Science Communication in Light of Moral and Social Concerns: Testing a Statistical Physics Model of Belief Change

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Abstract

When presented with scientific facts, why do some people change their beliefs and others do not? As science communicators often focus on disseminating only scientific facts, some people feel dissonance because of the contradictions between these facts and concerns driven by moral judgments and perceived beliefs of social circles. Without resolving these moral and social concerns, scientific facts might be difficult to accept. We use a model of belief dynamics inspired by statistical physics to understand individual differences in belief change. We predict that belief change is most likely when science communication includes information to reduce feelings of dissonance and also either highlights the importance of the particular social or moral concern it is designed to reduce or draws people's attention to their overall dissonance. We test our model predictions in two longitudinal studies with a total of 1,673 US participants who were presented scientific messages to alleviate and highlight different concerns about the safety of GM food and childhood vaccines. Our research underscores the value of statistical physics models for analysing psychological processes related to belief change, and our findings suggest that scientific messages should confront head-on important social and moral concerns to change public opinion.

Keywords: science communication, belief dynamics, computational modelling, dissonance, moral values, GM food, childhood vaccines.

1. Introduction

Accurate scientific information on health-related issues is critical for making beneficial personal and societal choices. However, not everyone is willing to change their beliefs to align with scientific consensus. Two prominent examples of such issues are genetically modified (GM) food and childhood vaccines. Despite the consensus within the scientific community regarding their safety [1,2], 57% of US adults believe currently approved GM food is unsafe to eat [3], and 22% of US adults believe that the benefits of childhood vaccines for measles, mumps, and rubella do not outweigh the risk of side effects [4].

When presented with scientific facts, why do some people change their beliefs and others do not? Some reluctance to change is driven by moral judgements and perceived beliefs of social circles [5,6]. Compared to people who believe that GM food and childhood vaccines are safe, sceptics rank the importance of moral concerns about health and the environment higher than other concerns [4,7] and assign a higher value to moral ideals of purity [8–11]. GM and vaccine sceptics also have less trust in scientific research, the medical community, and industry leaders [4,7,12]. Instead, messages from other – more trusted – social sources have a stronger influence on the acceptance of GM food [13–15], and parents' decisions about child vaccination are influenced by their friends [16] and greater social norms [17].

Due to potential contradictions between the above-mentioned moral and social concerns and new scientific information, some sceptics might feel *dissonance*; and reducing this dissonance is key to changing beliefs. According to a classic theory of belief change in social psychology [18,19], when people experience dissonance – a psychological state of being uncomfortable, uneasy, and bothered – they might change their beliefs to reduce this negative feeling. In the case of GM food and childhood vaccines, a sceptic might more readily accept scientific information about their safety if the message also shows that this resolves important moral and social concerns, such as their safety for the environment or their approval rate within the scientific community. How can we model the dynamics of belief change that occur because of the interplay of scientific facts, moral and social concerns, and psychological processes such as importance of different concerns and attention to dissonance?

In this paper, we propose a model of belief dynamics inspired by statistical physics to understand the mechanisms of belief change leading to individual differences in accepting scientific facts. Our quantitative modelling framework formalises multiple interacting processes (dissonance between the scientific fact and relevant moral and social concerns, importance of these concerns, and attention to overall dissonance), and produces testable predictions. This modelling framework was previously presented in a review paper [20] where we discussed its potential for modelling psychological processes of belief change in general. Here, we empirically test these theoretical ideas by specifically exploring individual-level processes leading to belief change. Based on our model, we predict that belief change is most likely when science communication includes information to reduce feelings of dissonance and also either 1) highlights the importance of the particular social or moral concern it is designed to reduce or 2) draws people's attention to their overall dissonance.

We estimate our model parameters and test our predictions in two longitudinal studies on large national samples. Participants were asked about GM food and childhood vaccination, as well as about a number of moral and social considerations that could lead to concerns about scientific issues. In both studies, participants were presented scientific information alongside different moral and social frames developed to alleviate the dissonance between the presented information and potentially important moral and social concerns. While these two longitudinal studies were designed to specifically test the model in this paper, the second study was used previously to test another belief change model based on statistical networks [21]. However, that paper does not explore the interaction between dissonance and other psychological processes, which is the focus of this paper.

To develop our model and empirical tests, we draw upon research in science communication and belief dynamics. In the science communication literature, researchers have been trying to design messages

and frames to change beliefs about a variety of scientific beliefs, with mixed results [e.g., 22,23]. Thus, there has been a call for more consistent measures and more comprehensive models of belief change [24,25]. We make a contribution by providing a simple, yet cognitively and socially plausible, model of the interplay between new scientific information with moral and social concerns. Although several models of belief dynamics have already been developed in disciplines ranging from economics [26,27], philosophy [28], political science [29], psychology [30–32], sociology [33] and statistical physics [34,35]. We expand on this line of work by combining realistic cognitive processes and influences from social networks [36,37] and by allowing empirically testable predictions for differences in belief change between individuals.

In what follows, we describe how we use our model to formalise psychological processes and derive two quantitative predictions on how new scientific information can lead to belief change. We then describe empirical results from two longitudinal studies and, including our estimated model parameters formalising psychological processes, test our two quantitative predictions about belief change in a hierarchical linear statistical model. We find that our model parameters can help explain which people change their beliefs towards the scientific information, which people do not change their beliefs, and even which people change their beliefs *away* from the scientific information.

2. Model

To quantitatively model psychological processes underlying belief change after receiving new information, we draw on a previously published theoretical framework [20]. Inspired by statistical physics models of belief dynamics, this framework was designed to combine both social network processes and interconnected individual beliefs using different integration and updating rules. In the model presented here, we focus on individual beliefs and derive new theoretical predictions to test empirically.

To model how belief systems change when individuals encounter new evidence, we use an analogy with Potts models in statistical physics. In these models, the energy of a system depends on both the agreement of the magnetic field within each component and on the agreement of the components with each other. These different sources of energy can be weighted if one source is more important than the other. If the temperature is low enough, the system will be drawn to a lower energy state. In the case of belief dynamics, energy can be seen to be analogous to the overall dissonance of a belief system. Similarly to energy, dissonance will depend partially on the agreement of each belief with other beliefs that one has (here, moral considerations), and partially on the agreement of one’s own beliefs with perceived beliefs of others in one’s social network (social considerations). As in the statistical physics analogy, people can assign different importance to these sources of dissonance. Moreover, people who pay sufficient attention to the dissonance due to the contradictions between their beliefs and new information (i.e., those who have a lower temperature in the statistical physics analogy) can reach a state of lower dissonance by updating their beliefs.

Statistical physics models have the advantage of using only a few components to reproduce a wide range of observed empirical patterns of belief spread. These models provide a simple representation of more complex psychological and social processes [38]. Although social systems certainly do not have a one-to-one mapping to physical systems, models inspired by statistical physics can incorporate psychological concepts that are essential for understanding belief dynamics, enable testing specific hypotheses, and help disentangling the relationships between key psychological processes.

2.1. Overview

Figure 1 shows how scientific messages can influence belief change in our model. We posit that when considering a specific scientific belief, which we will refer to as *focal belief*, people draw on various moral and social considerations, some of which might be a cause of concern. Here, we focus on two *focal beliefs*: the safety of GM food and the safety of childhood vaccines. To determine their level of support regarding the focal belief about the safety of childhood vaccines, people might consider other related

beliefs, such as whether the pharmaceutical industry makes too much profit from vaccines (a moral consideration) or whether their friends think childhood vaccines are safe (a social consideration). The support for a focal belief can engender feelings of dissonance with relevant moral and social considerations, depending on their relative importance and the level of attention (Figure 1a). Scientific messages about the focal belief that are framed in a way that addresses moral and social concerns (Figure 1b) could decrease the dissonance between the scientific fact presented and these concerns (Figure 1c). However, as we explain in the following paragraphs, successful scientific messages should also lead to 1) an increase in the relative importance of this source of dissonance and / or 2) an increase in the attention to the overall dissonance (Figure 1c). If there is enough importance or attention, individuals will change their beliefs to belief towards the scientific fact that minimizes the dissonance with their moral and social considerations (Figure 1c).

Figure 1. Modelling how scientific messages can lead to belief change. When thinking about their level of support for the focal belief, individuals will draw on relevant social and moral considerations, some potentially causing dissonance given their importance and the overall attention (a). Scientific messages can target this focal belief with a scientific fact along with relevant moral and social frames (b). These scientific messages can lead to a decrease in the dissonance between support for the focal belief and moral and social considerations, an increase in the relative importance of a specific source of dissonance (moral or social), and/or an increase in the attention paid to the overall dissonance, which will prompt a change of support for the focal belief towards the scientific fact (c).

For example, a scientific message can draw attention to the dissonance between believing vaccines are safe and a related moral belief that the pharmaceutical industry makes too much profit from vaccines. If the message at the same time helps to reduce this dissonance by explaining that the industry would profit even more from allowing people to get sick and then selling them medicine, it might help people accept that vaccines are safe. As another example, consider a scientific message that aims to promote the belief that GM food is safe for healthy adults. People who think GM food is not safe may have an erroneous perception that scientists are divided on this issue. If they were to accept that GM food was safe, they could experience dissonance due to this perception. A scientific message that provides accurate information on the overwhelming scientific consensus regarding the safety of GM food could lower the dissonance of

people who find this social concern important and help them accept the facts about safety. In the next section, we describe how these processes were mathematically derived from our model.

