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SPECIAL ISSUE/UNCERTAINTY

Communicating risk: How relevant and irrelevant probabilistic information influences risk perception in medical decision-making

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Abstract

Patients rely on knowing potential risks before accepting medical treatments, but risk perception can be distorted by cognitive biases and irrelevant information. We examined the interactive effects of subjective processes, objective knowledge, and demographic characteristics on how individuals estimate risks when provided with relevant and irrelevant probabilistic information. Participants read medical scenarios describing potential adverse effects associated with declining and accepting preventative treatment, as well as the objective likelihood of experiencing adverse effects associated with one of these two courses of action. We found that the perceived negativity of outcomes influenced perceptions of risk regardless of whether relevant probabilities were available and that the use of affect heuristics to estimate risk increased with age. Introducing objective estimates ameliorated age-related increases in affective distortions. Sensitivity to relevant probabilities increased with greater perceived outcome severity and was greater for men than for women. We conclude that relevant objective information may reduce the propensity to conflate outcome severity with likelihood and that medical judgments of risk vary depending on exposure to relevant and irrelevant probabilities. Implications for how medical professionals should communicate risk information to patients are considered.

Keywords Risk perception · Risk communication · Medical judgment and decision-making · Decision biases · Probability weighting

According to estimates by the Center for Disease Control and Prevention (2016a), more than 100,000 lives could be saved each year if everyone in the United States received appropriate clinical preventative treatment. More than a million U.S. adults suffer annually from diseases that could have been prevented by vaccines, resulting in substantial economic, personal, and societal losses for individuals and larger communities (Center for Disease Control, 2016b). Aside from external factors that could impede access to preventative care (e.g., financial resources), the high incidence of preventable diseases is partially attributable to how people interpret and respond to medical information.

When deciding whether or not to accept preventative care, not only should possible costs and benefits be considered (that is, potential negative outcomes that can result from and be prevented by accepting preventative treatment), but the likelihood of experiencing these negative outcomes needs to be taken into account as well. Risk perception is a key component of behavioral decision-making. The importance of accurate risk assessment and the consequences of miscalibration have been starkly exemplified during the course of the COVID-19 pandemic. Despite unprecedented access to information, there is widespread evidence of both harmful overestimations (e.g., unnecessary hoarding of essential resources), as well as underestimations (e.g., disregard for social-distancing measures) of risk. Uncovering the systematic ways in which people process and respond to risk- and health-related information is a critical step toward mitigating distortions in judgment and potentially dangerous behavior.

Distortions in the perceived risk of negative outcomes often result from biases and heuristics. Take for instance the affect heuristic, which describes the tendency to rely on emotional reactions toward an event to estimate the likelihood of its occurrence—namely judging an event as risky if it elicits negative reactions while judging it as relatively safe if it elicits positive feelings (Loewenstein et al., 2001).

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For instance, Kraus et al. (1992) found that strong negative feelings toward cancer led people to believe that any level of exposure to a cancer-causing agent was highly (and comparably) risky, despite the fact that objective risk varies with the level of exposure. Thus, in the context of deciding whether or not to accept preventative treatment, individuals may judge the likelihood of experiencing negative events based on how negative they feel about possible outcomes rather than accounting for objective probabilities.

Affective reactions also can directly bias our interpretation of risk-relevant information. Specifically, previous studies have found that affective responses can undermine people's ability to sufficiently adjust their risk estimates to align with objective probabilities (i.e., probability weighting bias; see Fox & Poldrack, 2009 for a review). According to Rottenstreich and Hsee (2001), when a potential outcome is negative and unfavorable, any deviation from impossibility (0%) would elicit fear, resulting in exaggerated estimates of low probability events. On the other hand, any deviation from certainty (100%) would prompt hope, resulting in underestimates of high probability events. An analysis by Bleichrodt and Eeckhoudt (2006) found that people tend to overpay for treatment when their probability of having a health problem is actually low and underpay when their probability is high. The consequences of distorted risk perception can extend beyond the individual, particularly when dealing with large-scale health crises (e.g., the COVID-19 pandemic). Catastrophizing possible threats can induce panic buying and a shortage of essential resources, whereas underestimations can result in insufficient protective actions, which can put entire communities at risk.

Risk perception also can be subject to the influence of anchoring effects (for a review, see Furnham & Boo, 2011). Previous studies have found that providing individuals with a number can bias their probability judgments toward that value (Chapman & Johnson, 1999; Plous, 1989), even when people are aware that the number is completely irrelevant. For instance, when asked to estimate the percentage of African countries in the United Nations, participants were found to align their answers with a random number they received from spinning a wheel (Tversky & Kahneman, 1974). This effect also may occur in the context of medical judgments, such that our evaluations of risk may be influenced by the likelihood of irrelevant events. Given the abundance of informational resources that are now available to us, it has become increasingly important to identify credible sources and avoid being influenced by irrelevant (and often inaccurate) facts and figures.

