliefs (Experiments 2–4 and 6). In fact, audiences that were most vulnerable to messages of denial (individuals with low vaccine confidence and US conservatives) benefitted the most from topic and technique rebuttal. Thus, an advocate for science does not need to back off from audiences that are assumed to be difficult to

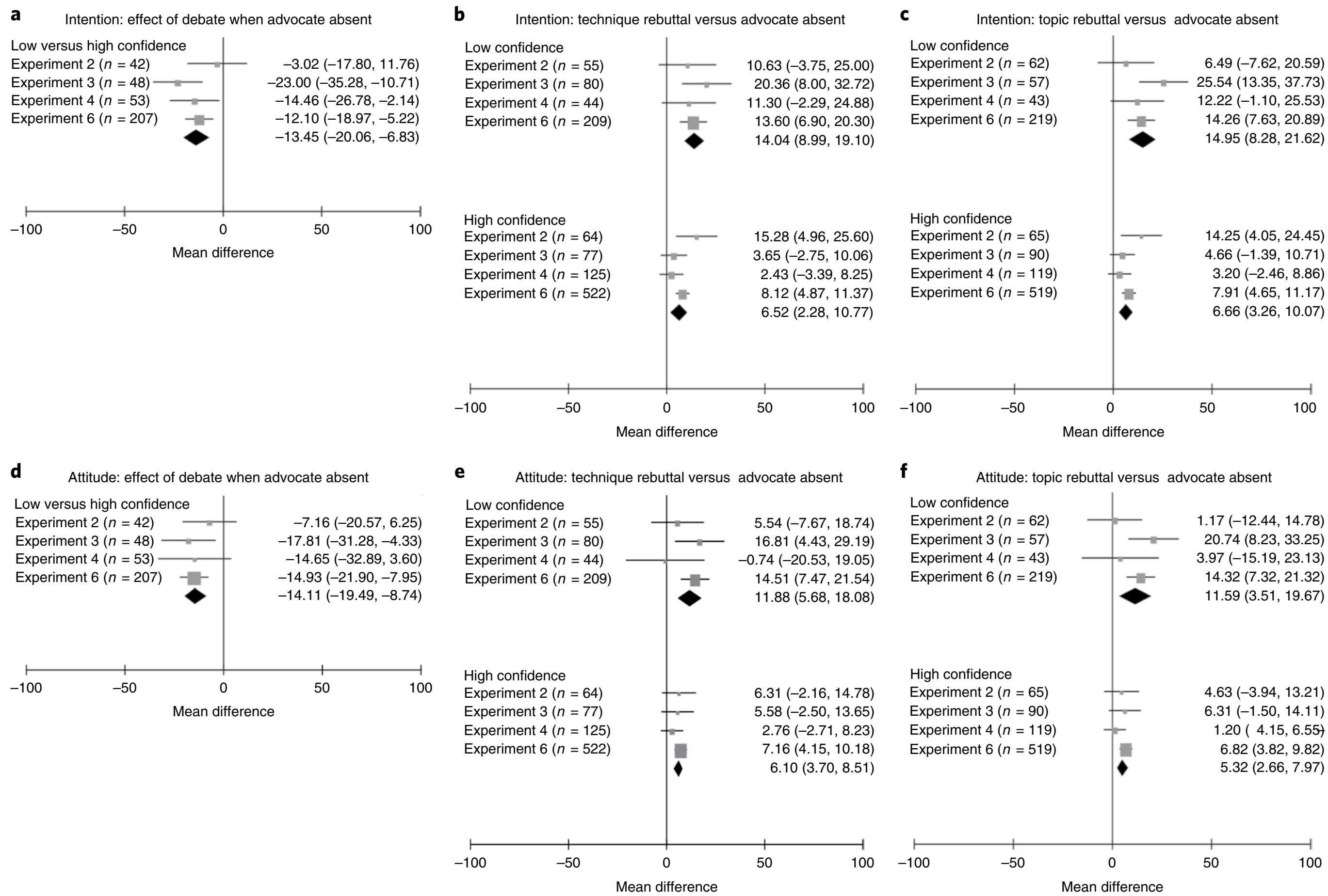

Fig. 5 | Effect of confidence in vaccination on changes in attitude and intention. a,**d**, The influence of the debate is stronger on audiences with low (versus high) confidence in vaccination when the advocate is absent (changes in intention (**a**); changes in attitude (**d**)). **b**,**c**,**e**,**f**, Rebuttal strategies are more beneficial for participants with low confidence than with high confidence (changes in intention: technique rebuttal (**b**), topic rebuttal (**c**); changes in attitude: technique rebuttal (**e**), topic rebuttal (**f**)). The *y* axes represent experiments and the *x* axes absolute mean differences. The sizes of the squares are proportional to the precision of the estimates. Error bars show 95% CIs. Diamonds show summary effects; the lateral points of each diamond indicate 95% CI values for these estimates. Numbers in brackets show the values of CIs.

convince: being present and rebutting science denial still makes a positive difference.

However, the absence of an advocate from the debate can have negative effects on important determinants of behaviour (attitude, intention[42]), as shown in the present experiments. We acknowledge that in some situations contextual factors may still force the advocate to avoid participation (for example, the format of the discussion is not serious or personal safety is at risk[31]). However, with regard to the effectiveness of messages in conventional contexts, not turning up at the discussion at all seems to result in the worst effect. There may be one exception to this: if the advocate's refusal to take part in a debate about scientific facts leads to its cancellation, this outcome should be preferred[21,51] so as to avoid a negative impact on the audience. Also, as can be seen in five of the six experiments (Fig. 2), the debate usually had an overall negative impact on attitudes and intentions even though an advocate for science was present.

