Journal of Health Communication, 23: 435–444, 2018

ISSN: 1081-0730 print/1087-0415 online
DOI: https://doi.org/10.1080/10810730.2018.1461961

Communication of Scientific Uncertainty about a Novel Pandemic Health Threat: Ambiguity Aversion and Its Mechanisms

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Communicating scientific uncertainty about public health threats is ethically desirable but challenging due to its tendency to promote avoidance of choice options with unknown probabilities—a phenomenon known as “ambiguity aversion.” This study examined this phenomenon’s potential magnitude, its responses to different communication strategies, and its mechanisms. In a factorial experiment, 2701 adult laypersons in Spain read one of three versions of a hypothetical newspaper article describing a pandemic vaccine-preventable disease (VPD), but varying in scientific uncertainty about VPD risk and vaccine effectiveness: No-Uncertainty, Uncertainty, and Normalized-Uncertainty (emphasizing its expected nature). Vaccination intentions were lower for the Uncertainty and Normalized-Uncertainty groups compared to the No-Uncertainty group, consistent with ambiguity aversion; Uncertainty and Normalized-Uncertainty groups did not differ. Ambiguity-averse responses were moderated by health literacy and mediated by perceptions of vaccine effectiveness, VPD likelihood, and VPD severity. Communicating scientific uncertainty about public health threats warrants caution and further research to elucidate its outcomes, mechanisms, and management.

Novel public health threats, such as emerging viral pandemics, pose difficult communication challenges. In these crisis situations, rapid dissemination of authoritative information about recommended protective actions such as vaccination is essential, both to minimize health risks and to reassure the public. Yet the emergent nature of novel public health threats entails scientific uncertainty about several issues: the nature, likelihood, and severity of adverse outcomes, and the effectiveness of protective actions. Indeed, it is scientific uncertainty about these issues that defines such public health threats as “crises” (Liu, Bartz, & Duke, 2016; Seeger, 2006). Communicating this uncertainty is essential to maximize public accountability, transparency, and trust (Berg, 2012; Covello, 2003; Seeger, 2006) and to promote deliberation about whether the available scientific evidence warrants action (Elwyn & Miron-Shatz, 2010; Han, 2013; Rimer, Briss, Zeller, Chan, & Woolf, 2004). These tasks are particularly important for interventions such as emergency vaccination, which benefits the public but requires implementation among individuals (Berg, 2012; Coughlin, 2006; Guttman, 1997).

Yet communicating scientific uncertainty during public health crises can have complex effects that raise the need for caution. Scientific uncertainty manifests what decision theorists have termed “ambiguity”—a lack of reliability, credibility, or adequacy of risk information (Ellsberg, 1961). Ambiguity in health care arises from numerous sources: missing or insufficient scientific evidence, conflicting evidence or expert opinion, or imprecision in risk estimates or practice guidelines. The communication of ambiguity is challenging because it can cause confusion (Mazor, Dodd, & Kunches, 2009) and negative psychological effects including avoidance of choice options with unknown probabilities—a response known as “ambiguity aversion” (Camerer & Weber, 1992; Ellsberg, 1961). Communicating ambiguity can also promote either heightened risk perceptions as an “alarmist,” ambiguity-averse response (Viscusi, Magat, & Huber, 1991, 1999), or diminished risk perceptions as a defensive responsive to threatening information, manifesting underlying motivations to avoid feelings of vulnerability (Dieckmann, Gregory, Peters, & Hartman, 2017).

These negative effects of communicating uncertainty are particularly concerning in the public health domain, where confusion, perceptions of vulnerability, and pessimistic attitudes are often socially amplified. Vaccine hesitancy is an exemplary case. Defined by the World Health Organization Strategic Advisory

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Supplemental data for this article can be accessed here.

Group of Experts on Immunization as "delay in acceptance or refusal of vaccination despite availability of vaccination services" (MacDonald, 2015), vaccine hesitancy is a response to perceived ambiguity about vaccine effectiveness and safety (Abeysinghe, 2015; Dube et al., 2013; Larson, Cooper, Eskola, Katz, & Ratzan, 2011; Seethaler, 2016). Perceived ambiguity about vaccination has been promulgated among various individuals, and has proven extremely resistant to change. Well-intentioned efforts to communicate scientific uncertainty about vaccine effectiveness and safety may further reinforce these perceptions. Potential responses to such efforts include diminished perceptions of the risk of vaccine-preventable diseases (VPDs) and the effectiveness of vaccination, and diminished vaccine uptake.