The first goal of the present study is to investigate how access to relevant and irrelevant probabilities moderates the influence of subjective processes on risk perception. We predict that when relevant probabilities are known (e.g., when judging the risks of declining treatment after being told the objective risks of declining treatment), people will demonstrate a probability weighting bias. In comparison, we predict that when relevant probabilities are unknown (e.g., when judging the risks of accepting treatment after being told the objective risks of declining treatment), estimates of risks may be anchored by irrelevant probabilities.

Based on evidence that judgments and decisions often are biased by affective reactions (i.e., the *affect heuristic*; for a review, see Slovic et al., 2007), we additionally predict that likelihood estimates will be biased by how negative the stimulus was perceived to be and that this may be particularly the case when relevant probabilities are unknown. When relevant probabilities are known, perceived negativity is expected to influence how participants incorporated objective risks in one of two ways. As noted by Rottenstreich and Hsee (2001), there has been debate regarding the role of emotions in probability-weighting biases. One possibility is that stronger affective responses exacerbate the tendency to overestimate small probabilities and underestimate large probabilities. In the context of the present study, events that are perceived as more negative could elicit greater fear when there is *some* possibility of experiencing disease symptoms/treatment complications relative to no possibility, resulting in increasingly exaggerated perceptions of risk at low probabilities. At the other end, more negative events could inspire greater hope when objective risks deviate from certainty, resulting in more significant underestimates of large probabilities. Alternatively, the intensity of emotional responses could generally increase perceptions of likelihood at every level of objective probability, without altering sensitivity to relative degrees of risk. In other words, participants' probability-weighing functions could become flatter (i.e., an effect of perceived negativity on the slope) or higher (i.e., an effect on the intercept) when evaluating more emotionally aversive outcomes.

A secondary goal of the present study is to explore the moderating effects of the individual (such as individual differences in gender and age) and the source of risk (such as evaluations of the disease vs. treatment) on the emergence of cognitive biases in response to known and unknown risks. Prior research has found robust gender differences in risk judgments and preferences (Harris & Jenkins, 2006; Weber et al., 2002), most commonly observing that women exhibit greater risk aversion relative to men (see Botterill & Mazur, 2004 and Croson & Gneezy, 2009 for reviews). Research on gender effects in medical decision making also indicates that women may be especially sensitive to the risks associated with potential treatments (Waters et al., 2007, 2009). To the extent that biased risk judgments are driven by negative affective responses, we may predict that affectively-driven distortions of (especially treatment-related) risks may be more pronounced for women compared with men.

While effects of age on risk perception and preferences are relatively more mixed (Rolison et al., 2012; Wood et al., 2005; Zamarian et al, 2008; see Best & Charness, 2015 and Mata et al., 2011 for reviews), reliance on heuristic and affective processes likely increases with age as a result of declines in controlled cognitive processes (Johnson, 1990; Mikels et al., 2010; Mutter & Pliske, 1994; Peters et al., 2000). If so, we may expect that older adults would be more susceptible to affect heuristics during judgments of risk, such as conflating the severity and probability of negative outcomes even when they are unrelated.

Finally, despite substantial research investigating judgments of disease risks (Branstrm & Brandberg, 2010; Peters et al., 2006; Ziebarth, 2018) and treatment risks (Betsch et al., 2011; Navar et al., 2021; Zikmund-Fisher et al., 2008) in isolation, much less is known regarding the relative impact of cognitive and affective biases when evaluating the joint consequences of accepting versus declining preventative care. Research on "side effect aversion" indicates that potential risks associated with treatments often loom larger than those of the disorder itself, even if forgoing treatment presents an objectively greater risk (Port et al., 2001; Waters et al., 2007, 2009; Wroe et al., 2004). Individuals also exhibit similar degrees of side effect aversion regardless of variability in the objective likelihood (Waters et al., 2007) or severity (Waters et al., 2009) of adverse effects. To the extent that evaluations of treatments are particularly insensitive to relative magnitudes of risk, we may expect a larger probability-weighting bias when judging the likelihood of treatment side effects compared with disease symptoms. In contrast, reduced sensitivity to the relative severity of outcomes may minimize the impact of perceived negativity on perceived likelihood (i.e., an affect heuristic) when evaluating risks of the treatment compared with the disease.