In relation to this, a third general take-home message is that advocates who take part in debates should not expect too much for their efforts. Therefore, facing deniers in public debates can be only one building block in the concerted effort to fight misinformation. Other recent approaches try to fight misinformation by pre-emptively providing laypeople with the ability to identify false information themselves[20,21,52]. For example, in a study conducted with Ugandan primary school children, researchers taught 10- to 12-yr-olds how to separate misconceptions about health treatments from facts[52]. Such educative approaches are in line with psychological research that attempts to inoculate individuals against misinformation[20,21]. The goal of inoculation is to make individuals aware of the arguments of denial before the actual information is obtained and to provide them with the ability to come up with counter arguments. An inoculated audience may be less susceptible to the arguments of deniers and the effects shown in the present experiments may be weaker in such an audience.

The presented studies have some limitations. In all the experiments, we collected data on individuals' intention to perform a behaviour rather than the actual behaviour. Research about the intention–behaviour gap[53] highlights that a behavioural intention does not necessarily translate into actual behaviour. Several practical or environmental barriers can hinder vaccination and actions against climate change despite individuals' high intentions to perform these behaviours. Moreover, we do not know whether the attitudes and behavioural intentions expressed in the experiments remain stable after a longer period of time. The presented meta-analyses report the short-term effectiveness of rebuttal, immediately after the public discussion. Therefore, we cannot estimate the effectiveness of the discussed strategies over time or after repeated exposure to science denial. Longitudinal studies should address this question.