The management of public health crises from viral pandemics and other novel threats thus presents a dilemma: open communication of scientific uncertainty is ethically desirable, but practically problematic in potentially perpetuating ambiguity-averse perceptions and behaviors that can undermine public health. This concern has been raised in other domains in which scientific evidence is communicated to the public (Frewer, 2004). A related concern is that communicating scientific uncertainty may reduce trust in experts (Frewer, Scholderer, & Bredahl, 2003; Johnson & Slovic, 1995). Yet little is known about the extent of these potential responses to the communication of uncertainty in the public health domain, their mechanisms, and their appropriate management (Liu et al., 2016). Conspicuously few empirical studies have examined the role of ambiguity aversion in vaccination decisions. In an experimental study utilizing hypothetical scenarios, Ritov and Baron demonstrated that ambiguity in the form of missing information about the risks of vaccine harms led to lower intentions for vaccination against an influenza epidemic (Ritov & Baron, 1990). In a study examining parental attitudes toward childhood pertussis vaccination, Meszaros and colleagues found that ambiguity in the form of expert disagreement on vaccine harms was associated with lower vaccination intentions (Meszaros et al., 1996). A qualitative study by Blaisdell and colleagues suggested that ambiguity about the outcomes of childhood immunization is an important factor in parental vaccine hesitancy (Blaisdell, Gutheil, Hootsmans, & Han, 2016).

Empirical studies on methods of minimizing ambiguity aversion in the communication of scientific uncertainty have also been limited, although past research suggests promising strategies. The "competence hypothesis," a leading theoretical explanation of ambiguity aversion, traces its origins to low perceived competence in decision making (Heath & Tversky, 1991). An extension of this explanation, the "comparative ignorance hypothesis," holds that ambiguity aversion results from an implicit comparison with less-ambiguous events or more knowledgeable individuals (Fox & Tversky, 1995). Specifically, the contrast between an ambiguous and less ambiguous prospect or information source "makes the less familiar bet less attractive or the more familiar bet more attractive" (Fox & Tversky, 1995). Ambiguity aversion is increased when perceived competence is decreased—e.g., when decision makers are made aware that relevant risk information is unavailable to them but available to others. In contrast, ambiguity aversion is decreased when perceived competence is increased—an effect that Chow and colleagues experimentally induced by making decision makers aware that the risks at hand are not only unknown to any given individual, but *unknowable* (Chow & Sarin, 2001, 2002; Heath & Tversky, 1991). These findings suggest that normalizing the unknowability of risk as an expected state may be a potentially effective strategy for minimizing ambiguity aversion in the communication of scientific uncertainty.

The aims of the current study were to examine (1) the potential magnitude of ambiguity-averse responses to the communication of scientific uncertainty regarding both the risks of VPD and the effectiveness of vaccination, and (2) the effects of different uncertainty communication strategies on ambiguity aversion. Focusing on the problem of vaccine hesitancy and the communication of scientific uncertainty regarding the risks of VPD and the effectiveness of vaccination, we tested the following primary hypotheses:

1. Communicating scientific uncertainty about VPD risk and vaccine effectiveness leads to ambiguity aversion, manifest by diminished interest in vaccination.
2. An Uncertainty-Normalizing communication strategy—emphasizing the unknowability of risk—diminishes aversion to ambiguity about VPD risk and vaccine effectiveness.

We also conducted exploratory analyses to examine potential mechanisms of ambiguity aversion in the communication of scientific uncertainty regarding VPD risk and vaccine effectiveness. Although ambiguity has been shown to influence risk perceptions as well as decision making, the causal pathways linking these effects, particularly with real-world decisions, remain to be elucidated. We tested whether any negative effects of scientific uncertainty on interest in vaccination were mediated through its effects on perceptions of vaccine effectiveness, VPD risk, and/or trust in experts. Research on ambiguity aversion suggests that communicating uncertainty about vaccine effectiveness may reduce vaccine interest by lowering perceptions of vaccine effectiveness and trust in the information source. Perceptions of VPD risk might also play a mediating role; however, they might be either increased or decreased depending on whether "alarmist" appraisals (Viscusi et al., 1991) or defensive processing (Dieckmann et al., 2017) were the dominant effect. Finally, we explored whether responses to communicating scientific uncertainty were moderated by individual differences that past research has suggested to be potentially associated with lower ambiguity aversion, including higher health literacy, dispositional optimism, and other trait-level differences in individuals' tolerance of uncertainty and ambiguity (Han et al., 2011, 2014).

Methods

This study was part of a larger project, funded by the European Union, to develop and evaluate evidence-based strategies to improve the general public's responses to infectious disease pandemics. The current research was one of nine studies, run across 11 European countries, employing hypothetical vignettes consisting of a newspaper article describing a serious new influenza pandemic, and featuring a public health official who advocated vaccination for the general public. The current experiment was conducted among members of the general public in Spain.