Method

Design

The current study follows a 10 × 2 mixed design, with the objective probability of experiencing adverse effects as a within-subject independent variable (i.e., 10 probabilities of adverse effects, ranging from 2 to 98% at 7% intervals), and knowledge of disease versus treatment risks as a between-subject variable; that is, whether the probability was associated with the adverse effects of not accepting preventative treatment (i.e., disease symptoms) or with accepting preventative treatment (i.e., treatment complications). Rating scales ranging from 0–100 were used to assess four measures of interest (see Appendix 1 for full text and additional details):

1. Perceived likelihood of experiencing disease symptoms
2. Perceived likelihood of experiencing treatment complications
3. Perceived negativity of disease symptoms
4. Perceived negativity of treatment complications

Participants

A power analysis (using the *simr* R package; Green & Macleod, 2016) with 500 simulations of fitted pilot data (N = 24) indicated that a sample size of 80 was sufficient to detect predicted interaction effects with a power of 80% (95% confidence interval [CI]: 73.6, 85.8) and alpha level of 0.05. Eighty monolingual native English speakers (50% female; median age = 36 years, range: 20–70) were recruited on the Amazon Turk Prime platform, and workers were compensated $3 for their participation. Participants randomly assigned to receive probabilistic information about the disease symptoms (N = 42) and treatment complications (N = 38) did not differ in either gender ($p = 0.654$) or age ($p = 0.642$).

Stringent criteria were implemented to ensure the quality of the participants and the resulting data, including a required record of at least 5,000 approved HITs and an approval rate of at least 95%. The survey was administrated to participants by using the online Qualtrics platform.

Procedure

Informed consent was obtained from all participants, and the research protocol was approved by the university's Institutional Review Board. After providing informed consent, participants responded to ten medical scenarios describing a medical condition and a treatment, including potential adverse effects associated with both.

Structure of Scenarios

Each scenario adhered to the following structure:

1. Description of a potential medical problem (one sentence)
   - *You find out that millions of people are likely to get sick from the flu this year.*
2. Description of five adverse effects associated with not accepting preventative treatment (i.e., disease symptoms; two sentences)
   - *If you get the flu, you may experience a number of unpleasant symptoms, such as sore throat and fever. It could even turn into pneumonia, which can cause severe body aches and difficulty breathing.*

3. Description of one benefit of accepting preventative treatment (one sentence)
   - *You will greatly reduce your chance of catching the flu if you get a flu shot, but there are risks involved in getting the injection.*
4. Description of five adverse effects associated with accepting preventative treatment (i.e., treatment complications; three sentences)
   - *Specifically, there may be soreness at the injection site. You may also experience weakness in your arms, making it difficult to perform normal tasks. You may also have allergic reactions to the shot and experience negative symptoms, such as difficulty breathing.*

Half of the participants were provided with the probability of experiencing adverse effects associated with not accepting preventative care (i.e., disease symptoms). These participants read the following information after the description of the medical condition:

- *According to estimates, approximately x% of people will experience one or more of these negative effects after choosing not to _____ as preventative care.*

The remaining participants were provided with the probability of experiencing adverse effects associated with accepting preventative care (i.e., treatment complications). These participants read the following information after the description of the preventative treatment:

- *According to estimates, approximately x% of people will experience one or more of these negative effects after choosing to _____ as preventative care.*

The precise probabilities (x in the sentences above) varied across the ten scenarios within a given range (e.g., 2–30% in what was classified as "low probability" and 70–98% in what was classified as "high probability," both with a 7% interval between probabilities). Each scenario was randomly paired with a probability for each participant. Participants received half of the scenarios with low probabilities and half with high probabilities in a random order. Following each scenario, participants responded to four scales assessing the perceived likelihood and negative impact of each course of action. The full list of medical scenarios used in the study can be found in Appendix 2.

Data analysis

Linear mixed-effects models were used to examine the emergence and moderators of cognitive and affective biases (probability weighting bias, anchoring effect, and affect heuristic) during medical judgments of risk. For each scenario, participants rated the *perceived* likelihood of both disease- and treatment-related risks but were only provided with the *objective* probability of either disease symptoms or treatment complications. The known objective probability was therefore directly relevant for one likelihood judgment (e.g., judging the likelihood of disease symptoms after learning the objective probability of disease symptoms) but irrelevant for the other likelihood judgment (e.g., judging the likelihood of treatment complications after learning the objective probability of disease symptoms). Ratings of perceived likelihood (0–100) were included as the outcome variable in the primary model, with each participant contributing a total of 20 likelihood ratings (10 disease symptom ratings + 10 treatment complication ratings).