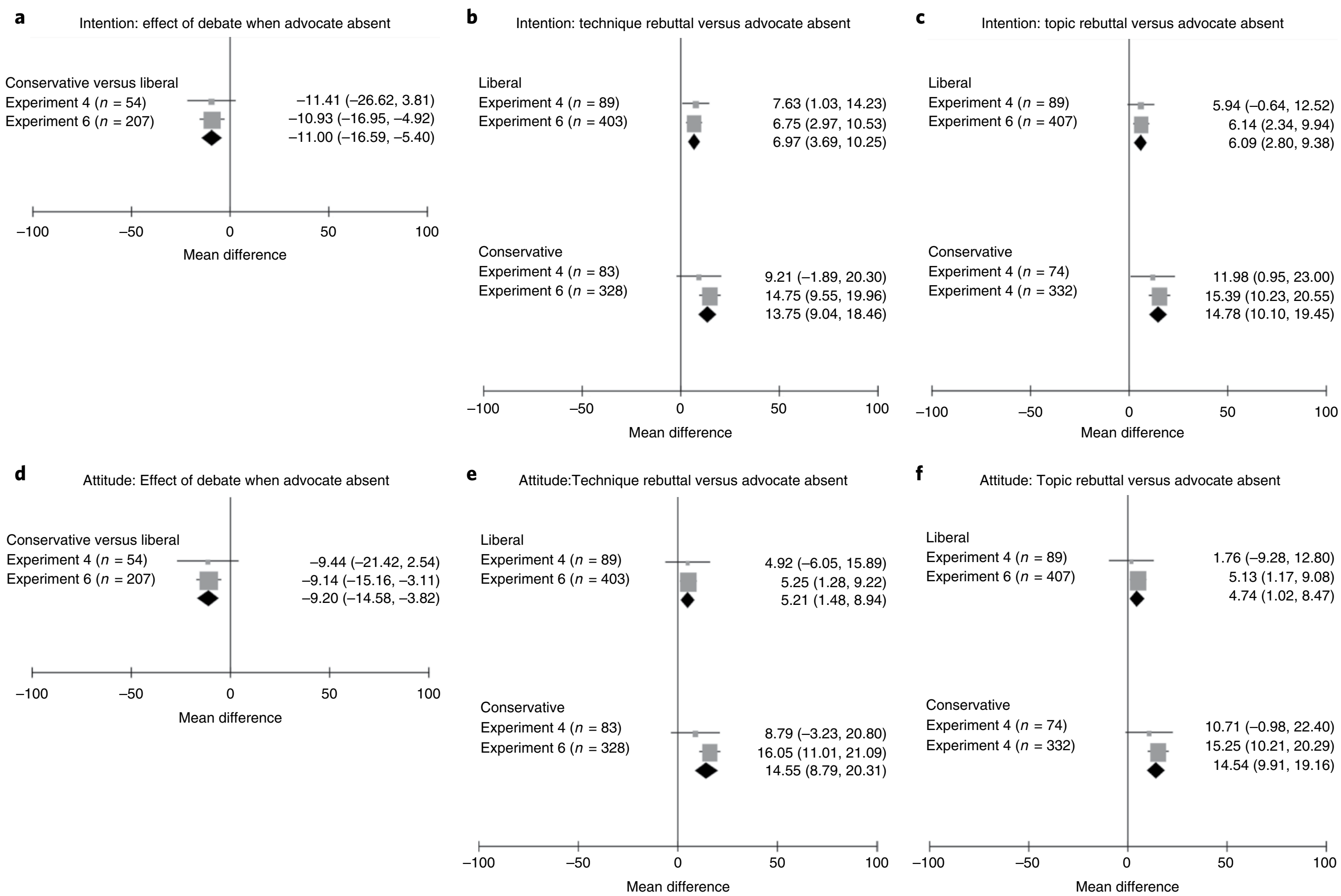

Fig. 6 | Effect of political ideology on changes in attitude and intention. a,**d**, The influence of the debate is stronger on US conservative (versus liberal) audiences when the advocate is absent (changes in intention (**a**); changes in attitude (**d**)). **b**,**c**,**e**,**f**, In the US samples, rebuttal strategies were more beneficial for conservative participants than for liberal participants (changes in intention: technique rebuttal (**b**), topic rebuttal (**c**); changes in attitude: technique rebuttal (**e**), topic rebuttal (**f**)). The *y* axes represent experiments and the *x* axes absolute mean differences. The sizes of the squares are proportional to the precision of the estimates. Error bars show 95% CIs. The diamonds show summary effects; the lateral points of each diamond indicate 95% CI values for these estimates. Numbers in brackets show the values of CIs.

All experiments were conducted online. This media channel represents a natural habitat of misinformation and public debate. However, it may also lead to an underestimation of effects compared to laboratory experiments because participants are more easily distracted from instructions and stimulus materials. Following the elaboration likelihood model[40], distractions impair the ability to process strong arguments. Distracted individuals could be persuaded by peripheral cues rather than the content of the argument. We therefore included two attention checks[54] in Experiment 4 to assess whether participants were able to process the varying content of the arguments presented in that experiment (see Supplementary Information for an explanation). Encouragingly, 94% of the participants passed both checks and we therefore assume a highly attentive sample. Generally speaking, it cannot be expected that the entire audience of a public discussion is equally motivated or capable of processing strong arguments. Whether peripheral cues (for example, celebrity status of the science advocate) could facilitate rebuttal strategies by drawing the attention of an unmotivated or distracted audience to the content of arguments remains an important question.