Sample Population and Recruitment

During November 2015, we recruited a stratified random sample of Spanish adults from an opt-in voluntary panel of Internet users administered by Survey Sampling International (SSI). SSI uses a probability-weighted random process to identify which panel members should receive different surveys based on sample requirements. To achieve demographic diversity representative of the Spanish population, and to offset variation in response rates, we established quotas based on respondent age and gender. Participants who completed surveys were entered by SSI into drawings for modest prizes. Because the study involved a non-invasive intervention and anonymous survey with adult participants, it was designated as minimal-risk and exempted from Internal Review Board (IRB) review by the University of Michigan IRB.

Study Design

The current experiment utilized a factorial design in which respondents were randomly assigned to one of three ambiguity communication strategies: (1) No-Uncertainty (control); (2) Uncertainty; and (3) Normalized-Uncertainty. The No-Uncertainty strategy lacked any mention of scientific uncertainty. The Uncertainty strategy contained text describing scientific uncertainty about two issues relevant to real viral pandemic crises: (1) VPD risk (including both the potential severity of the VPD and the probability or affecting individuals) and (2) vaccine effectiveness. The Normalized-Uncertainty strategy contained the same text describing scientific uncertainty about VPD risk and vaccine effectiveness, supplemented by additional text designed to convey the unknowability of VPD risk and vaccine effectiveness and the normal, expected nature of this unknowability (Figure 1). After reading their randomly assigned vignettes, participants completed several measures. The Spanish versions of the vignettes are in the Supplemental Online **Appendix A**.

Measures

Sociodemographic variables (age, sex, and education) were assessed along with several outcome variables and potential moderators.

Outcome Variables and Potential Mediators

Interest in vaccination, the primary outcome variable, was measured using a single item: "When the vaccine that will help to prevent against H7N3 becomes available, would you get the vaccination?" A 7-point Likert scale was used, with end-points labeled "Definitely would not get a vaccination" and "Definitely would get a vaccination."

Perceived likelihood of VPD was measured using a single item: "How likely does it feel like you will get H7N3?" A 7-point Likert scale was used, with the end-points labeled "Very unlikely" and "Very likely."

Perceived severity of VPD was measured using a 3-item scale (α = 0.86) consisting of the following: (1) "How serious of a threat do you think H7N3 is to the public in the next two months?" (2) "How likely do you think people who get H7N3 will die from it?" (3) "How scary does H7N3 seem to you?" 7-point Likert scales were used, with end-points labeled, respectively, "Not a serious threat"/"Very unlikely"/"Not at all scary," and "An extremely serious threat"/Very likely"/"Extremely scary."

Perceived effectiveness of vaccination was measured using a single item: "How *effective* do you think the vaccine would be at preventing H7N3?" A 7-point Likert scale was used, with end-points labeled "Not at all" and "A great deal."

Trust in public health officials was measured using a 10-item scale (α = .95) assessing the perceived honesty, competence, and trustworthiness of the public health department issuing vaccination recommendations (Eisenman et al., 2012). Exemplary items included, "How confident are you that the Ministerio de Sandidad provided *accurate* information to the public?" and "How trustworthy do you think the Ministerio de Sandidad was in their talking about H7N3 and the vaccine that is being developed?" A 7-point Likert scale was used, with end-points labeled "Not at all [confident/trustworthy]" and "Very [confident/trustworthy]."

Potential Moderators

Subjective Health literacy was measured using an item from the 3-item health literacy screening measure developed by Chew and colleagues (Chew et al., 2008): "How often do you have someone (like a family member, friend, hospital/clinic worker, or caregiver) help you read health materials?" A 5-point Likert scale was used, with endpoints labeled "None of the time" and "All of the time"; scores were reverse-coded so that higher scores indicated higher health literacy. This single item was shown to predict inadequate health literacy among patients in various clinical settings, including a VA preoperative clinic and a university-based vascular surgery clinic. (Chew, Bradley, & Boyko, 2004; Morris, MacLean, Chew, & Littenberg, 2006; Wallace et al., 2007). In a validation study involving a large diverse sample of primary care patients, this same single item predicted inadequate levels of health literacy as assessed by longer "gold standard" measures (Chew et al., 2008). Area under the Receiver Operating Characteristic Curve (AUROC) values for detecting inadequate health literacy based on the Short Test of Functional Health Literacy in Adults (S-TOFHLA) and the Rapid Estimate of Adult Literacy in Medicine (REALM), respectively, were 0.67 and 0.72 (Chew et al., 2008).

Risk aversion was measured using the 6-item Pearson Risk Attitude (PRA) scale (α = .61)(Pearson et al., 1995); exemplary items include "I enjoy taking risks," and "I try to avoid situations that have uncertain outcomes." A 6-point Likert scale was used, with endpoints "Strongly Disagree" and "Strongly Agree."

Aversion to ambiguity was measured using the 6-item Ambiguity Aversion in Medicine (AA-Med) scale (α = .68) (Han, Reeve, Moser, & Klein, 2009). This scale measures ambiguity aversion as a trait-level personality variable, reflecting an individual's propensity toward aversive responses to ambiguity in health information; exemplary items include "Conflicting expert opinions about a medical test or treatment would make me upset" and "I would avoid making a decision about a medical test or treatment if experts had conflicting opinions about it." A 6-point Likert scale was used, with endpoints "Strongly Disagree" and "Strongly Agree."