2.2. Model Details

In our model, focal belief, as well as other related moral and social considerations, are represented as probability vectors describing individual levels of support, in line with probabilistic models of belief change [39]. Representing beliefs as vectors rather than as a single number allows for a more nuanced representation of beliefs and belief change. For example, if one answers 3 on a scale from 1 (completely disagree with a consideration, e.g., that GM food is natural) to 7 (completely agree), then the corresponding probability vector for this consideration would be $[0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0]$. If one is undecided between 3 or 4, the corresponding vector would be $[0 \ 0 \ 0.5 \ 0.5 \ 0 \ 0 \ 0]$. If one is conflicted about an issue, their belief vector can be represented as $[0.5 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0.5]$, although we expect that such vectors are rare.

The probability vectors of all relevant social and moral considerations are integrated into the social and moral fields, respectively. The literature on semantic [40] and social belief integration [41] has described a number of different rules to integrate these considerations. Here, we assume a weighted average rule, whereby the vectors are weighted by how important specific moral and social considerations are to each individual. This assumption is well aligned with our data (see Section 5 of the *Supplementary Material* for a comparison of different integration rules). For example, if one holds two moral beliefs related to GM food, one represented as $[0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0]$ and the other as $[0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1]$, and if the latter belief is twice as important as the former, the moral field according to the weighted average rule would be $[0 \ 0 \ .33 \ 0 \ 0 \ 0 \ .67]$.

Dissonance is represented as the squared distance between the probability vectors for each possible level of support for the focal belief and the probability vectors that describe the moral and social fields. This way of representing dissonance is in line with a widely used bounded confidence model of opinion dynamics [42], and produces similar patterns as absolute distance [43] and exponential distance [44]. For example, the moral dissonance between one's moral field of $[0 \ 0 \ .33 \ 0 \ 0 \ 0 \ .67]$ and the highest level of support for the focal belief $[0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1]$ would be $\Sigma([0 \ 0 \ .11 \ 0 \ 0 \ 0 \ .11])=2$. We calculate this dissonance with the moral field for each possible level of support for the focal belief α , ranging from 1 to m (in the examples here, $m=7$), finally obtaining vector $\vec{d}^{mor}$ where each component d_{α}^{mor} contains the moral dissonance from considering the α level of support for the focal belief. The social dissonance vector, $\vec{d}^{soc}$, is derived separately using the same process.

Moral and social dissonances are then incorporated into a single vector using a parameter w which determines the relative importance of the two sources of dissonance. For each individual or group of individuals i at a given time step t , we define the total dissonance that may be felt when considering each of the different levels of support for the focal belief as:

$$\vec{H}_{i,t} = w_t \vec{d}_{i,t}^{soc} + (1 - w_t) \vec{d}_{i,t}^{mor}, \quad (1)$$

where $0 \leq w_t \leq 1$ and $\vec{H}_{i,t}$ is the vector of dissonance, with $\vec{d}_{i,t}^{soc}$ the social and $\vec{d}_{i,t}^{mor}$ the moral dissonance (calculated as described above). The larger the value of parameter w_t , the more weight is put on social as opposed to moral dissonance. The additive assumption of the model is in line with findings that additive processes underlie human judgments in many domains [45].

Based on the dissonance vector $\vec{H}_{i,t}$, probabilities of different levels of support for the focal belief $\sigma_{i,t,\alpha}$ are calculated using the softmax function [see 20 for more details]:

$$\sigma_{i,t,\alpha} = e^{-\beta_t H_{i,t,\alpha}} / \sum_{\alpha=1}^m e^{-\beta_t H_{i,t,\alpha}} \quad (2)$$

where $\beta_t = [0, \infty)$ is a parameter that represents the “noisiness” of the belief updating process, here corresponding to the attention people pay to the dissonance, which in turn determines how much dissonance they feel when considering different levels of support for the focal belief.

2.3. Model Predictions

This model allows us to derive specific quantitative predictions to explain individual-level variations in belief change. Specifically, we expect that the relationship between dissonance reduction and belief change will be moderated by 1) the increase in the relative importance of social vs. moral dissonance, as estimated by the parameter w , and 2) the increase in the amount of attention people pay to their overall dissonance, as estimated by the parameter β . In other words, the higher the importance of a particular source of dissonance and/or the higher the attention to the overall dissonance, the stronger the relationship between belief change and reduction in dissonance.

3. Results

To test our model and understand individual-level variations in belief change, we conducted two longitudinal studies on a total of 1,673 participants sceptical of the safety of GM food or childhood vaccines. Data and measures are described in the *Methods Section*. The following sections discuss individual-level variations in belief change, how our model parameters can help explain these differences, and the validity of the parameters as psychological processes.

3.1. Individual-level Variations in Belief Change

Table 1. Summary of scientific messages (see Table S4 in the *Supplementary Material* for the full text).

Frames	Study 1		Study 2	
	GM food	Childhood vaccines	GM food	Childhood vaccines
<i>Basic scientific information</i>	<i>There is no evidence that GM food is harmful when consumed (NAS).</i>	<i>There is no evidence that childhood vaccines cause long-term harm (CDC).</i>	<i>There is no evidence that GM food is harmful when consumed (NAS).</i>	<i>There is no evidence that childhood vaccines cause long-term harm (NAS).</i>
+ Scientific consensus	88% of US scientists.	86% of US scientists.	88 % of US scientists.	86 % of US scientists.
+ Favourite media	Favourite news source.	Favourite news source.		
+ Public	37% of the US general public.	69% of the US general public.		
+ Authority			Imitates traditional techniques.	
+ Care	Beneficial to children	Beneficial to children		
+ Fairness	Benefits large- and small-scale farmers.	Benefits big pharmaceutical companies and individuals.	Benefits big biotechnology companies and farmers.	Benefits pharmaceutical companies and patients.
+ Freedom			Information shared with the public.	Information shared with the public.
+ Purity	Imitates nature.	Imitate nature.		

4. *Note: The part in italics is repeated for each experimental condition.*

To help reduce feelings of dissonance, we presented participants with a variety of scientific messages with basic scientific information on the safety of GM food or childhood vaccines and additional moral or social frames developed to tackle important social and moral concerns (summary in Table 1 and description of frames in the *Methods Section*). For each study and topic, we then conducted a linear model

of belief change and estimated the marginal mean belief change for each experimental group (see the *Empirical Analyses of Belief Change* Section in the *Methods*). However, even though some scientific messages successfully changed participants' beliefs towards more acceptance of scientific facts, we did not find evidence that these framings were better than the basic scientific information due to opposite individual responses to the framings in each condition. We expand on these points below.

Success of scientific messages. Several scientific messages were successful in changing focal beliefs towards greater acceptance of the safety of GM food (Figure 2a&c). For GM food, the most effective message in Study 1 used moral frames related to fairness and purity. Participants who received those messages had the largest belief change towards accepting the safety of GM food, significantly greater than the control group which received nothing (for both, difference between marginal mean focal belief change compared to nothing: $diff_{nothing} = 0.34, p < 0.05$). For GM food in Study 2, frames using the scientific consensus and authority were associated with significantly more belief change compared to the control group ($diff_{sci,nothing} = 0.23, p < 0.05$; $diff_{auth,nothing} = 0.24, p < 0.05$). However, in both Study 1 and Study 2 none of these messages was associated with a positive belief change significantly more than the basic scientific information (formal comparison of marginal means Table S7 last two columns).

Figure 2. Estimated marginal mean values of belief change in each experimental condition, averaging change right after receiving the scientific message, and during the last wave, all other covariates held at their sample values (full models in the *Supplementary Material* Section 6). Results from Study 1, $N_{1GM}=361$ and $N_{1Vac}=364$ and Study 2, $N_{2GM}=531$ and $N_{2Vac}=417$. Bars denote SE around the mean.

Several scientific messages were also associated with focal belief change for childhood vaccines (Figure 2b&d). The most effective scientific messages in Study 1 compared to the control were those with social frames using the scientific consensus ($diff_{sci,nothing} = 0.22, p < 0.05$) and citing one's favourite media ($diff_{media,nothing} = 0.26, p < 0.05$). In Study 2, only the scientific message using the fairness

moral foundation was associated with more belief change than the control group $diff_{fair,nothing} = 0.19, p < 0.05$). As in the experiment about GM food beliefs, none of the messages about childhood vaccines were significantly better than the basic scientific information (Table S7 last two columns).

Some scientific messages were not associated with any significant belief change, and some were associated with an estimated belief change even lower than the control group, where participants did not see any scientific information (Figure 2a-d). For example, using the general public opinion as a frame was largely unsuccessful in changing focal beliefs about GM food, which was expected given that only 37% of the US general public believes that GM food is safe (Table 1). Framing GM food in terms of fairness was more successful in Study 1, where it focused on the positive effects of GM food for both large and small farmers, than in Study 2, where it focused on the positive effects for both biotech companies and small farmers. The moral frame used in Study 2 that focused on freedom of information was not very effective for both GM food and childhood vaccines.