All moderator analyses were explorative rather than confirmatory. Furthermore, a priori statistical power analyses were based on the size of expected main effects rather than interaction effects of moderation. Therefore, the results of subgroup analyses should be treated as only suggestive.

The spread of misinformation among the public has become one of the major challenges of the scientific community. The public speak about a post-truth era[6] and even the US Environmental Protection Agency has been feared to adopt techniques of science denialism[55]. Despite these alarming developments, researchers have proved capable of detecting: patterns of science denialism in history[16]; the underlying motivations for the rejection of science[14,15]; and the spread of the deniers' false claims in media channels[26]. This has led researchers to better understand and respond by inoculating the public against misinformation[20,21] and debunking misconceptions[22]. With the introduction of rebuttal strategies, the present study adds another tool for effectively mitigating the influence of denial.

Methods

All experiments conform to the ethical principles for psychological research provided by the German Research Foundation. The research was exempt from the requirement for ethical approval by the Institutional Review Board of the University of Erfurt as it is negligible-risk research and involves only non-identifiable data about human beings. Participants gave their informed consent and could quit the experiments at any time. All participants received a debriefing after the experiment and the option to contact researchers for further information.

In total, $N=2{,}202$ completed the experiments and $N=1{,}773$ (Experiment 1: $n=112$; Experiment 2: $n=164$; Experiment 3: $n=201$; Experiment 4: $n=227$; Experiment 5: $n=148$; Experiment 6: $n=921$) were found to be eligible for further analyses (see exclusion criteria below). No statistical methods were used to predetermine the sample size of Experiment 1. The samples sizes of Experiments

2–5 were predetermined using power analyses to provide at least 0.80 power to detect a medium effect of Cohen's f (standard deviation of standardized means) = 0.25 in an analysis of variance (ANOVA) with four groups. As a result of the meta-analyses of Experiments 1–5, we adjusted our assumption for the effect sizes of Experiment 6. Thus, the sample size of Experiment 6 was predetermined using a power analysis to provide at least 0.80 power to detect a small effect of $f = 0.10$, for all confirmatory analyses. Deviations from the preregistered sample sizes are due to the fact that: more (Experiments 2, 5 and 6) or fewer individuals (Experiment 4) than expected met the preregistered exclusion criteria or the recruiting agency invited more individuals than planned (Experiment 3). For the demographics of the samples see the Supplementary Methods. All preregistration protocols are available at aspredicted.org (Experiment 2: https://aspredicted.org/3hv7m.pdf; Experiment 3: https://aspredicted.org/ve6hv.pdf; Experiment 4: https://aspredicted.org/bf9qe.pdf; Experiment 5: https://aspredicted.org/ce2am.pdf; Experiment 6: https://aspredicted.org/ij55n.pdf).

Participants under 18 years of age were screened out at the beginning of all experiments. The following exclusion criteria were preregistered for Experiments 2–6: participants were excluded if they did not finish the experiment; if the duration of participation exceeded 30 min or fell below 5 min (Experiment 5: 3 min); and if they failed to answer a simple attention check question. All exclusion criteria were applied to increase the quality of the responses in online experiments. The attention check for all experiments was a single choice question about the content of the discussion that they had read or heard depending on the experiment (see Supplementary Table 6 for the wording). The attention check was not preregistered in Experiment 5 by mistake. We still applied this exclusion criterion to align the quality of the results with those of the previous four experiments. We also applied these exclusion criteria to Experiment 1. Thus, we excluded the following numbers of participants from further analyses: $n = 13$ for Experiment 1, $n = 42$ for Experiment 2, $n = 60$ for Experiment 3, $n = 29$ for Experiment 4, $n = 69$ for Experiment 5 and $n = 216$ for Experiment 6. A sensitivity analysis tested the robustness of the results keeping all previously excluded participants in the analyses.