Need for Closure, a related construct assessing an "individual's desire for a firm answer to a question" and aversion to general uncertainty, was measured using the 15-item short-form version of the Need for Closure (NFC) Scale (α = .85) (Kruglanski & Webster, 1996); exemplary items include "I

General instructions and introductory text for all vignettes:

Imagine there has been an outbreak of the flu. The following article that you will read describes the current status of the outbreak.

Ministerio de Sandidad Reports H7N3 Infection Spain, Vaccine in Development

Maria De la Vega

The number of people with the H7N3 influenza virus is continuing to rise, according to health officials at the Ministerio de Sandidad.

"H7N3 is quickly infecting Spain, moving from city to city with alarming speed," said Dr. Javier Anglada, the director of the Ministerio de Sandidad. "The concern is that it will continue to grow and infect people across Spain."

…

Strategy 1: No-Uncertainty

Health officials are confident that this outbreak will be a bad one.

"H7N3 is a severe virus, and people are at risk for serious illness or death," said Dr. Anglada. "Although we believe that many people will only have relatively mild symptoms, we expect to see severe cases, some of which will lead to death."

Dr. Anglada emphasized that these projections are based on the information currently available to health officials.

With a growing number of cases of the virus, Dr. Anglada promised that the soon to be released vaccine will prevent people from getting H7N3.

"The H7N3 vaccine uses many of the same elements of vaccines from previous flu seasons and is undergoing standard development and testing. We have every reason to believe the vaccine will be effective, and it's the best option available right now to protect people against the H7N3 virus," said Dr. Anglada.

Once the vaccine becomes available, Dr. Anglada urged people to get vaccinated, even if they have questions about their risks of H7N3 or the effectiveness of the vaccine.

"The vaccine is the most effective way we have to prevent the H7N3 virus," he said.

Strategy 2: Uncertainty

Yet, health officials say it's still too soon to tell just how bad the outbreak will be.

"It's simply too early to predict how severe H7N3 will turn out to be, or who in the population is at greatest risk for serious illness or death," said Dr. Anglada. "It might turn out to be relatively mild like most seasonal flu, but it could also be much more severe than usual, particularly for some people."

Dr. Anglada emphasized that these projections are based on the information currently available to health officials.

With a growing number of cases of the virus, Dr. Anglada is hopeful that the soon to be released vaccine will prevent people from getting H7N3.

"The H7N3 vaccine has small changes compared to vaccines used during the last few regular flu seasons and is undergoing standard development and testing. We are not sure exactly how effective it will be, but it's the best option available right now to protect people against the H7N3 virus," said Dr. Anglada.

Once the vaccine becomes available, Dr. Anglada urged people to get vaccinated, even if they have questions about their risks of H7N3 or the effectiveness of the vaccine.

"The vaccine is the most effective way we have to prevent the H7N3 virus," he said.

Fig. 1. Experimental vignettes for different uncertainty communication strategies.

Strategy 3: Normalized-Uncertainty

Yet, health officials say it's still too soon to tell just how bad the outbreak will be.

"It's simply too early to predict how severe H7N3 will turn out to be, or who in the population is at greatest risk for serious illness or death," said Dr. Anglada. "It might turn out to be relatively mild like most seasonal flu, but it could also be much more severe than usual, particularly for some people."

But Dr. Anglada also emphasized that this kind of uncertainty about how severe the flu will be is normal and expected. "Often at the beginning of outbreaks, we just don't have all the information we wish we had, so for now we have to do the best we can with the information we do have," he said.

With a growing number of cases of the virus, Dr. Anglada is hopeful that the soon to be released vaccine will prevent people from getting H7N3.

"The H7N3 vaccine has small changes compared to vaccines used during the last few regular flu seasons and is undergoing standard development and testing. We are not sure exactly how effective it will be, but it's the best option available right now to protect people against the H7N3 virus," said Dr. Anglada.

"The vaccine is the most effective way we have to prevent the H7N3 virus," he said, "In life, we never have perfect knowledge of any health risks, and our information commonly changes. All we can ever do is take action with the limited knowledge we have."

Once the vaccine becomes available, Dr. Anglada urged people to get vaccinated, even if they have questions about their risks of H7N3 or the effectiveness of the vaccine.

"The vaccine is the most effective way we have to prevent the H7N3 virus," he said.

Vignettes translated and administered in Spanish; portions of text varied between uncertainty communication strategies are indicated in bold.

Fig. 1. Continued.

don't like situations that are uncertain," and "I do not usually consult many different opinions before forming my own view." A 6-point Likert scale was used, with endpoints "Strongly Disagree" and "Strongly Agree."