Individual differences. Within each experimental group, our scientific messages using social and moral frames were not more successful at changing beliefs compared to the basic scientific information. Within each experiment group, some individuals changed their beliefs towards greater acceptance and some went against the proposed evidence (Figure 3a-d). For example, even after seeing the most successful scientific message, such as the scientific consensus on GM food in Study 2, 28% of the participants in that experimental group did not change their beliefs and 27% went against the proposed information, suggesting a backlash. Among the participants who were in the worst experimental condition, receiving the public's beliefs about GM food in Study 1, 36% still changed their beliefs towards greater acceptance of GM food, while 33% did not change their beliefs at all.

Figure 3. Distribution of belief change in focal belief, on average, from their original beliefs. Results from Study 1, $N_{IGM}=361$ and $N_{IVac}=364$ and from Study 2, $N_{2GM}=531$ and $N_{2Vac}=417$. Violin plots include a marker for the median of the data, a box indicated the interquartile range, and spikes that extend to the upper and lower adjacent values overlaid with an estimated kernel density.

Why did some individuals change their beliefs in accordance with new scientific information while others went against the proposed information? Initial belief and belief change explain some of the differences: People who were most sceptical of the safety GM food and childhood vaccines were less likely to change their beliefs towards greater acceptance, and those who had a lot of variability in their beliefs before the experiment were more likely to change their beliefs towards greater acceptance (*Supplementary Material Table S6*). However, most of the differences between individuals and between scientific messages remain unexplained. We next examine how our model can shed light on some of these unexplained variations.

4.1. Testing Model Predictions

We fitted our model parameters to the data (see *Parameter Fit* Section in the *Methods*) and investigated if they could explain some of the individual-level differences in belief change, in line with our predictions. Specifically, we predicted that the relationship between dissonance reduction and belief change would be moderated by the increase in the relative importance of social vs. moral dissonance, as estimated by the parameter w , and the increase in the amount of attention people pay to their overall dissonance, as estimated by the parameter β . In Figure 6, we show the relationship between predicted marginal mean belief change with change in social dissonance and its relative importance (a), change in moral dissonance and its relative importance (b), and change in overall dissonance and attention (c). Details on the statistical hierarchical model to predict belief change are given in the *Empirical Analyses of Belief Change* Section in the *Methods* Section.

In line with our first prediction, belief change towards the scientific information was negatively related to changes in social and moral dissonance but only for individuals who experienced an increase in importance of that particular source of dissonance after seeing the scientific messages (Figure 4a&b). Specifically, for people who showed an increase in the importance of social or moral dissonance, a reduction in the relevant dissonance was associated with a greater belief change compared to an increase in that dissonance (red fitted lines Figure 4a&b). A reduction in social dissonance was related to larger belief change when the importance of that source of dissonance increased or stayed the same (see red and grey fitted line in Figure 4a, difference between increase and decrease in dissonance for those with an increase in importance: $diff_{soc,more_imp} = -2.585, p < 0.001$), whereas it was not related to more belief change when this source of dissonance decreased in importance (yellow fitted line in Figure 4a, $diff_{soc,less_imp} = 0.229, p = 0.733$). Similarly, the reduction in moral dissonance was associated with a larger change in focal beliefs only when the importance of this source of dissonance increased or remained the same after the scientific message (compare red and grey lines with the yellow fitted lines in Figure 4b, $diff_{soc,more_imp} = -2.593, p < 0.001$ vs. $diff_{soc,less_imp} = -0.417, p = 0.544$). For both types of dissonance, belief change was greater when there was an increase in importance compared to when the importance remained the same, although this difference was reliable only for social dissonance (Figure 4a-b and Table S9). For both types of dissonance, belief change *away* from the scientific message occurred when there was an increase in dissonance. For social dissonance, this backlash occurred regardless of the changes in importance.

Despite these similarities, the relationships between focal belief change, dissonance, and importance were not completely the same for social and moral dissonance. Specifically, when social dissonance was reduced and was important, focal beliefs showed the most positive change (left-hand side of Figure 4a). At the same time, when moral dissonance was reduced and was important, focal beliefs showed a similar amount of positive change as when moral dissonance was less important (left-hand side of Figure 4b). But if their change in moral dissonance became positive, participants were much more likely to change their beliefs away from the direction suggested by scientific messages if moral dissonance was

more important to them (right-hand side of Figure 4b). In other words, among participants with an increase in moral dissonance, there was a stronger backlash among those who considered this dissonance more important compared to those who valued this dissonance similarly or less over time. This suggests that focal beliefs may have been more sensitive to a rise in moral dissonance than to a reduction in social dissonance.

Figure 4. Relationship between average individual changes over time in focal beliefs (estimated marginal means) and the changes in social dissonance (a), moral dissonance (b), and total dissonance (c) across changes in parameters w (panels a and b) and β (panel c). The estimated marginal mean values of belief change are derived from a linear mixed model with random intercepts for different topics nested in studies (detailed model in Tables S8 in the *Supplementary Material*) and with all other covariates held at their sample values. Results from Study 1, $N_{IGM}=361$ and $N_{IVac}=364$ and Study 2, $N_{2GM}=531$ and $N_{2Vac}=417$. Areas denote SE around the mean.

Consistent with our second prediction, belief change was only associated with a reduction in total dissonance when individuals paid sufficient attention to the dissonance. Specifically, when attention (β) increased or remained the same, individuals who experienced a reduction in total dissonance before and after seeing the scientific message were more likely to change their beliefs compared to those who did not have a dissonance reduction, as reflected in the negative slopes of the red and grey lines in Figure 4c (difference between increase and decrease in dissonance for those with an increase in attention: $diff_{tot,more_att} = -2.585, p < 0.001$). The largest positive belief change occurred among individuals who had an increase in attention to dissonance (red line) compared to those whose attention to dissonance stayed the same (grey line), though both had a positive belief change if they also experienced a decrease in dissonance. Similarly to social dissonance, the most positive belief change was among participants with a decrease in dissonance and an increase in attention (left-hand side Figure 4c) and there was a backlash against the scientific information among participants with an increase in total dissonance, regardless of the attention towards it (right-hand side Figure 4c). We explored the relationship between dissonance, attention, and importance at the group level and found similar results, though the small number of groups precludes a formal statistical analysis (*Supplementary Material* Section 7).

4.2. Psychological Interpretation of Model Parameters

We also investigated whether the model parameters corresponded to the psychological constructs they were assumed to represent. As discussed above, in our model, w is the weight given to social dissonance compared to moral dissonance, and therefore should reflect the relative importance of social considerations compared to moral considerations. Furthermore, β is the inverse of the noise added to the total dissonance and should therefore reflect the amount of attention paid to the overall dissonance during the belief updating process and the resulting certainty about one's beliefs. To examine whether these parameters were indeed correlated with related psychological concepts, we fitted them on groups of participants who had different levels of focal belief change after receiving the scientific message (more details in the *Parameter Fit* Section of the *Methods*). We then correlated the estimated changes in the parameters before and after the scientific messages with changes in the self-reported measures of importance and certainty. At the beginning of the study, participants rated the importance of each moral and social consideration. We averaged these ratings for each type of consideration. In addition, participants reported certainty about their focal beliefs on a 7-point scale after each time they reported their focal beliefs (details on measures in the *Methods Section*).

In line with our interpretation, parameter w is related to how much more important social considerations are compared to moral values, as stated by the participants. As Figure 5 (top panel) shows, there was an overall positive relationship between w and the relative importance of social considerations compared to moral considerations (calculated as the difference in their average ratings). The only exception was in Study 1 for the GM topic, where the values of w were high across all values of the relative importance of social vs. moral considerations. Furthermore, in line with our interpretation, positive changes in the parameter β from before to after receiving the scientific message (suggesting greater attention to the overall dissonance induced by the scientific message) were mainly positively related to participants' stated changes in certainty about their focal beliefs (Figure 5, bottom panel).

Taken together, these results suggest that the model parameters approximated actual psychological variables important for belief change.

Figure 5. Top: Relationship between participants reported relative importance of social vs. moral considerations and initial levels of parameter w (fitted separately for groups of participants with different levels of belief change, see the *Methods* Section for more details). Bottom: Relationship between change in reported certainty of one’s focal belief and change in parameter β from before to after scientific message.

5. Discussion

Our study provides evidence that scientific messages should confront related moral and social concerns head-on and also provide information to reduce the potential contradictions between these concerns and scientific facts. Both of these processes are critical for belief change towards the scientific consensus. First, science communication must highlight the dissonance between core scientific facts and important moral and social concern. This recommendation is somewhat counterintuitive, as hiding any potential conflicting beliefs may seem as the wiser choice. Second, science communication must provide a path to reduce this dissonance. When scientific messages highlight the dissonance between scientific facts and people’s social or moral concerns, but do not help to resolve this moral dissonance, it is likely that a backlash against the new scientific information will occur. We find support for these findings across different frames of the scientific messages, topics, and samples.

To understand individual-level variations in response to scientific facts, it is important to take into account the complex underlying system of cognitive and social processes. Individuals hold various related beliefs, are embedded in different social settings, integrate their beliefs differently given the situation, sometimes care more about reducing social or moral dissonance, and can be distracted or otherwise not notice that changing their beliefs would actually reduce their overall dissonance. All these mechanisms can be difficult to study rigorously to understand and predict belief change. We propose here a simple, realistic, quantitative, and empirically testable model of these psychological processes, which produces a practical recommendation for science communication. Although several models of belief dynamics have been proposed, few incorporate specifically psychological mechanisms and are amenable to empirical testing.