Predictors. Mean-centered continuous predictors included the known objective probability of the disease symptoms or treatment complications (Objective Probability: 2%, 9%, 16%, 23%, 30%, 70%, 77%, 84%, 91%, 98%), the perceived negativity of the disease symptoms or treatment complications being evaluated (Perceived Negativity: ratings between 0 and 100), and participant age (22–70 years old). The addition of quadratic and cubic probability terms was not found to improve model fit and were therefore dropped from the final model. Categorical predictors included the type of risky outcome being evaluated (Risk Source: treatment: – 0.5 vs. disease: + 0.5), the relevance of the known objective probability to the likelihood judgment (Probability Relevance: relevant: – 0.5, e.g., objective probability of disease symptoms when rating the likelihood of disease symptoms vs. irrelevant: + 0.5, e.g., objective probability of disease symptoms when rating the likelihood of treatment complications), and the gender of the participant (male: – 0.5 vs. female: + 0.5). To address issues of multicollinearity that could arise from modelling correlated predictors, pairwise correlations were run between the continuous measures of objective probability, perceived negativity and likelihood of outcomes with known risks (i.e., judgments for which the known objective probability was relevant) and perceived negativity and likelihood of outcomes with unknown risks (i.e., judgments for which the known objective probability was irrelevant). Following model selection, VIF scores were computed for all effects and confirmed that there was minimal risk of multicollinearity (all VIF scores < 2).

Models. Before the main analysis, we examined whether the perceived negativity of disease- and treatment-related outcomes varied by gender, age, and knowledge of relevant objective probabilities. Perceived negativity was entered as the outcome variable in a linear mixed effects model, with fixed effects of Risk Source (treatment vs. disease), Probability Relevance (relevant vs. irrelevant), plus main effects and all two- and three-way interactions with gender and age. The maximally converging model included random intercepts for participant and scenario, as well as by-participant random slopes for risk source and probability relevance and by-scenario random slopes for gender, risk source, and probability relevance.

For the primary analysis, mean-centered ratings of perceived likelihood were entered as the outcome variable. To determine whether risk estimates were subject to the probability weighting bias, anchoring effect, and affect heuristic, critical fixed effects included objective probability, probability relevance (relevant vs. irrelevant), and perceived negativity. To the extent that participants exhibit a probability weighting bias (whereby objectively low risks are overestimated and objectively high risks are underestimated), we should observe that the estimated slope for the effect of objective probability is significantly lower than 1 (i.e., that the *perceived* difference in the likelihood of low vs. high risk outcomes will be smaller than the actual difference in objective probabilities). We would additionally expect to find a significant interaction between objective probability and probability relevance such that participants should be more likely to account for objective probabilities (e.g., of disease symptoms) when the information is directly relevant to the judgment (e.g., when judging disease risks) than when it is irrelevant (e.g., when judging treatment risks). On the other hand, if a significant effect of objective probability is found even when objective estimates are irrelevant to the judgment, this would provide evidence for an anchoring effect. Finally, a significant effect of perceived negativity on perceived likelihood would be indicative of an affect heuristic (whereby the severity of an outcome is conflated with the likelihood of its occurrence). Notably, the influence of perceived negativity on perceived risk is predicted to be especially pronounced when relevant objective estimates are not available to inform the likelihood judgments (i.e., an objective probability x probability relevance interaction).

Individual and contextual moderators of the biases were investigated by also including main effects of gender (male vs. female), age, and risk source (treatment vs. disease), plus two- and three-way interactions between each of the moderating variables and objective probability, probability relevance, and perceived negativity. The maximally converging model included random intercepts for participant and scenario, as well as by-participant and by-scenario random slopes for probability relevance and risks source. Significance of parameters was estimated with the Satterwhite method using the *lmerTest* R package. Tukey-adjusted follow-up tests of simple effects were conducted using the *emmeans* and *emtrends* functions of the *emmeans* R package.

Results

Perceived negativity of known and unknown risks

Main effects of gender ($p = 0.029$), risk source ($p < 0.001$), and probability relevance ($p = 0.022$) revealed that the perceived negativity of outcomes was greater for women ($M = 66.88$, standard error [SE] = 3.8) than men ($M = 60.65$, $SE = 3.79$), for disease symptoms ($M = 72.96$, $SE = 3.52$) than treatment complications ($M = 54.57$, $SE = 4.37$), and for outcomes with unknown ($M = 65.98$, $SE = 3.91$) than known ($M = 61.55$, $SE = 3.34$) objective risks. There were no significant effects of age or interactions (Table 1).

Perceived likelihood of known and unknown risks

Probability weighting bias and anchoring effect

As shown in Table 2, a significant interaction between Objective Probability and Probability Relevance ($p < 0.001$) revealed that the perceived likelihood of experiencing adverse effects increased with higher relevant (*Estimate* = 0.34, $SE = 0.02$, $t(1414) = 15.19$, $p < 0.001$) but not irrelevant objective probabilities (*Estimate* = −0.01, $SE = 0.02$, $t(1417) = -0.21$, $p = 0.84$). In other words, we found no evidence that participants anchored on unrelated probabilistic information when judging unknown risks. Although participants did account for relevant probabilities when assessing the likelihood of known risks, a linear test comparing the estimated slope against 1 (i.e., perfect sensitivity) revealed that the adjustment was insufficient ($F(1, 1415.5) = 111.63$, $p < 0.001$; Fig. 1). A 1% increase in objective risk was associated with a significantly smaller