Dispositional optimism was measured using the 3-item optimism subscale of the Life Orientation Test (α = .82) (Scheier, Carver, & Bridges, 1994); exemplary items include "In uncertain times, I usually expect the best." A 5-point Likert scale was used, with endpoints "Strongly disagree" and "Strongly agree."

Data Analysis

We conducted multivariate analysis of variance (MANOVA) and univariate analysis of variance (ANOVA), with the five primary and secondary outcomes as dependent variables, to assess the overall extent of ambiguity aversion and to explore potential moderating and mediating relationships. Independent variables included experimental condition (No-Uncertainty, Uncertainty, and Normalized-Uncertainty), sociodemographic characteristics, and potential moderators. To explore moderating effects, we fit separate univariate ANOVA models including relevant interaction terms. Analyses were conducted using PROC GLM (SAS version 9.3).

To explore mediating effects, we used Structural Equation Modeling (SEM), as implemented in the Lavaan package of R, to fit models examining (1) our multiple secondary outcomes as potential mediators of the effect of uncertainty communication condition on vaccine intentions (mediation models), and (2) individual difference variables (health literacy, optimism, and uncertainty tolerance) as potential moderators of these mediational effects (moderated mediation models). We used the bootstrap estimator for standard errors to account for non-normality of the mediated effects, and the FIML (Full Information Maximum Likelihood) method to account for missing data using all available data.

Results

A total of 2705 completed surveys were received, of which 4 were excluded due to respondent age <18, yielding a final sample size of 2701. Sample population characteristics are shown in Table 1.

Main Effects of Uncertainty Communication

MANOVA showed a significant overall main effect of Uncertainty communication strategy, with significant differences between the Uncertainty and No-Uncertainty groups (Wilks' $\lambda = 0.973$, $p < 0.0001$), but not between the Uncertainty and Normalized-Uncertainty groups (Table 2). Univariate ANOVAs showed that the main effect of uncertainty condition emerged on the primary outcome of vaccination interest ($p < 0.0001$). As predicted and consistent with the phenomenon of ambiguity aversion, the Uncertainty group showed significantly lower vaccination interest (M = 4.72, 95% CI: 4.57–4.87) than the No-Uncertainty group (M = 5.09, 95% CI: 4.94–5.24, $p < 0.0001$). Contrary to predictions, however, vaccination interest for the Normalized-Uncertainty group (M = 4.66, 95% CI: 4.51–4.81) was similar to that of the Uncertainty group, and the difference between the Normalized-Uncertainty and Uncertainty groups was not statistically significant ($p = .53$).

Table 1. Demographic characteristics of study population ($N = 2701$).

	N	%
Age		
18–29	528	19.6
30–39	584	21.6
40–49	576	21.3
50–59	375	13.9
60–69	515	19.1
70 and up	86	3.2
Missing	37	1.4
Sex		
M	1340	49.6
F	1344	49.8
Missing*	17	0.6
Highest education		
1–4 (tertiary or less)	614	22.7
5–7 (bachelors or more)	1932	71.5
Missing	155	5.7

*Transgender, other, and missing are all treated as missing

The Uncertainty condition also showed significant main effects on the secondary outcome variables of perceived vaccine effectiveness, perceived VPD likelihood, perceived VPD severity, and trust in public health officials (Table 2). Consistent with predictions, the Uncertainty group demonstrated significantly lower perceived vaccine effectiveness ($p < 0.0001$), perceived VPD likelihood ($p = 0.0068$), perceived VPD severity (<.0001), and trust in health officials ($p < 0.0001$) than the No-Uncertainty group. There were no significant differences between the Normalized-Uncertainty and Uncertainty groups for any of these secondary outcomes.

Moderation Effects

There was a significant interaction between health literacy and uncertainty communication condition on the primary outcome of vaccination interest ($p = 0.0019$) (Figure 2). As health literacy increased, the difference in vaccination interest between both uncertainty groups (Uncertainty and Normalized-Uncertainty) and the No-Uncertainty group increased, consistent with greater ambiguity aversion for higher-literate individuals and greater ambiguity tolerance for lower-literate individuals—i.e., a potential protective effect of lower literacy against ambiguity aversion. There was also a similar significant interaction between health literacy and uncertainty communication condition on the secondary outcomes of perceived vaccine effectiveness ($p = 0.019$), perceived VPD likelihood ($p = 0.0047$), and perceived VPD severity ($p < 0.0001$). However, none of the other potential moderators—including trait-level ambiguity aversion—demonstrated significant interactions with uncertainty communication condition on any outcome variable. Correlations between trait-level ambiguity aversion, health literacy, and vaccine interest are shown in the supplemental online **Appendix B**.