All experiments were conducted online using an Enterprise Feedback Suite survey by Questback[56]. Participants received invitations via different recruiting systems and received compensation that varied depending on the experiment (see the Supplementary Methods). All experiments used a similar procedure. First, participants were randomly assigned to one of the four rebuttal conditions (advocate absent, topic only, technique only, combination of topic and technique). All participants were asked to read or listen to two vignettes from an audiotaped or written radio discussion. The vignettes presented a radio discussion with a science denier who argued against a behaviour favoured by science (vaccination: Experiments 1–4 and 6; taking action against climate change: Experiment 5). The two vignettes presented two different arguments from the denier. In all the experiments in the domain of vaccination, the denier used the topic and technique combination of safety and impossible expectation in the first vignette (see Fig. 1 for the specific argument) and the combination of trust and conspiracy in the second vignette (see ref. [57] for all stimuli). In Experiment 5 (climate change) the denier used the combination of consequence and selectivity (see Supplementary Fig. 1 for the specific argument) in the first vignette and consequence and fake expert in the second vignette[57]. Depending on the condition, the science advocate was either absent from the debate (no topic and no technique rebuttal condition) or present at the discussion (remaining three conditions). Conditions including a science advocate differed regarding the rebuttal of the denier. The advocate corrected the facts about the topic, uncovered the technique of the denier or used a combination of both methods (see Fig. 1 and Supplementary Fig. 1 for examples and ref. [57] for all stimuli). Before the discussion, all participants indicated their attitude towards the evidence-based behaviour under discussion and their intention to perform that behaviour (see Supplementary Table 6 for scales, reliability scores and references of all items). Participants indicated their attitude and intention a second time after they read or listened to the discussion. In addition, we collected US residents' political ideology (Experiments 4 and 6) and general confidence in vaccination (Experiments 2–4 and 6). Changes in the intentions and attitudes for single experiments (post/pre) are reported in Fig. 2 using the POMP scores[47] of the original scale, with higher values indicating a greater intention and a more positive attitude. Using POMP values allows for easy interpretation of model parameters as each variable in the models ranges from 0–100 after the POMP transformation (changes in intention and attitude can be positive or negative, leading to a range of −100 to 100 after the POMP transformation). An increase of one unit on a POMP scale can be translated into an increase of 1% of the maximum possible score of the original scale. For example, a decrease in the attitude towards vaccination by 20 units (%) of the POMP scale would translate into a decrease of one point (20%) on the original five-point scale. In the forest plots, values of political ideology and confidence are reported as low and high (based on median splits) to report rebuttal strategies as a function of these moderating variables. Median values for both moderators were identical in both studies (confidence: median = 75 (low < 75; high ≥ 75); US conservatism: median = 37.5 (liberal ≤ 37.5; conservative > 7.5)). Contrary to the preregistered protocol of Experiment 6, we used the median rather than predetermined categories to define subgroups for explorative analyses. The predetermined categories resulted in highly unbalanced group sizes. The median was used to reduce this bias. Data describing moderator variables and dependent variables are provided in the Supplementary Information. In addition to these moderator variables and dependent measures, in some experiments we collected data on potential mediator variables, control variables (knowledge, source relevance, gender, age, education) and additional variables for explorative reasons. Supplementary Table 6 presents the full list of assessed variables.

In all the experiments, we used repeated measurements ANOVAs to analyse the influence of the denier and the effectiveness of topic rebuttal and technique rebuttal to mitigate the influence. In Experiments 2, 3 and 5, ANOVAs on difference scores rather than repeated measures ANOVAs were preregistered. Both approaches led to identical results. However, we chose to report the repeated measures ANOVAs preregistered in Experiments 4 and 6 for all experiments because they reveal the influence of the denier on individuals' attitudes and intentions and the effectiveness of the rebuttal approaches in a single test. To compare the effectiveness of any kind of rebuttal we used a planned contrast to compare the three rebuttal conditions with the advocate absent condition (advocate absent versus any kind of rebuttal: −3 1 1 1). A second planned contrast assessed the effectiveness of the combination of topic and technique rebuttal compared to the single strategies (single strategies versus combined strategy: 0 −1 −1 2). The contrast analyses were not specified in the preregistration protocols of Experiments 2 and 3. All ANOVA results of single experiments are reported in the Supplementary Information.

As recommended[44,45], we report and derive our conclusions using an internal random effects meta-analysis including all six experiments in the main manuscript. The effects in confirmatory analyses are presented as Hedges' adjusted g (standardized mean differences), because the scales measuring attitude and intention differ between studies. In explorative subgroup analyses, the scales to measure attitude and intention are identical between studies. In these analyses, we report the results in absolute mean differences[46]. Meta-analyses of interaction effects of subgroups by experimental conditions (moderator analyses) are based on Cochran's Q test and a Higgin's I^2 threshold of 50%[58]. Calculations of statistical power for the confirmatory meta-analyses are reported in the Supplementary Information. The participants of all experiments were blinded to group allocation. Owing to the automatic randomization mechanism, the investigators were blind to the group allocation process. The analyses were not performed blind to the conditions of the experiments.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data supporting the findings of this study are available from the Open Science Framework (https://doi.org/10.17605/OSF.IO/XX2KT)[57].