Table 1 Effects of risk source, probability relevance, gender, and age on perceived negativity

	Estimate	*SE*	*df*	*t*	*p*
Intercept	63.77	3.31	15.33	19.27	< 0.001 ***
Risk source	18.40	3.51	14.33	5.25	< 0.001 ***
Probability relevance	− 4.39	1.87	42.32	− 2.35	0.023 *
Gender	6.22	2.76	81.89	2.25	0.027 *
Age	0.18	0.14	72.67	1.28	0.205
Source:relevance	− 2.27	5.34	79.49	− 0.43	0.672
Source:gender	− 4.43	3.58	78.99	− 1.24	0.220
Source:age	0.13	0.18	64.01	0.68	0.499
Relevance:gender	− 1.03	3.52	74.57	− 0.29	0.770
Relevance:age	− 0.16	0.18	64.01	− 0.85	0.400
Source:relevance:gender	1.59	10.97	79.49	0.15	0.885
Source:relevance:age	0.40	0.56	79.49	0.71	0.481

SE, standard error; df, degree of freedom

Table 2 Effects of objective probability, probability relevance, perceived negativity, gender, age, and risk source on perceived likelihood

	Estimate	*SE*	*df*	*t*	*p*
Intercept	−1.93	1.95	35.03	−0.99	0.329
Objective probability	0.17	0.02	1410.76	10.58	<0.001 ***
Probability relevance	1.20	2.05	12.73	0.59	0.568
Gender	3.97	3.00	78.02	1.32	0.190
Age	0.21	0.15	76.18	1.45	0.152
Risk source	7.72	1.44	90.69	5.35	<0.001 ***
Perceived negativity	0.29	0.03	1309.42	11.42	<0.001 ***
Probability:relevance	−0.34	0.03	1412.39	−10.90	<.001 ***
Probability:gender	−0.08	0.03	1410.42	−2.43	0.015 *
Probability:age	0.00	0.00	1406.73	−1.20	0.229
Probability:source	−0.07	0.03	1423.60	−2.10	0.036 *
Probability:negativity	0.00	0.00	1482.83	2.49	0.013 *
Relevance:gender	2.05	2.78	77.00	0.74	0.463
Relevance:age	0.08	0.13	72.14	0.58	0.562
Relevance:source	14.98	5.99	79.98	2.50	0.015 *
Relevance:negativity	0.09	0.05	698.12	1.93	0.054 ~
Gender:negativity	0.01	0.04	1230.48	0.15	0.883
Age:negativity	0.00	0.00	1290.23	2.13	0.034 *
Source:negativity	0.14	0.05	1035.28	3.06	0.002 **
Probability:relevance:gender	0.17	0.06	1413.72	2.62	0.009 **
Probability:relevance:age	0.00	0.00	1411.76	−0.47	0.636
Probability:relevance:source	0.05	0.07	1422.77	0.74	0.458
Probability:relevance:negativity	0.00	0.00	1493.11	−2.37	0.018 *
Relevance:gender:negativity	0.03	0.09	1204.96	0.39	0.693
Relevance:age:negativity	0.01	0.00	1245.91	2.57	0.010 *
Relevance:source:negativity	0.14	0.10	1453.78	1.48	0.138

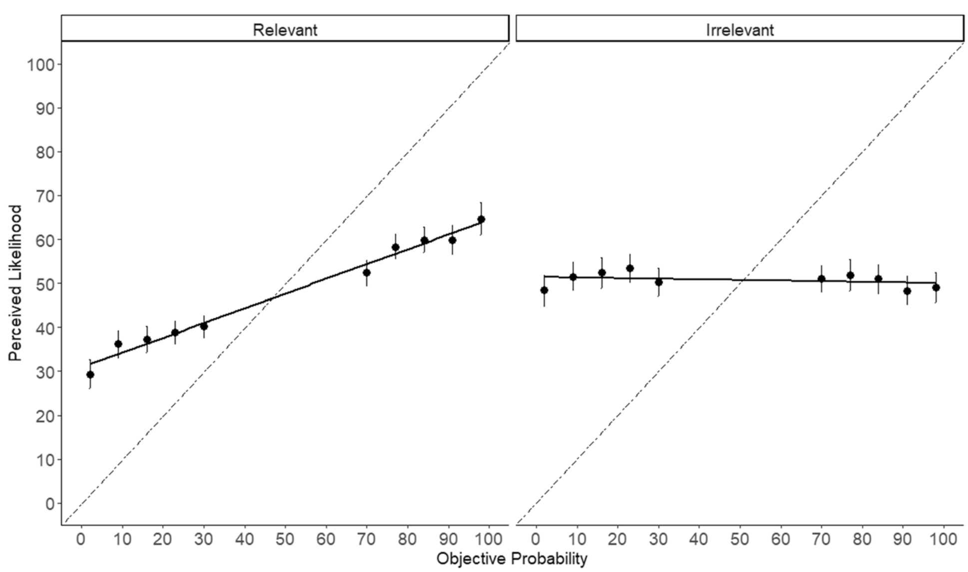

Fig. 1 Perceived likelihood by objective relevant probabilities (left; e.g., judging disease symptoms while knowing the probability of disease symptoms) and irrelevant probabilities (right; e.g., judging disease symptoms while knowing the probability of treatment complications). Error bars represent standard error. Dashed line represents reference for perfect sensitivity to known probabilities