The statistical physics framework we apply here [20] allows us to formalise psychological processes and investigate specific mechanisms leading to belief change after different scientific messages. This framework draws on just one of many possible analogies that can be useful to understand belief dynamics; other analogies have been borrowed from fields such as epidemiology [46] and evolution [47]. The main value of our framework is that it enables the derivation of precise quantitative predictions about

the relationship between dissonance and belief change that can be tested empirically. While simple and minimal, our theoretical model goes beyond existing psychological accounts of belief updating, including the information deficit model [48] and the direct motivated reasoning model [49,50] by explicitly incorporating the dissonance between scientific beliefs and social and moral considerations, as well as the importance and attention given to these dissonances. It also goes beyond most existing models of belief dynamics in statistical physics [34], by drawing explicit analogies with psychological concepts, and testing model assumptions and predictions with empirical data.

Our results are limited to beliefs related to the two topics we investigated, GM food and childhood vaccines. Further research should explore whether the same modelling framework can be used to explain and predict changes in other science-related beliefs, as well as beliefs about political and societal issues for which there is no scientific consensus. We have limited the related considerations to moral judgements and social groups that were previously shown to be important for GM food and childhood vaccines, but other beliefs could also be relevant. Finally, our studies were conducted on representative samples of the U.S. population, but people in other countries likely have somewhat different constellations of relevant beliefs, which should be determined for each cultural context separately.

Still, this study opens several new and exciting research pathways. First, it is important to explore further how scientific messages can reduce not only the dissonance between science-related beliefs with moral and social concerns but also how they can increase the importance and attention given to this dissonance. Second, it would be useful for future work to analyse whether our modelling framework, here very simple to preserve parsimony, should include additional factors that might affect belief dynamics. An example of such an additional parameter could represent the process of updating social networks. Third, moral and social concerns not only influence focal beliefs, but also interact with each other, forming networks of related beliefs [32,51,52]. Future research should investigate how this network of related considerations and the relationships among them might explain the success or failure of scientific messages.

Our research underscores the importance of addressing moral and social concerns when communicating scientific facts and sheds light on how these messages can be included in educational campaigns. Science communication should take into account potential moral or social sources of concern among science sceptics and integrate them into their scientific messaging. By drawing attention to important sources of conflict, messages can confront people's uncertainties head-on and potentially change their beliefs about the scientific issues.

6. Methods

5.1. Data and Measures

The two studies were conducted on two different samples and had somewhat different timing of questionnaire waves, but otherwise used the same methodology. In what follows, we describe separately for each study the participant selection and questionnaire procedures, then describe other aspects of the method for both studies together. In Section 2 of the *Supplementary Material*, we describe each subsample selected for the studies (Table S1 and Figure S3).

Participants in Study 1. We recruited $N_{\text{initial}}=1,566$ participants from Mechanical Turk using quotas to ensure that participants were selected across the political spectrum and with different levels of education. We sampled equally Mechanical Turk workers with lower education (up to an associate degree) vs. higher education (at least a bachelor's degree) and who identified themselves as conservative or moderate vs. liberal. To select participants who were sceptical about GM food or childhood vaccines, we used two screening questions: "Do you think it is unsafe or safe to eat GM food?" and "Do you think childhood vaccines are unsafe or safe for healthy children?", on a 7-point scale from 'completely unsafe' to 'completely safe'. We invited $N_{\text{sceptical}}=1,121$ participants who answered up to six on the scale to complete three study waves.

Our final sample size for Study 1 was $N_1=725$, which consisted of participants who completed the three waves. Our participants ranged from 18 to 77 years old. These participants were first assigned to one of two topics, depending on which one they were more sceptical about: the safety of GM food ($N_{1GM}=361$) or of childhood vaccines ($N_{1Vac}=364$). Second, each participant was randomly assigned to an experimental condition receiving different scientific messages.

Procedure in Study 1. The three study waves were 12 and 7 days apart from each other (see Section 3 in the *Supplementary Material*). In the first wave, participants reported their beliefs about the safety of GM food or childhood vaccines with related moral and social concerns (see Measures below). The second wave included most of the same questions and, in addition, an experimental condition testing different scientific messages: participants were randomly assigned to either a control group receiving no message, or experimental groups receiving either basic scientific information about safety of GM food (or childhood vaccines), or the same information included within one of several social or moral frames. The third wave included the same questions as in the second wave.

Participants in Study 2. We recruited $N_{2initial}=2,472$ participants, randomly sampled from a probabilistic sample of the U.S. population as a part of the RAND American Life Panel. Using the same two screening questions as in Study 1, we selected $N_{2sceptical}=1,839$ participants who answered between one and six on the 7-point scale about the safety of GM food and childhood vaccines. Of these participants, we selected $N_2=948$ who completed the three waves. Again, these participants represented a wide range of ages in the population, here between 23 and 90 years old. Depending on whether they were more sceptical about the safety of GM food or childhood vaccines, participants were assigned to one of these topics ($N_{2GM}=531$, $N_{2Vac}=417$). When assigning participants to experimental conditions, we made sure to maintain a similar representation of political views, educational attainment, gender, and parental status in each condition.

Procedure in Study 2. The three study waves were 20 and 10 days apart from each other (Table S2). In the first wave, participants reported their beliefs about the safety of GM food or childhood vaccines with related moral and social concerns. They were again asked about the safety of each scientific topic at the end of the wave. The second wave included most of the same questions and, in addition, an experimental condition testing different scientific messages, similarly as in Study 1. In this study, after the scientific messages, we did not only ask participants again about their beliefs in safety but also about their moral and social considerations. The third wave included the same questions and a repetition of scientific messages.

Measures. As described above, we focused on two *focal beliefs*: the safety of GM food and childhood vaccines. Additionally, we asked participants in both studies about twelve related potential moral concerns and seven potentially influential social groups. The exact wording of these questions is presented in Table S3 of the *Supplementary Material* and the average beliefs and importance of each concern is presented in Figure S3.

To develop questions about relevant *moral considerations* which might be sources of concerns about new scientific information, we used the Moral Foundations Theory developed by Haidt [53]. This theory identifies six moral foundations that could affect people's judgments about different issues: care, fairness, ingroup loyalty, authority, purity, and liberty. If, for example, one perceives that believing in the safety of GM food contradicts an important moral value, one might be reluctant to believe that GM food is safe. We developed twelve questions, two per moral foundation, relevant for GM food and childhood vaccines. For each moral consideration, we asked participants to report their beliefs about the issue (e.g., "Select a number between 1 and 7 that most closely represents your opinion: Producing [GM food/childhood vaccines] is harmful or beneficial to the environment") and its relevance for the focal belief ("When you are considering your beliefs about [GM food/childhood vaccines], to what extent do the following considerations influence your thinking? Rate each consideration on a scale from 1 (not at all influential) to 7 (extremely influential)").

To choose **social considerations**, we focused on direct social networks of individuals (family and friends), the larger social context (online community and general public), and specific sources of information about GM food and childhood vaccines (government officials, journalists, online influencers, doctors, and scientists). For each social consideration, we asked participants to report their beliefs about the issue (e.g., “% of my online community believe [GM food/childhood vaccines] is safe” and its relevance for the focal belief (“When you are considering your beliefs about [GM food/childhood vaccines], to what extent do the following groups influence your thinking? Rate each group on a scale from 1 (not at all influential) to 7 (extremely influential)).

5.2. Experimental Conditions

For our experimental conditions, we developed a variety of scientific messages with frames that focus on relevant social and moral considerations. These messages were developed through six rounds of pretesting (see Section 3 in the *Supplementary Material*). Each scientific message included **basic scientific information** on the safety of GM food or childhood vaccines and sometimes additional moral or social frames (see detailed phrasing Table S4 in the *Supplementary Material*).

For **moral frames**, we used moral concerns that were found to be important for GM food and childhood vaccines in previous empirical research [9,10,12,54–57]. For example, the Purity frame for GM food used the sentence “The production of GM crops imitates natural farming techniques. The NAS report explains how all food crops have been modified from their wild relatives by farmers for thousands of years.” To develop messages using **social frames**, we focused on various social groups for which we could use direct quotes about their beliefs about the safety of GM food and vaccines: the news media, the general public, and scientists. For example, the frame using the scientific consensus for childhood vaccines was written as: “A survey of the largest scientific society in the country revealed that 86 % of US scientists believe that all children should be required to be vaccinated.” The scientific consensus has been shown to be effective in changing beliefs [6,58–60] and we have added other known social groups that may share information on GM foods or childhood vaccines [61,62].

We calculated three measures of **focal belief change**, or changes in levels of support for the safety of GM food and childhood vaccines, taking the difference between time points after receiving the scientific message (at the end of wave 2, at the beginning of wave 3, and at the end of wave 3 in Study 2) and the average beliefs before receiving the scientific message (average of beliefs in wave 1, at the end of wave 1 only in Study 2, and at the beginning of wave 2). To investigate different individual-level variations in the timing of belief change and compare the two studies, we averaged these three (or two in Study 1) measures of belief change. The results are substantively similar if we only measure the change from the end of the study to before the experiment. As a control, we included the average change in beliefs before the experiment to account for individuals who could change their beliefs more randomly compared to others.