Code availability

The syntax used to analyse the datasets in this study is available from the Open Science Framework (https://doi.org/10.17605/OSF.IO/XX2KT)[57].

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Author contributions
Both authors substantially contributed to this article. P.S. and C.B. developed and designed the study, conducted the analyses and wrote the Article and Supplementary Information. P.S. visualized and curated the data. C.B. secured the funding.

Competing interests
The authors declare no competing interests.

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☐	☒	Clearly defined error bars *State explicitly what error bars represent (e.g. SD, SE, CI)*

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Software and code

Policy information about availability of computer code

Data collection	Data of all experiments in the study were collected using the web-based Enterprise Feedback Suite (EFS) by Questback.
Data analysis	For data analysis of single studies (Supplementary Information), we used IBM SPSS 23 for Mac OS X. For analysis of meta results and forest plots (manuscript) we used review manager 5.3 from the Cochrane Collaboration. In addition we used Meta Essentials to calculate meta effect-sizes of repeated measures. For bar and dot plots (manuscript and supplement) we used the R-package ggplot2. For a-priori statistical power analysis we used G*Power 3.1.9.2 (Experiment 1 and Experiment 2) and 3.1.9.3 (Experiment 3, 4, 5 and 6) for Mac OS X. Statistical power for meta-analyses were calculated using the R-Script by Tiebel.

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

All experiments in the study are quantitative experimental.

Research sample

Experiment 1: University of Erfurt undergraduates. (Age: Mean = 22.81, Standard Deviation = 4.10; Gender: 84% female; Education: 99% reported a university entrance diploma or a higher education; Nationality: German)*. Reason for sample selection: Pilot experiment.

Experiment 2: Participants from panel survey company. Representative of the general German population with regard to age, gender and education. (Age: M = 49.58, SD = 14.70; Gender: 54% female; Education: 40% reported a university entrance diploma or a higher education; Nationality: German)*. Reason for sample selection: Replication in a more heterogeneous, non-student sample.

Experiment 3: Participants from panel survey company. (Age: M = 50.90, SD = 15.90; Gender: 55% female; Education: 42% reported a university entrance diploma or a higher education; Nationality: German)*. Reason for sample selection: Replication in a more heterogeneous, non-student sample.

Experiment 4: Amazon Mechanical Turk Worker. (Age: M = 39.43, SD = 12.02; Gender: 47% female; Education: 74% reported an associate's degree or a higher education; Nationality: US-citizen)*. Reason for sample selection: Replication in a heterogeneous, English-speaking sample.

Experiment 5: University of Erfurt undergraduates. (Age: M = 29.14, SD = 12.08; Gender: 62% female; Education: 87% reported a university entrance diploma or a higher education; Nationality: German)*. Reason for sample selection: Replication of Experiment 1 in a similar sample but different subject domain.

Experiment 6: Amazon Mechanical Turk Worker. (Age: M = 36.81, SD = 10.92; Gender: 46% female; Education: 71% reported an associate's degree or a higher education; Nationality: US-citizen)*. Reason for sample selection: Replication in a sample of US residents.

*All demographic data are provided for final samples after application of exclusion criteria (see below).

Sampling strategy

Experiment 1: Convenience sampling procedure.

Experiment 2: Quota (by age, gender and education of the German general population) sampling procedure; preregistered sample size based on a priori statistical power calculations (Power = 0,8) for all analyses. See https://aspredicted.org/3hv7m.pdf for preregistration files.

Experiment 3: Quota (by age, gender and education of the German general population) sampling procedure; preregistered sample size based on a priori statistical power calculations (Power = 0,8) for all analyses. See https://aspredicted.org/ve6hv.pdf for preregistration files.

Experiment 4: Convenience sampling procedure; preregistered sample size based on a priori statistical power calculations (Power = 0,95) for all analyses. See https://aspredicted.org/bf9qe.pdf for preregistration files.