increase of just 0.34% in perceived likelihood. Consistent with a probability weighting bias, separate tests of low (≤ 30%) and high (≥ 70%) mean-centered probabilities showed that objectively small probabilities ($M = 16\%$) were significantly overestimated ($M = 38.4\%$; *Estimate* = 20.19, $SE = 2.31$, $t(39.82) = 8.74$, $p < 0.001$) while objectively large probabilities ($M = 84\%$) were significantly underestimated ($M = 59.02\%$; *Estimate* = − 25.2, $SE = 2.57$, $t(29.71) = -9.79$, $p < 0.001$).

The effects of objective probability and probability relevance were further moderated by three-way interactions with gender ($p = 0.009$) and perceived negativity ($p = 0.018$). When relevant probabilities were unknown, simple effects by gender revealed no evidence that either men ($p = 0.82$) or women ($p = 0.96$) were anchored by irrelevant probabilities. In contrast, when relevant probabilities were known, men (*Estimate* = 0.42, $SE = 0.03$, $t(1411.29) = 13.13$, $p < 0.001$) were significantly more sensitive to objective risks than women (*Estimate* = 0.26, $SE = 0.03$, $t(1412.74) = 8.22$, $p < 0.001$; Gender Effect: *Estimate* = 0.16, $SE = 0.04$, $t(1414.46) = 3.58$, $p < 0.001$; Fig. 2a).

Simple effects by negativity revealed no effects of irrelevant probabilities for either low (bottom quartile = 40/100; $p = 0.84$) or high negativity outcomes (top quartile = 88/100; $p = 0.93$; Negativity Effect: *Estimate* = − 0.004, $SE = 0.04$, $t(1467) = -0.09$, $p = 0.932$). In contrast, when relevant probabilities were known, participants were more sensitive to objective risks of more negative outcomes (*Estimate* = 0.41, $SE = 0.03$, $t(1462.25) = 13.15$, $p < 0.001$) than less negative outcomes (*Estimate* = 0.27, $SE = 0.03$, $t(1453.55) = 9.81$, $p < 0.001$; Negativity Effect: *Estimate* = − 0.14, $SE = 0.04$, $t(1486.69) = -3.52$, $p < 0.001$; Fig. 2b).

Overall, highly negative outcomes were perceived to be more likely than less negative outcomes (see *Affect Heuristic* below). Consequently, underestimations of objectively high probabilities ($M = 84\%$) were greater for low negativity ($M = 48.8\%$) than high negativity outcomes ($M = 71.1\%$; *Estimate* = − 12.53, $SE = 2.39$, $t(354.53) = -5.24$, $p < 0.001$), while overestimations of objectively low probabilities ($M = 16\%$) were greater for high negativity ($M = 40.9\%$) than low negativity