Power. We conducted a pilot study that focused on beliefs about the safety of GM food and related social and moral considerations and compared the use of various experimental conditions. A group ($N=30$) received basic scientific information that GM food was safe from the National Academies of Science report. We found that participants in that group changed their beliefs about GM safety after seeing a scientific message on average of 1.6 points on a scale of 1 to 7 with a standard deviation of 2.33. To see this effect size for a power of 0.8 and an alpha of 0.05 we would need at least 19 participants per experimental group. For Study 1, we decided to have at least 45 participants per experimental group within each topic and included additional waves of data as comparisons to increase power. Given the smaller effect sizes in Study 1 compared to the pilot study, we sought to increase the statistical power in Study 2 by having group sizes of at least 75 participants and showing the scientific message twice.

5.3. Parameter Fit

We fit our model parameters on data from studies 1 and 2 to capture processes that we predicted would moderate the relationship between dissonance and belief change: increase in the importance of each source of dissonance and increase in the attention towards total dissonance. To this end, we fitted the model parameters on groups of participants with different levels of focal belief change. Note that, for the purpose of predicting unseen data, we also fitted the model on just half of participants in each group and predicted the other half (see Section 5 in the *Supplementary Material* for details).

We split the participants in quantiles with different levels of belief change and fit parameters w and β using grid search through a range of possible parameter values. In Study 1, there were 6 groups of participants for GM food (5 groups for childhood vaccines) with different levels of change in beliefs about safety. In Study 2 there were 14 (13) such groups, respectively (the larger number of groups in Study 2 was due to a larger number of measurement points over time, allowing for a finer measurement of change). This resulted in a total of 38 groups of participants for which we found the best fitting parameters w and β (separately for each time point and assuming weighted average integration rule). We chose the parameter combination that minimized the group root mean squared deviation at each time step, and checked that it uniquely identified the model by exploring the landscape of errors associated with different parameter values. The best fitting parameters were always at the unique minimum of this landscape. For each participant, we also calculated individual moral and social dissonance as the difference between total support for focal belief, which is that GM food and childhood vaccines are completely safe, and the weighted average of moral and social considerations.

5.4. Empirical Analyses of Belief Change

All empirical statistical analyses of belief change were performed using STATA version 17.0. To analyse the effects of experimental conditions on belief change (Figure 2), we used a linear model with the experimental group as predictor and initial beliefs about safety, initial change in these beliefs in pre-experiment waves, gender, education, presence of children up to 18 years of age in the household, and political ideology as controls. We derived marginal means by estimating average belief change across the sample. We also ran these analyses with longitudinal linear models which provided the same results.

To compare the effects of estimated model parameters on focal belief change (Figure 4), we conducted a hierarchical linear mixed-effects model with random intercepts for topics nested within studies and controls for the specific scientific message and demographics. We used a mixed model instead of a regular regression model to combine the two studies and topics. The full model is presented in Table S8 of the *Supplementary Material* and the differences between marginal means are presented in Table S9 of the *Supplementary Material*. We then estimated the marginal means of focal belief change with all other covariates held at their sample values.

Data, code, and materials

Data for Study 1 is available on OSF: <https://osf.io/yg24v/>. All data for Study 2 is available after registration on RAND American Life Panel's public depository: <https://alpdata.rand.org>. Study numbers: 524-526. The model pseudocode is in Section 4 of the Supplementary Material. The raw data for each wave was merged before removing any identifying information.

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Ethics

This study was deemed exempt of review by the University of New Mexico Office of the Institutional Review Board.

Competing interests

Nina Fedoroff is a science adviser for the Olsson Frank Weeda Terman Matz PC Law firm.

Contributor Roles Taxonomy

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Data curation: TvD

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Supplementary Material available online - reviewed

1. Population descriptives

In Figure S1, we present the distribution of beliefs about GM food and childhood vaccines in the general population obtained in the large probabilistic national sample in Study 2, before screening sceptical participants. Beliefs about the safety of GM food and childhood vaccines had different distributions in the population: for GM food, we found a symmetric distribution with a mean answer of 4.2 on a 7-point scale (median 4), while for childhood vaccines, we find a left-skewed distribution with mean and median of 6.

Figure S1. Distribution of beliefs about the safety of GM food (top) and childhood vaccines (bottom) in the US population, estimates from the probabilistic national sample in Study 2 ($N=2,472$).

Figure S2. Predicted marginal means of beliefs about safety in the general US population by sociodemographic characteristic, estimates from the probabilistic national sample in Study 2 (N=2,459<2,472 due to missing values on relevant covariates). Bars denote 95% confidence intervals.

2. Sample descriptives

For Study 1, of the invited sceptical participants $N_{1\text{three}} = 815$ completed all three waves. We excluded participants who were part of an experimental condition which was not comparable to other scientific messages (the text was half the length), for a final total of $N_1 = 725$. For Study 2, of the invited sceptical participants $N_{2\text{three}} = 1,046$ completed all three waves. We excluded participants who were assigned to inconsistent experimental conditions in early waves due to a programming error (49 participants) and who had missing values on core variables (also 49 participants), for a final total of $N_2 = 948$.

Table S1. Description of samples of participants who were included in Study 1 and Study 2 selected based on their hesitancy about the safety of GM food or vaccine shown in the screening study (rating safety as less than 7 on a 7-point scale).

	Study 1, $N_1=725$		Study 2, $N_2=948$	
	<i>GM, $N_{1GM}=361$</i>	<i>Vac, $N_{1Vac}=364$</i>	<i>GM, $N_{2GM}=531$</i>	<i>Vac, $N_{2Vac}=417$</i>
<i>Beliefs about safety pre-experiment (range 1-6):</i>				
Mean (Median)	4.45 (4.50)	5.25 (6.00)	3.84 (4.00)	4.92 (5.33)
Standard deviation	1.50	1.33	1.32	1.37
<i>Demographics (proportion):</i>				
Women	.52	.57	.59	.57
Men	.48	.43	.41	.43
Children under 18 living at home	.40	.40	.19	.27
Holds at least a college degree	.59	.55	.56	.45
<i>Political ideology</i>				
Left	.46	.44	.37	.32
Moderate	.26	.21	.22	.29
Right	.28	.36	.40	.39

Figure S3 shows the average belief and relevance of each social and moral consideration among sceptics before any scientific message was shown to participants. Reflecting their general beliefs about safety, participants were on average more positive about social and moral considerations related to GM food compared to childhood vaccines. Across the two studies, participants believed that doctors and scientists are the most relevant social groups to their beliefs and emphasized the risk to children and family as the most important moral concerns. On the other side of the spectrum, the generally public and online communities or influencers were on average listed as the least relevant, and so were moral concerns surrounding tradition and naturalness. Bolded moral and social considerations are those targeted by the scientific message in our experiment.

Figure S3. Average belief and importance pre-experiment of different social (left of dashed vertical line) and moral considerations (right of dashed vertical line) related to GM food (green) and childhood vaccines (blue). The top panel shows the results for Study 1 and the bottom panel for Study 2. A higher position of the markers along the vertical axis denotes more positive beliefs. The size of the symbols denotes the importance of beliefs for the participants when considering the safety of GM food and childhood vaccines. Bold captions represent considerations targeted in the scientific message. Study 1, $N_{GM}=361$ and $N_{Vac}=364$ and Study 2, $N_{GM}=531$ and $N_{Vac}=417$.

3. Study design and pretests

Table S2. Timing and questions in the two studies.

	Study 1	Study 2
Screening	Focal belief	Focal belief
<i>Time screening – wave 1</i>	<i>On average 2 days</i>	<i>On average 90 days</i>
Wave 1	Focal belief Social and moral considerations	Focal belief Social and moral considerations Focal belief
<i>Time wave 1- wave 2</i>	<i>On average 12 days</i>	<i>On average 20 days</i>
Wave 2	Focal belief Scientific message Social and moral considerations Focal belief	Focal belief Social and moral considerations Scientific message Social and moral considerations Focal belief
<i>Time wave 2 – wave 3</i>	<i>On average 7 days</i>	<i>On average 10 days</i>
Wave 3	Focal belief Social and moral considerations	Focal belief Social and moral considerations Scientific message reminder Focal belief

We conducted six pretests to investigate the best wording for questions related to moral and social considerations as well as for scientific messages. Pretest 1 ($N=200$) compared beliefs about GM food to other beliefs (e.g., climate change, immigration) and their change over time. Pretest 2 ($N=182$) focused on the beliefs about safety of GM food and related social considerations as well as the use of text, images, and figures for the scientific messages. Pretest 3 ($N=60$) focused on various moral considerations relevant for GM food in addition to beliefs about social sources of information. Pretest 4 ($N=80$) tested how convincing, trustworthy, or manipulative the basic scientific information and different moral and social frames were perceived. Pretest 5 ($N=77$) tested the relevance of the moral and social considerations and scientific messages for childhood vaccines. And finally, Pretest 6 ($N=30$) further tested different wording choices for the scientific messages. The resulting questions used for moral and social considerations are presented in Table S3 and the scientific messages are in Table S4.