Mediation Effects

Because they demonstrated significant associations with uncertainty communication condition, the secondary outcome variables of perceived vaccine effectiveness, perceived VPD likelihood, perceived VPD severity, and trust in public health officials were each tested as potential mediators of the relationship between uncertainty communication and vaccination interest. Individual mediation models fit for each secondary outcome demonstrated significant mediating effects for all outcome variables except trust in public health officials. We then jointly modeled the effects of all three mediators (perceived vaccine effectiveness, perceived VPD likelihood, and perceived VPD severity) (Edwards & Lambert, 2007). For this analysis, we combined the two uncertainty groups (Uncertainty and Normalized-Uncertainty) given the lack of between-group differences in these outcomes, and fit a path model with the three mediators acting in parallel. This model demonstrated good fit ($X^2 = 0.266$ on df = 1, $p = 0.606$, CFI = 1.0, RMSEA = 0.0, SRMR = 0.001), and these three mediators were found to fully mediate the effect of uncertainty condition on vaccination intentions—i.e., with no direct effect of uncertainty on vaccine intentions. The first part of Table 3 shows the parameter estimates and standard errors, with vaccine effectiveness contributing 71%, perceived severity 20.3%, and likelihood 8.6% of the total mediating effect.

A second path model was fit to account for the potential moderating effect of health literacy on the indirect (mediated) paths between uncertainty and vaccination intentions (moderated mediation). The final model included the interaction between health literacy and uncertainty condition for all three mediators (first-stage moderation) as well as the interaction between health

Table 2. Outcome variables by uncertainty communication condition, and estimate of the effect of No-Uncertainty vs. the combined Uncertainty conditions, each given as mean (95% confidence interval).

Outcome	No-Uncertainty	Uncertainty	Normalized Uncertainty	Uncertainty Effect
Vaccination intentions	5.09 (4.94, 5.24)	4.72 (4.57, 4.87)**	4.66 (4.51, 4.81)**	0.40 (0.56, 0.24)**
Perceived vaccine effectiveness	5.03 (4.91, 5.15)	4.65 (4.53, 4.77)**	4.68 (4.56, 4.79)**	0.37 (0.49, 0.24)**
Perceived likelihood	3.78 (3.67, 3.90)	3.59 (3.47, 3.70)*	3.51 (3.40, 3.63)*	0.23 (0.36, 0.11)*
Perceived severity	4.35 (4.25, 4.45)	4.03 (3.92, 4.13)**	3.94 (3.84, 4.04)**	0.37 (0.48, 0.26)**
Trust in health officials	4.55 (4.45, 4.65)	4.30 (4.20, 4.40)**	4.37 (4.27, 4.47)*	0.22 (0.33, 0.11)**

*$p < .01$ for comparison with No-Uncertainty group (reference).
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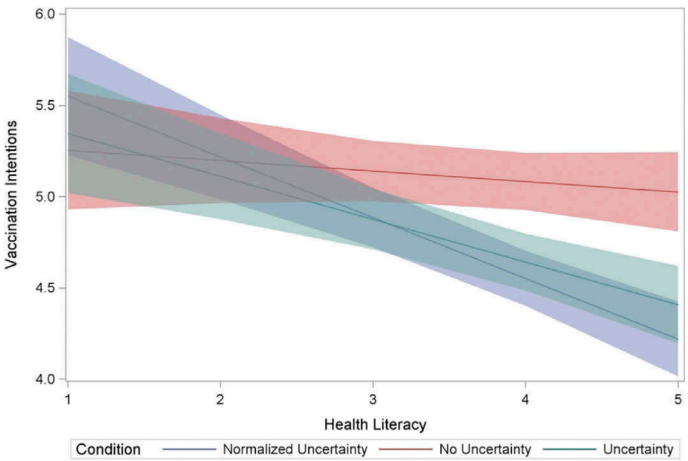

Fig. 2. Interaction between uncertainty communication condition and health literacy on ambiguity aversion in vaccination intentions.
Shaded areas indicate 95% confidence intervals for the effects of each uncertainty communication condition.
Higher values for both vaccination intentions and health literacy represent greater levels of each.