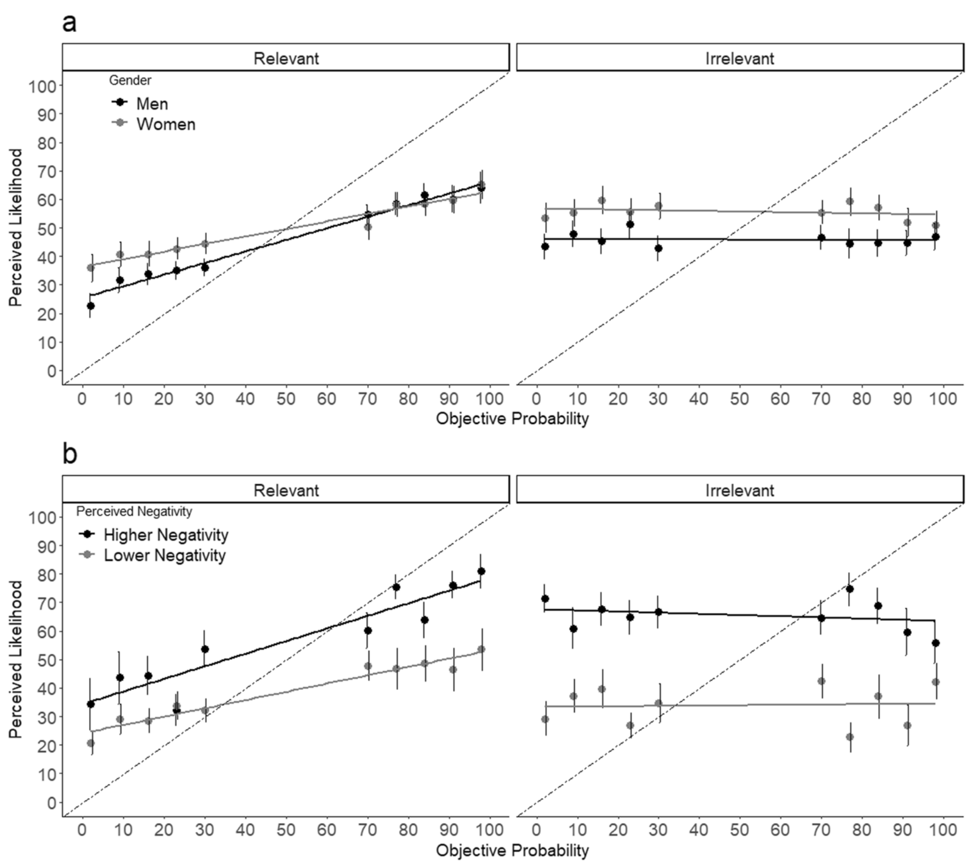

Fig. 2 Perceived likelihood of experiencing adverse effects by relevant (left) and irrelevant (right) objective probabilities and (**a**) gender or (**b**) perceived negativity. Sensitivity to relevant known probabilities was greater among men (black) than woman (gray), and for outcomes that were perceived to be more negative (black; top quartile [88–100]) than less negative (gray; bottom quartile [0–40]). Error bars represent standard error. Dashed line represents reference for perfect sensitivity to known probabilities

outcomes ($M = 28.9\%$; Estimate $= -7.7$, $SE = 2.15$, $t(363.74) = -3.58$, $p < 0.001$). Perceived negativity therefore moderated sensitivity to *changes* in magnitudes of risk (i.e., the slope), as well as *absolute* levels of estimated risks (i.e., the intercept).

Affect Heuristic

Consistent with an affect heuristic, there was a significant main effect of Perceived Negativity, indicating that overall, the perceived likelihood of adverse outcomes increased with greater perceived negativity (*Estimate* $= 0.29$, $SE = 0.03$, $t(1309.42) = 11.42$, $p < 0.001$). In addition to the three-way interaction between perceived negativity, probability, and probability relevance noted previously, the effect of negativity was moderated by a two-way interaction with risk source ($p = 0.002$), as well as a three-way interaction with age and probability relevance ($p = 0.010$). Simple effects by risk source revealed that while greater perceived negativity increased the perceived likelihood of both disease symptoms (*Estimate* $= 0.38$, $SE = 0.04$, $t(761.55) = 9.29$, $p < 0.001$) and treatment complications (*Estimate* $= 0.24$, $SE = 0.03$, $t(645.1) = 7.19$, $p < 0.001$), the effect of perceived negativity on perceived risk was significantly greater for disease- than treatment-related adverse outcomes (*Estimate* $= -0.14$, $SE = 0.05$, $t(673.62) = -2.65$, $p = 0.008$; Fig. 3a).

Simple effects by age (younger: bottom quartile ≤ 30; older: top quartile ≥ 43) and probability relevance indicated that when relevant probabilities were unknown, the effect of perceived negativity on perceived risk was significantly greater for older adults (*Estimate* $= 0.40$, $SE = 0.04$, $t(897.47) = 9.02$, $p < 0.001$) than younger adults (*Estimate* $= 0.27$, $SE = 0.05$, $t(794.14) = 5.13$, $p < 0.001$; age effect: *Estimate* $= -0.14$, $SE = 0.05$, $t(1305.68) = -2.57$, $p = 0.01$). In contrast, when relevant probabilities were known, the effect of perceived negativity on perceived risk did not significantly differ for older adults (*Estimate* $= 0.27$, $SE = 0.04$, $t(951.47) = 7.1$, $p < 0.001$) and younger adults (*Estimate* $= 0.28$, $SE = 0.04$, $t(701.28) = 6.39$, $p < 0.001$; Fig. 3b).

Correlations between objective probability, perceived likelihood, and perceived negativity

Objective probability was significantly correlated with the perceived likelihood of adverse outcomes but only when the objective risk estimate was directly relevant to the judgment. In other words, objective disease risks were correlated with the perceived likelihood of disease symptoms, but not with the likelihood of associated treatment complications. In contrast, known objective probabilities were not correlated with the perceived negativity of adverse outcomes (regardless of whether relevant objective risks were known; Table 3).

Ratings of perceived likelihood were significantly correlated with ratings of perceived negativity, both when relevant objective risks were known and unknown. Significant correlations were additionally found between the perceived likelihood of known and unknown risk outcomes, as well as between the perceived negativity of known and unknown risk outcomes.