Table S3. Questions measuring moral and social considerations related to scientific beliefs about GM food and childhood vaccines

Social considerations	Moral considerations
Instructions: As far as you know, what is the percentage of people within the following groups who believe [scientific issue] is safe to eat/for healthy children? Please give your best estimate.	Instructions: For each of the following considerations, select a number between 1 and 7 that most closely represents your opinion.
% of my family and close friends believe [scientific issue] is safe.	[scientific issue] is not approved by all the appropriate agencies, or that it is approved by all the appropriate agencies?
% of representatives of governmental agencies believe [scientific issue] is safe.	[scientific issue] is not part of our tradition, or that it is part of our tradition?
% of journalists at your favourite news outlet believe [scientific issue] is safe.	[scientific issue] is harmful or beneficial to children?
% of medical doctors believe [scientific issue] is safe.	Producing [scientific issue] is harmful or beneficial to the environment?
% of my online community believe [scientific issue] is safe.	Big biotechnology/pharmaceutical companies benefit more from [scientific issue] than farmers/patients, or that both big biotechnology/pharmaceutical companies and farmers/patients benefit from [scientific issue]?
% of online experts and influencers I follow believe [scientific issue] is safe. (This measure was not included in Study 1.)	Large-scale farmers/medical doctors benefit more from [scientific issue] than small-scale farmers/patients, or that both large-scale/medical doctors and small-scale farmers/patients benefit from [scientific issue]?
% of the US general public believe [scientific issue] is safe.	You are forced to eat/use [scientific issue] without your consent, or that you are free to choose whether to eat/use [scientific issue]?
% of US scientists believe [scientific issue] is safe.	Some important information about [scientific issue] is not shared with the public, or that all important information is shared?
	[scientific issue] negatively or positively affects our country?
	[scientific issue] negatively or positively affects your family?
	God disapproves or approves of [scientific issue]?
	[scientific issue] is unnatural or natural?

Table S4. Text for scientific messages included in experimental conditions within the GM and Vaccine studies.

<i>The part in italic is repeated for each scientific message</i>	Study 1		Study 2	
	GM food	Childhood vaccines	GM food	Childhood vaccines
Basic scientific information	<p><i>There is no evidence that GM food currently on the market is harmful when consumed by people or farm animals. This information comes from a 2016 report by the National Academies of Science (NAS).</i></p> <p>The NAS report was published by the National Academies Press. It is titled "Genetically Engineered Crops: Experiences and Prospects" and has a total of 420 pages.</p>	<p><i>There is no evidence that currently recommended childhood vaccines cause long-term harm to healthy children. This information comes from the website of the Center for Disease Control and Prevention (CDC), a federal agency.</i></p> <p>The CDC operates under the Department of Health and Human Services and has 22 centers, institutes, and offices. Their website contains links to contact representatives.</p>	<p><i>There is no evidence that GM food currently on the market is harmful when consumed by people or farm animals. This information comes from a summary of recent studies compiled by the National Academies of Science, Engineering, and Medicine.</i></p> <p>These studies investigated evidence about the effects of GM food when consumed by people or farm animals. This summary comes in the form of a written report.</p>	<p><i>There is no evidence that currently recommended childhood vaccines cause long-term harm to healthy children. This information comes from a summary of recent studies compiled by the National Academies of Science, Engineering, and Medicine.</i></p> <p>These studies investigated evidence about the effects of childhood vaccines on children's health. This summary comes in the form of a written report.</p>
Scientific consensus	A survey of the largest scientific society in the country revealed that 88% of US scientists say that it is generally safe to eat GM food.	A survey of the largest scientific society in the country revealed that 86% of US scientists say that all children should be required to be vaccinated.	A survey of the largest scientific society in the country revealed that 88 % of US scientists believe that it is safe to eat GM food.	A survey of the largest scientific society in the country revealed that 86 % of US scientists believe that all children should be required to be vaccinated.
Journalists	Journalists at [favourite news source] have reported the following news story: [basic scientific information] The NAS report was published by the National Academies Press. It is titled "Genetically Engineered Crops: Experiences and Prospects."	Journalists at [favourite news source] have reported the following news story: [basic scientific information] The CDC operates under the Department of Health and Human Services and has 22 centers, institutes, and offices.		
Public	A survey of a nationally representative sample revealed that 37% of the US general public says that it is generally safe to eat GM food.	A survey of a nationally representative sample revealed that 69% of the US general public says that all children should be required to be vaccinated.		
Authority (Tradition)			The production of GM crops imitates traditional farming techniques. These studies explain how all food crops have been	-

			modified from their wild relatives by farmers for thousands of years.	
Care (Children)	Childhood vaccines can be beneficial to children. The CDC website explains how, every year, vaccines prevent an estimated 2.5 million deaths among young children.	GM food can be beneficial to children. The NAS report explains how some GM food has been developed to contain more vitamin A to help children with nutritional deficiencies.		
Fairness (Farmers/Big corporations)	Both large-scale and small-scale farmers benefit from growing GM crops. The NAS report explains how adopting insect resistant GM crops on average decreases yield losses on both large and small farms.	Big pharmaceutical companies do not benefit more from vaccines than individuals. The CDC website explains how big pharmaceutical companies would make more money from people getting sick than from selling vaccines.	Both big biotechnology companies and farmers benefit from GM crops. These studies show how adopting GM crops increases yield and reduces costs for both large-scale and small-scale farmers.	Big pharmaceutical companies do not benefit from vaccines at the expense of patients. These studies explain how companies would profit more from people getting sick than from selling vaccines.
Freedom (Information)			This information is shared with the public. This organization maintains a website which includes a list of reports on research conducted about GM food (https://www.nap.edu/topic/298/agriculture/crop-and-plant-production).	This information is shared with the public. This organization maintains a website which includes a list of reports on research conducted about childhood vaccines. (https://www.nap.edu/collection/55/vaccines)
Purity (Natural)	The production of GM crops imitates natural farming techniques. The NAS report explains how all food crops have been modified from their wild relatives by farmers for thousands of years.	Childhood vaccines imitate natural infections. The CDC website explains how vaccines work with the body's natural defense to help it safely develop immunity to diseases.		

4. Model Pseudocode

This pseudocode explains how to implement the model described in the main text.

- 1) Recode moral and social considerations of each individual i in a given time step t to probability vectors $\vec{\sigma}_{i,t}^{mor}$ and $\vec{\sigma}_{i,t}^{soc}$. For example, if a consideration is measured on a scale of 1-7, and an individual answered that their level of support for the consideration is 6, its probability vector would be [0 0 0 0 0 1 0]. If the scale is 0-10, and an individual's level of support for the consideration is 3, the probability vector would be [0 0 0 1 0 0 0 0 0 0].
- 2) Integrate vectors of all moral considerations $\vec{\sigma}_{i,t}^{mor}$ into a moral field $\vec{h}_i^{mor}$, and of social considerations $\vec{\sigma}_{i,t}^{soc}$ into a social field $\vec{h}_i^{soc}$, using a specific integration rule (chosen based on previous research or a fit to a part of the current data set). For example, if one holds two moral beliefs related to GM food, one represented as [0 0 1 0 0 0 0] and the other as [0 0 0 0 0 0 1], the moral field calculated by a simple average rule would be $\vec{h}_i^{mor} = [0.0 \ .5 \ 0 \ 0 \ 0 \ .5]$.
- 3) Derive moral dissonance $d_{i,\alpha}^{mor}$ for each possible level α of support for the focal belief σ_i^f by:
 - i) Calculating the squared distance between the moral field and the probability vector corresponding to the α level of support, $d_{i,\alpha}^{mor} = (\vec{\delta}_\alpha - \vec{h}_i^{mor})^2$, where the components of $\vec{\delta}_\alpha$ are Kronecker δ -functions: $\vec{\delta}_\alpha = \delta_{\alpha,\alpha'} = \begin{cases} 1 & \text{if } \alpha' = \alpha \\ 0 & \text{if } \alpha' \neq \alpha \end{cases}$. For example, the squared distance between the moral field from the previous step and the highest possible level of support for the focal belief (assuming it is also measured on a 7-point scale, $\vec{\delta}_\alpha = [0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1]$) would be [0 0 .25 0 0 0 .25].
 - ii) Taking the average of the vector of squared distances for each level α to get the moral dissonance for that level of support for the focal belief σ_i^f . In the example above, the moral dissonance for the highest level of support for the focal belief would be $d_{i,7}^{mor} = .5$. Follow the same steps to derive social dissonance $d_{i,\alpha}^{soc}$ between the social field $\vec{h}_i^{soc}$ and each level of support α for the focal belief.
- 4) Derive the total dissonance $\vec{H}_{i,t}$ by taking a weighted average of moral and social dissonances $\vec{H}_{i,t} = w_t \vec{d}_{i,t}^{soc} + (1 - w_t) \vec{d}_{i,t}^{mor}$, where w_t is the weight put on social as opposed to moral dissonance. The value of w_t can be estimated from prior studies or by fitting the model on a part of the current data set.
- 5) Calculate probabilities of different levels of support $\vec{\sigma}_{i,t}^f$ for the focal belief using the softmax function $\sigma_{i,t,\alpha}^f = e^{-\beta_t H_{i,t,\alpha}} / \sum_{\alpha=1}^m e^{-\beta_t H_{i,t,\alpha}}$, where $\beta_t = [0, \infty)$ is a parameter that represents the “noisiness” of the belief updating process with larger β_t values corresponding to smaller noise or uncertainty of this process. The value of β_t can be estimated from prior studies or by fitting the model on a part of the current data set.
- 6) Repeat steps 3-5 for each time step t .