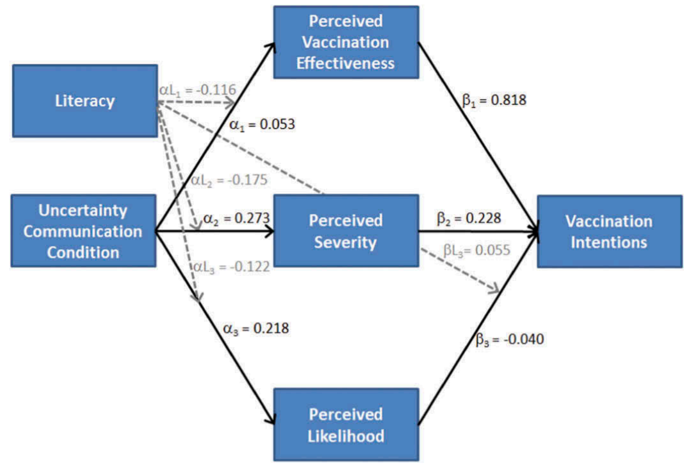

Fig. 3. Final path model, showing mediation and moderation effects for the influence of uncertainty condition on vaccine intentions.
Regression coefficients (unstandardized) reported for each path:
α = Path from Uncertainty Condition (No-Uncertainty, Uncertainty, Normalized Uncertainty) to Mediator
β = Path from Mediator to Vaccine Intentions
αL = Moderated effect of uncertainty condition on mediator (first-stage moderation effect)
βL = Moderated effect of mediator on vaccine intentions (second-stage moderation effect)

literacy and perceived likelihood on vaccine intentions (second-stage moderation); the other two second-stage moderation effects were not found to be significant (Edwards & Lambert, 2007). This model showed good fit (X^2 = 2.67 on 3 df, p = 0.445, CFI = 1.0, RMSEA = 0.0, and SRMR = 0.002). Figure 3 shows the moderating and mediating paths with individual effects of the three mediators. All of the mediated negative effects of uncertainty condition on vaccination intentions increased with greater health literacy (moderated

Table 3. Results of overall mediation and moderated mediation models.

I. Overall Mediation Model	α	β	αβ (Mediated Effect)
Mediator			
1. Perceived vaccine effectiveness	−0.370 (0.064)	0.819 (0.019)	−0.303 (0.053)
2. Perceived severity	−0.369 (0.057)	0.235 (0.029)	−0.087 (0.017)
3. Perceived likelihood	−0.233 (0.061)	0.158 (0.024)	−0.037 (0.011)
II. Moderated mediation: First stage	**α**	**L**	**αL (Moderated Effect)**
Mediator			
1. Perceived vaccine effectiveness	0.053 (0.196)	−0.045 (0.043)	−0.116 (0.054)
2. Perceived severity	0.273 (0.193)	−0.125 (0.042)	−0.175 (0.052)
3. Perceived likelihood	0.218 (0.224)	−0.117 (0.047)	−0.122 (0.060)
III. Moderated mediation: Second stage	**β**	**L**	**βL (Moderated Effect)**
Mediator			
1. Perceived vaccine effectiveness	0.818 (0.020)	−0.022 (0.022)	n.s.
2. Perceived severity	0.228 (0.028)	−0.022 (0.022)	n.s.
3. Perceived likelihood	−0.040 (0.047)	−0.022 (0.022)	0.055 (0.013)

Regression coefficients reported as estimate (standard error) for each path:
α = Path from Uncertainty Condition (No-Uncertainty, Uncertainty, and Normalized Uncertainty) to Mediator
β = Path from Mediator to Vaccine Intentions
L = Path from Health Literacy to Mediator or Vaccine Intentions
αβ = Total mediated (indirect) effect by specified mediators
αL = Moderated effect of uncertainty condition on mediator (first-stage moderation effect)
βL = Moderated effect of mediator on vaccine intentions (second-stage moderation effect).

mediation), with moderation occurring primarily in the first stage of the mediation pathways (Table 3).

Discussion

This experimental study tested whether communicating scientific uncertainty about VPD risk and vaccine effectiveness to the general public reduces interest in a hypothetical vaccination and alters vaccine-related cognitions, and whether a new communication strategy focused on normalizing scientific uncertainty diminishes these effects. To our knowledge, it is the first study to examine these questions in the context of the important public health problem of vaccination for emerging viral pandemics. The study's findings are clearly preliminary given its use of hypothetical vignettes; however, they have several important implications for future public health communication and research efforts.

First, as predicted and consistent with the phenomenon of ambiguity aversion, the study showed that communicating scientific uncertainty reduces the public's interest in vaccination. It also reduces perceptions of vaccine effectiveness, the likelihood and severity of VPD, and trust in health officials. The observed reduction in perceived VPD likelihood and severity suggest that the communication of scientific uncertainty about VPD risk produces ambiguity aversion not by promoting pessimistic, "alarmist" risk appraisals (Viscusi et al., 1991), but diminished risk appraisals that may manifest motivated reasoning processes (Dieckmann et al., 2017). For example, expressed uncertainty may provide informational "elasticity" that enables people to interpret potentially threatening risk information in a self-serving manner that reduces feelings of vulnerability (Hsee, 1995). Together, our findings lend credence to concerns about adverse effects of communicating scientific uncertainty to the general public (Frewer, 2004; Johnson & Slovic, 1995), and support the need for caution in such efforts. At the same time, our study also affirmed that perceptions of vaccine effectiveness and VPD risk (likelihood and severity) mediate the effect of uncertainty on vaccination interest. These findings are not surprising, since uncertainty about each of these issues was explicitly communicated in our experimental manipulation. Trust in health officials, however, did not play a mediating role, suggesting that diminished trust is an independent negative outcome with lesser effects on vaccination intentions.