Experiment 5: Convenience sampling procedure; preregistered sample size based on a priori statistical power calculations (Power = 0,8) for all analyses. See https://aspredicted.org/ce2am.pdf for preregistration files.

Experiment 6: Convenience sampling procedure; preregistered sample size based on a priori statistical power calculations (Power = 0,8) for all analyses. See https://aspredicted.org/ij55n.pdf for preregistration files.

Data collection

Data of all experiments in the study were collected using the web-based Enterprise Feedback Suite (EFS) by Questback. Data was stored

Data collection	and analyzed on a computer. Owing to the automatic randomization mechanism (see below), the investigators were blind to the group allocation process.
Timing	Experiment 1: 11.03.2016 - 08.04.2016 Experiment 2: 07.04.2017 - 19.04.2017 Experiment 3: 15.09.2017 - 16.10.2017 Experiment 4: 09.04.2018 - 13.04.2018 Experiment 5: 05.07.2017 - 31.07.2017 Experiment 6: 27.11.2018 - 29.11.2018
Data exclusions	Participants under the age of 18 were screened out at the beginning of all experiments. The following exclusion criteria were preregistered for Experiments 2–6: Participants were excluded when they did not finish the experiment, when the duration of participation exceeded 30 minutes or fell below five minutes (Experiment 5: three minutes) and when participants failed to answer a simple attention check. All exclusion criteria were applied to increase quality of responses in online experiments. The attention check for all experiments was a single choice question about the content of the discussion that they had read or heard depending on the experiment (see Supplementary Table 6 for wording). The attention check was not preregistered in Experiment 5 by mistake. We still applied this exclusion criterion to align the quality of results with those of the previous four experiments. We also applied these exclusion criteria to Experiment 1.
Non-participation	Experiment 1: N = 202 participants clicked on the link of the study, 168 proceeded after the introduction page and 125 finished the experiment. The exclusion of 13 participants due to the exclusion criteria (see above) resulted in a sample size of n = 112 for all analyses. Experiment 2: N = 260 participants clicked on the link of the study, 238 proceeded after the introduction page and 206 finished the experiment. The exclusion of 42 participants due to the exclusion criteria (see above) results in a sample size of n = 164 for all analyses. Experiment 3: N = 383 clicked on the link of the study, 333 proceeded after the introduction page and 261 finished the experiment. The exclusion of 60 participants due to the exclusion criteria (see above) results in a sample size of n = 201 for all analyses. Experiment 4: N = 345 clicked on the link of the study, 276 proceeded after the introduction page and 256 finished the experiment. The exclusion of 29 participants due to the exclusion criteria (see above) results in a sample size of n = 227 for all analyses. Experiment 5: N = 1,149 clicked on the link of the study, 339 proceeded after the introduction page and 217 finished the experiment. The exclusion of 69 participants due to the exclusion criteria (see above) results in a sample size of n = 148 for all analyses. Experiment 6: N = 2105 clicked on the link of the study, 1416 proceeded after the introduction page and 1137 finished the experiment. The exclusion of 216 participants due to the exclusion criteria (see above) results in a sample size of n = 921 for all analyses.
Randomization	Participants of all experiments in the study were randomly allocated to one out of four experimental conditions. An automatic randomization mechanism provided by the Enterprise Feedback Suite (see above) was used for randomization. At the start of the study the software randomly selected which rebuttal information was to be communicated to participants.

Reporting for specific materials, systems and methods

Materials & experimental systems

n/a	Involved in the study
☒	☐ Unique biological materials
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☐	☒ Human research participants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics	see above
Recruitment	Participants were recruited via Email (Experiment 1 and 5) or via a direct link to the study provided by Amazons Mechanical Turk (Experiment 4 and 6), the survey company Norstat (Experiment 2 and 3) or social media (Experiment 5). All experiments were conducted online. Participation was a voluntary decision and participants could quit the survey at any time. Therefore, individuals intrinsically interested in the topic of the survey could have been more willing to finalize the study. We tried to reduce this potential bias with adequate compensation of participants. Moreover, it could be assumed that highly educated people are more willing to participate in surveys about the topic of this study (vaccination, climate change). We addressed this potential bias with samples representative of the German general population with regard to education (Experiment 2 and 3).