5. Predicting empirical trends

We explored how well the models using different integration rules predict empirical belief changes. To predict unseen data and compare different integration rules, we fit the model on just half of participants in each of the groups (total 27 groups, including control groups with no scientific messages, see Table 1) and predicted the other half. For each possible integration rule, we fit parameters w and β using grid search through a range of plausible parameter values ($0 \leq w \leq 1$, and $0 \leq \beta \leq 100$; with $\beta=100$ leading to practically fully deterministic choice rule). We fit these parameters separately for each time step in which focal beliefs were measured (in Study 1, at the start of wave 1 and 3, and at the start and end of wave 2; in Study 2, at the start and end of each wave). We chose the parameter combination that minimized group root mean squared deviation between predicted and actual distributions of support for focal beliefs at each time step, and checked that it uniquely identifies the best fitting model. We then used the best fitting parameters w and β at each time step to predict the data for the other, “unseen” half of participants in each group. We repeated this procedure for 50 random splits of each experimental group and then averaged predictions across these splits within each integration rule.

Overall, the models describe the data of ‘unseen’ participants reasonably well (Figure S4, Table S5, and Figure S5). Models assuming that people integrate their considerations using “weighted average” and “most important” rules are typically more successful than the model assuming “simple average” rule. These results suggest that people take into account a few or a single most important moral or social consideration when updating their focal beliefs about the safety of GM food and childhood vaccines rather than taking into account all of the moral and social considerations equally.

Figure S4. Relationship between model-predicted and true empirical change in focal beliefs about safety of GM food and childhood vaccines for different belief integrations rules, studies, and topics. Change is calculated as the difference in beliefs reported in the last measurement point (wave 3) and the first point (beginning of wave 1).

Table S5. Modelling belief dynamics: Average root-mean-squared deviations (RMSDs) and correlations of fitted and predicted trends with actual trends of belief change across experimental groups and time points. Smallest RMSDs and largest correlations in each column are marked in bold font.

	Study 1				Study 2			
	GM food		Childhood vaccines		GM food		Childhood vaccines	
	Fit	Predict	Fit	Predict	Fit	Predict	Fit	Predict
RMSDs								
Weighted average	0.130	0.175	0.094	0.110	0.134	0.152	0.144	0.175
Most important	0.137	0.183	0.120	0.109	0.138	0.164	0.090	0.108
Average	0.146	0.191	0.142	0.169	0.141	0.161	0.181	0.206
Correlations								
Weighted average	0.443	0.367	0.726	0.761	0.683	0.505	0.136	0.089
Most important	0.456	0.449	0.687	0.685	0.804	0.576	0.130	0.069
Average	0.255	0.308	0.620	0.604	0.562	0.417	0.016	-0.032

Figure S5a. True and predicted dynamics of safety beliefs over time for Study 1. Left panels: model fits to random half of participants (averaged across 50 random splits). Right panels: predictions on the other, unseen, halves of participants. Top panels: results for GM food. Bottom panels: results for Childhood vaccines. Predicted trends are made assuming three different belief integration rules (weighted average, most important, and average rule).

Figure S5b. True and predicted dynamics of safety beliefs over time for Study 2. Left panels: model fits to random half of participants (averaged across 50 random splits). Right panels: predictions on the other, unseen, halves of participants. Top panels: results for GM food. Bottom panels: results for Childhood vaccines. Predicted trends are made assuming three different belief integration rules (weighted average, most important, and average rule).

6. Empirical analyses of belief change

Table S6. Success of scientific messages. Model results for effects of scientific messages (standard errors in parentheses; see Figure 2 for estimated marginal means based on these models).

	GM	Study 1 Vaccines	GM	Study 2 Vaccines
<i>Scientific message (control=Nothing)</i>				
Basic scientific information	0.118 (0.150)	0.076 (0.107)	0.071 (0.116)	0.143 (0.095)
Favourite media	0.146 (0.152)	0.215* (0.106)		
Sci. consensus	0.232 (0.150)	0.264* (0.106)	0.232* (0.118)	0.137 (0.096)
Public	0.055 (0.150)	0.138 (0.108)		
Care	0.142 (0.150)	0.059 (0.107)		
Fairness	0.343* (0.150)	0.203 (0.107)	0.104 (0.116)	0.185* (0.094)
Purity	0.336* (0.151)	0.035 (0.107)		
Authority			0.239* (0.116)	
Freedom			0.103 (0.117)	-0.006 (0.094)
Study wave	0.044 (0.046)	-0.033 (0.034)	-0.056** (0.021)	0.034 (0.021)
<i>Pre-experiment:</i>				
Average belief safety	-0.062* (0.026)	-0.009 (0.020)	-0.126*** (0.027)	-0.107*** (0.022)
Average change belief safety	0.102* (0.041)	0.200*** (0.036)	0.208*** (0.035)	0.097* (0.039)
<i>Controls</i>				
Women	-0.054 (0.078)	0.007 (0.054)	-0.131 (0.072)	-0.063 (0.061)
Less than a college education	0.047 (0.077)	-0.024 (0.055)	0.074 (0.069)	0.046 (0.061)
Children at home	0.015 (0.079)	0.001 (0.055)	-0.175* (0.086)	-0.039 (0.067)
<i>Political ideology (ref=moderate)</i>				
Liberal	0.096 (0.092)	-0.056 (0.071)	-0.148 (0.091)	0.086 (0.078)
Conservative	-0.000 (0.103)	-0.062 (0.075)	-0.110 (0.089)	-0.034 (0.073)
Constant	0.154 (0.189)	0.104 (0.153)	0.698*** (0.163)	0.576*** (0.148)

Standard errors in parenthesis, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table S7. Marginal means and difference with the control and the basic scientific information derived from Table S6 with all other covariates held at their sample values.

		Marginal mean	Confidence interval		Standard error		Difference with control		Difference with basic		
Experimental condition			low	high	low	high	estimate	p-value	estimate	p-value	
Study 1	GM	Control= nothing	-0.061	-0.270	0.148	-0.167	0.045			-0.118	0.432
		Basic scientific info	0.057	-0.152	0.265	-0.049	0.162	0.118	0.432		
		Favourite media	0.085	-0.125	0.295	-0.022	0.192	0.146	0.336	0.029	0.850
		Scientific consensus	0.171	-0.037	0.379	0.065	0.277	0.232	0.122	0.115	0.444
		Public	-0.006	-0.214	0.202	-0.112	0.100	0.055	0.713	-0.063	0.676
		Care	0.081	-0.126	0.289	-0.024	0.187	0.142	0.342	0.025	0.868
		Fairness	0.282	0.073	0.490	0.176	0.387	0.343	0.022	0.225	0.134
		Purity	0.274	0.066	0.483	0.168	0.380	0.336	0.027	0.218	0.148
	Vaccines	Control= nothing	0.016	-0.134	0.165	-0.060	0.091			-0.076	0.478
		Basic scientific info	0.091	-0.056	0.239	0.017	0.166	0.076	0.478		
		Favourite media	0.231	0.085	0.377	0.157	0.305	0.215	0.044	0.140	0.188
		Scientific consensus	0.279	0.133	0.425	0.205	0.354	0.264	0.013	0.188	0.076
		Public	0.154	0.005	0.302	0.078	0.229	0.138	0.200	0.062	0.556
		Care	0.075	-0.074	0.223	-0.001	0.150	0.059	0.580	-0.017	0.877
		Fairness	0.219	0.072	0.366	0.144	0.294	0.203	0.059	0.128	0.228
		Purity	0.050	-0.097	0.198	-0.025	0.126	0.035	0.745	-0.041	0.700
Study 2	GM	Control= nothing	0.043	-0.119	0.205	-0.039	0.125			-0.071	0.540
		Basic scientific info	0.114	-0.046	0.275	0.032	0.196	0.071	0.540		
		Scientific consensus	0.276	0.110	0.441	0.191	0.360	0.232	0.050	0.161	0.171
		Authority	0.282	0.122	0.442	0.201	0.363	0.239	0.040	0.168	0.147
		Fairness	0.147	-0.013	0.307	0.066	0.229	0.104	0.370	0.033	0.775
		Freedom	0.146	-0.015	0.308	0.064	0.229	0.103	0.376	0.032	0.782
	Vaccines	Control= nothing	0.046	-0.088	0.179	-0.022	0.114			0.132	0.132
		Basic scientific info	0.189	0.059	0.318	0.123	0.254	0.143	0.132		
		Scientific consensus	0.182	0.049	0.315	0.115	0.250	0.137	0.156	0.947	0.947
		Fairness	0.230	0.104	0.357	0.166	0.295	0.185	0.049	0.649	0.649
	Freedom	0.039	-0.089	0.167	-0.026	0.104	-0.006	0.945	0.107	0.107	

Table S8. Interaction of dissonance, importance, and attention. Linear mixed effects estimate for individual average change of focal belief over time (standard errors in brackets; see Figure 6 for estimated marginal means based on these models).