Contrary to predictions, an Uncertainty-Normalizing strategy did not diminish the negative effect of uncertainty communication on vaccination intentions. This finding suggests that although communicating the unknowability of risk might be an effective method of reducing ambiguity aversion in games of chance conducted in laboratory settings (Chow & Sarin, 2002), it may not be effective in real-life public health communication contexts. An equally plausible possibility, however, is that our experimental manipulation may simply have been too weak to change perceptions of unknowability or normalize uncertainty in participants' minds. More research is needed to evaluate these and other possibilities, and to develop effective methods of normalizing scientific uncertainty.

Additional research is also needed to confirm our finding of a moderating effect of health literacy on the public's responses to the communication of scientific uncertainty about VPD risk and vaccine effectiveness. Ambiguity aversion—manifest by diminished intentions to be vaccinated—was greater for individuals with higher health literacy, and lesser for individuals with lower health literacy. To our knowledge, this finding has not been previously reported and has several potential explanations. Lower-literate individuals may be less attentive to or less able to process uncertainty in health messages. Alternatively, higher-literate individuals may have greater expectations of certainty in health information, which may, in turn, promote greater disappointment and aversive responses if such expectations are deemed unrealistic. Our findings should be viewed as preliminary, however, given that our single-item measure of health literacy, which assessed individuals' need for help reading health materials, does not capture the full range of capacities that constitute health literacy. More research is needed to examine the effects of health literacy and to identify other factors that may moderate responses to the communication of uncertainty. Contrary to predictions, trait-level, individual differences in tolerance of risk, ambiguity, and general uncertainty as well as dispositional optimism, did not moderate responses to the communication of ambiguity. These null findings might reflect inadequate power of our study to detect these moderating effects. However, individual differences in people's tolerance of uncertainty or ambiguity may sometimes be less important than situational factors in determining people's responses to ambiguous health information (Hillen, Gutheil, Strout, Smets, & Han, 2017), and our findings may support this conclusion in the case of public attitudes regarding a novel pandemic health threat.

Our study had several limitations that qualify its findings and call for additional research. The population consisted of a convenience sample of residents of a single European country; further work is needed to establish the representativeness of our findings for other populations and cultures. The study did not assess several potentially important explanatory variables posited by theories of health behavior—e.g., individuals' past experience with or attitudes towards vaccination, self-efficacy, perceived social norms regarding vaccination. The study instead focused on exploring the effects of a single variable—ambiguity—that has been understudied in empirical studies of vaccination and unaccounted for in major health behavior theories; we believe our data endorses the need to address these knowledge gaps. Single-item measures were used to ascertain some key variables including health literacy. Although this item has been shown to perform reasonably well in screening for inadequate health literacy (Chew et al., 2008), it does not distinguish between different specific components of health literacy, such the ability to read vs. the ability to read and understand health information specifically. Additional research using more comprehensive measures is needed to validate our findings. Our study also manipulated multiple scientific uncertainties at once (perceived likelihood and severity of VPD, perceived effectiveness of vaccination); while this approach is representative of real-world circumstances and thus has ecological validity, it prohibits isolation of the effects of individual issues of uncertainty on the outcomes of interest. Finally, our study utilized hypothetical experimental vignettes. Although this approach has established value in the study of health communication, enabling researchers to draw strong causal inferences, further research with real communication strategies and settings is needed.

Notwithstanding these limitations, the current study provides important preliminary evidence to guide further research, and has several strengths including its large sample size and assessment of multiple potential effect modifiers. We are not aware of any prior studies that have documented the potential extent of aversion to ambiguity in vaccine messages or evaluated the potential effects of an Uncertainty-Normalizing communication strategy in this context. We believe our findings have important implications for public health crisis communication efforts. They support the urgency of understanding how to help people appreciate the irreducible scientific uncertainties inherent to *all* public health interventions, while not promoting overly pessimistic appraisals of these interventions or inordinate distrust in scientific experts. They raise important questions about the role of the news media in influencing people's responses to novel public health threats, and about how mass mediated communication about these threats might be improved. The pressing need is to convey scientific uncertainty in a way that avoids the extremes of both overconfidence and underconfidence and that ensures thoughtful, deliberative decision making. The current study provides a basis for future work to address this crucial need.

Acknowledgments

This study was presented at the 38th Annual Meeting of the Society for Medical Decision Making, Vancouver, BC, Canada, October 25, 2016.

Declaration of interest

The authors have no conflicts of interest relevant to this article to disclose. The authors have no financial relationships relevant to this article to disclose.

Funding

Funding for this research was provided to Dr. Fagerlin from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement [#278763]. The funding agreement ensured the authors' independence in designing the study, interpreting the data, writing, and publishing the report.

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