	<i>Basic model</i>	<i>Social dissonance and w</i>	<i>Moral dissonance and 1-w</i>	<i>Total dissonance and B</i>
<i>Scientific messages (control=Nothing)</i>				
Basic science msg.	0.097 (0.058)	0.082 (0.052)	0.080 (0.052)	0.085 (0.052)
Favourite media	0.136 (0.083)	0.125 (0.076)	0.117 (0.076)	0.114 (0.076)
Sci. consensus	0.195*** (0.059)	0.127* (0.053)	0.126* (0.053)	0.127* (0.053)
Public	0.064 (0.083)	0.075 (0.077)	0.080 (0.077)	0.086 (0.077)
Care	0.068 (0.083)	0.024 (0.076)	0.027 (0.076)	0.034 (0.076)
Authority	0.232** (0.083)	0.188* (0.077)	0.176* (0.076)	0.182* (0.077)
Fairness	0.176** (0.058)	0.123* (0.052)	0.125* (0.052)	0.129* (0.052)
Freedom	0.053 (0.066)	0.061 (0.060)	0.060 (0.060)	0.059 (0.060)
Purity	0.152 (0.083)	0.052 (0.077)	0.056 (0.077)	0.074 (0.076)
<i>Pre-experiment:</i>				
Pre-experiment: Average belief safety	-0.071*** (0.012)	-0.072*** (0.011)	-0.072*** (0.011)	-0.071*** (0.011)
Pre-experiment: Average change belief safety	0.159*** (0.019)	0.131*** (0.017)	0.130*** (0.017)	0.134*** (0.017)
<i>Controls</i>				
Women	-0.050 (0.033)	-0.046 (0.030)	-0.042 (0.030)	-0.043 (0.030)
Less than a college education	0.041 (0.033)	0.007 (0.030)	0.005 (0.030)	0.009 (0.030)
Children at home	-0.051 (0.036)	-0.050 (0.033)	-0.052 (0.033)	-0.051 (0.033)
<i>Political ideology (ref=moderate)</i>				
Liberal	-0.011 (0.042)	0.001 (0.038)	0.003 (0.038)	0.002 (0.038)
Conservative	-0.053 (0.043)	-0.068 (0.038)	-0.063 (0.038)	-0.058 (0.039)

Table continued next page

Standard errors in parenthesis, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table S8. Continued	Basic model	Social dissonance and w	Moral dissonance and 1-w	Total dissonance and B
<i>Model parameters</i>				
Increase in social dissonance		-0.785*** (0.180)	-0.840*** (0.180)	
Increase in moral dissonance		-0.961*** (0.193)	-1.003*** (0.194)	
Increase in relative importance		0.821*** (0.050)	-0.855*** (0.050)	0.843*** (0.049)
Relative importance # dissonance		-1.173* (0.493)	-0.907 (0.532)	
Increase total dissonance				-1.382*** (0.199)
Increase in attention		0.003*** (0.000)	0.003*** (0.000)	0.003*** (0.000)
Attention # Total dissonance				-0.011* (0.004)
Constant	0.390*** (0.082)	0.418*** (0.085)	0.418*** (0.084)	0.405*** (0.083)
<i>Random effects</i>				
Variance intercept studies	-15.392 (13.623)	-18.119 (725.753)	-18.447 (1083.402)	-19.085 (17.386)
Variance intercept topics	-3.549*** (0.923)	-2.502*** (0.416)	-2.557*** (0.424)	-2.561*** (0.428)
Error	-0.412*** (0.017)	-0.519*** (0.017)	-0.518*** (0.017)	-0.518*** (0.017)

Standard errors in parenthesis, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table S9. Marginal means and difference for different levels of model parameters derived from Table S8 with all other covariates held at their sample values.

<i>Parameters</i>	Difference increase and decrease dissonance		Difference with difference when decrease importance or attention	
	<i>estimate</i>	<i>p-value</i>	<i>estimate</i>	<i>p-value</i>
<i>Social dissonance</i>				
Decrease importance (-0.8)	0.229	0.733		
Stable importance (0)	-1.178	0.000	-1.407	0.017
Increase importance (+0.8)	-2.585	0.000	-2.814	0.017
<i>Moral dissonance</i>				
Decrease importance (-0.8)	-0.417	0.544		
Stable importance (0)	-1.505	0.000	-1.088	0.088
Increase importance (+0.8)	-2.593	0.000	-2.176	0.088
<i>Total dissonance</i>				
Decrease attention (-90)	-0.324	0.388		
Stable attention (0)	-1.106	0.000	-0.782	0.015
Increase attention (90)	-1.888	0.000	-1.564	0.015

7. Comparison of experimental conditions

To test the relationship between dissonance reduction, relative importance and overall attention at the level of experimental conditions, we first calculated the average moral and social dissonance in each group as the difference between total support for the focal belief – that GM food and childhood vaccines are completely safe – and the moral and social fields for participants in that group. The fields were calculated as the weighted average of participants' moral and social considerations. We then constructed models using different values of parameters w , the measure of the importance of social relative to moral dissonance, and β , the measure of attention to overall dissonance between focal beliefs and the individual's moral and social fields. We examined how well these different models fit the average belief change in different scientific message groups to find the best values of parameters w and β (see Methods for details). We then examined the relationship between changes in focal beliefs, changes in moral, social, and total dissonance, and changes in model parameters, in each group from before to after the scientific message.

We predicted that successful scientific messages would reduce moral or social dissonance while at the same time 1) increasing the importance of that source of dissonance (as described by parameter w) or 2) fostering attention to the overall dissonance (parameter β). Figure S6a-c shows the marginal mean change of the focal belief for each group of participants who received the same scientific message within each study and topic, across different values of changes in dissonance (social dissonance panel a, moral dissonance panel b, and total dissonance panel c). To investigate the predicted interactions between dissonance and importance, we separated groups between those where participants on average experienced an increase in relative importance of a specific source of dissonance (social or moral) and those where participants experienced a decrease in its relative importance (estimated by the change in parameter w , panels a and b). To investigate the predicted interaction between dissonance and attention, we separated experimental groups between those where participants experienced an increase in attention to total dissonance and those where participants experienced a decrease in estimated attention (estimated by the change in parameter β , panel c).

The small number of observations in this analysis (conducted on the level of 27 groups across the two studies and topics) precludes statistical analyses, but we can make several qualitative observations. As expected, participants who did not receive any scientific messages ("Nothing") had low belief change, though some had an increase and decrease in the importance of social dissonance and moral dissonance. The four groups receiving nothing had a decrease (yellow) or no change (grey) in attention over time. Participants who received the basic scientific information had generally a change in social, moral, and total dissonance close to zero (except for a large decrease in dissonance in Study 2 for GM food). While we would expect social frames to mostly influence social dissonance and moral frames to mostly influence moral dissonance, we see many scientific messages that influenced both. For example, presenting the scientific consensus in Study 1 was associated in a decrease in both social and moral dissonance. This could be due to beliefs about scientists being linked to both other social and moral considerations. Both social and moral frames increased the importance of social dissonance (Figure S6a) but very few scientific messages changed the importance of moral dissonance (Figure S6b).

Figure S6. Relationship between estimated marginal means of belief change and relative change in social dissonance (a), moral dissonance (b), and total dissonance (c), for decrease (yellow markers) vs. increase (red markers) in parameters w (a, b) and β (c). All changes calculated from values before to after scientific messages. Each dot shows a different scientific message used in a specific study (Study 1 or 2) and topic (GM food or childhood vaccines). Fitted lines show overall trends estimated for each type of parameter change.

In line with our first prediction, scientific messages that led to a decrease in moral or social dissonance were followed by more belief change, but only if participants also experienced an increase, or at least no change, in the relative importance of that specific source of dissonance. Specifically, reduction in social dissonance was related to larger belief change when this source of dissonance increased or remained stable in importance (see red and grey fitted line in Figure S6a), whereas it was not related to more belief change when this source of dissonance decreased in importance (yellow fitted line in Figure S6a). Similarly, reduction in moral dissonance was associated with a larger change in focal beliefs only when the importance of this source of dissonance increased after the scientific message (compare red and yellow fitted lines in Figure S6b).

As we observed for individual-level results (Figure 6), the relationships between focal belief change, dissonance, and importance were not completely the same for social and moral dissonance. Specifically, the largest difference in focal belief changes between experimental groups in which social dissonance increased vs. decreased in importance occurred when social dissonance was reduced (left-hand side of Figure S6a). At the same time, the largest difference in focal belief changes between experimental groups in which moral dissonance increased vs. decreased in importance occurred when moral dissonance increased (right-hand side of Figure S6b). This suggests that focal beliefs might have been more sensitive to a rise in moral dissonance but to a reduction in social dissonance.

In contrast to our second prediction, the negative relationship between the change in total dissonance and focal belief was stronger when β (attention to overall dissonance) decreased after the

scientific message (yellow fitted line in Figure S6c). When β increased, there was no relationship between dissonance and belief change and when β remained constant there was only a slight negative relationship. This might partly be due to the complicated relationship between attention and belief change, which might have been difficult to capture by analysing the small number of data points. This finding was not observed at the individual level (Figure 4c), potentially pointing to the advantages of estimating β at a finer-grained individual level, but also suggesting that changes in attention might be more under control of individuals than influenced by scientific messages. In other words, some individuals might have paid more attention to scientific messages because of idiosyncratic reasons unrelated to the presented information.