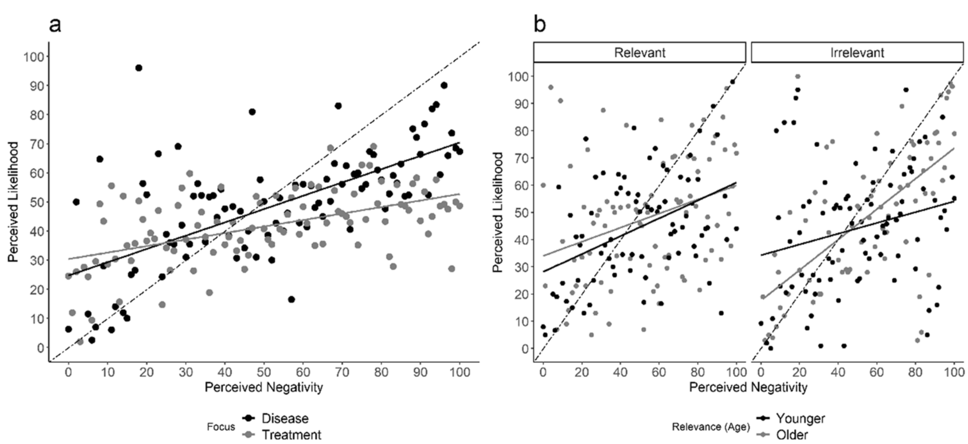

Fig. 3 Perceived likelihood of experiencing adverse effects by perceived negativity and (**a**) risk source or (**b**) age and probability relevance. Effects of perceived negativity on perceived likelihood were greater for disease symptoms (black) than treatment complications (gray). Effects of perceived negativity on perceived likelihood were greater for older (gray; top quartile [43–70]) than younger adults (black; bottom quartile [22–30]) when relevant objective probabilities were unknown (right) but not when they were known (left). Dashed line represents reference for perfect correlation between perceived likelihood and negativity

Table 3 Correlation coefficients for associations between objective probability (i.e., the known risk) and the perceived likelihood and negativity of outcomes with known and unknown objective risks

	Perceived likelihood of known risk (e.g., disease)	Perceived negativity of known risk (e.g., disease)	Perceived likelihood of unknown risk (e.g., treatment)	Perceived negativity of unknown risk (e.g., treatment)
Objective probability (e.g., of disease)	0.40***	0.05	−0.02	0.00
Perceived likelihood of known risk		0.27***	0.16***	0.05
Perceived negativity of known risk			−0.06	0.13***
Perceived likelihood of unknown risk				0.42***

***$p < 0.001$

Discussion

Judgments of risk in medical settings can be distorted by mental heuristics and affective biases. The results of the present study demonstrate that the magnitude of bias when evaluating medical risks varies depending on the availability of relevant probabilistic information, as well as by the moderating effects of gender, age, and the source of risk (i.e., adverse effects of a disease vs. treatment). When relevant probabilities were known, participants adjusted their estimates of personal risk to align with the objective information. However, the adjustment was insufficient, which resulted in exaggerated small probabilities and underestimated large probabilities. Rottenstreich and Hsee (2001) similarly found that individuals do not sufficiently adjust their judgments to align with objective probabilities and that judgments are more distorted for outcomes that trigger stronger emotional reactions. Based on prior research indicating that women may be especially averse to treatment complications (Waters et al., 2007, 2009), we initially predicted that probability-weighting biases for treatment risks may be more pronounced for women compared with men. Results of the present study, however, indicated that women perceived both disease and treatment risks to be more negative than men. Accordingly, we observed that women exhibited a larger probability-weighing bias when judging disease- and treatment-related risks, which was primarily driven by heightened perceptions of risk at objectively lower probabilities.

While the observed gender effects are largely consistent with the presumed association between heighted affect and insensitivity to magnitude (Rottenstreich & Hsee, 2001), a direct examination of the relationship between perceived negativity and risk revealed a different pattern. Rather than exacerbating probability-weighting biases, greater perceived negativity was associated with moderately greater sensitivity to objective probabilities. Furthermore, we did not find evidence that the probability-weighing bias differed for disease- versus treatment-related risks, despite the fact that the former was perceived to be more emotionally aversive. These findings may indicate that the influence of affective processes on probability weighting may not be sensitive to fine-grained differences in the emotional impact of particular outcomes (i.e., moderately emotional vs. highly emotional) but rather that qualitatively different types of processes are engaged depending on more general levels of emotionality (i.e., emotional vs. not emotional). Specifically, it may be the case that more deliberate processes are engaged when making judgments of affect-poor events (e.g., the probability of obtaining a coupon for textbooks), but more emotional processes are engaged when judging affect-rich events (e.g., the probability of getting a kiss from a favorite celebrity; Rottenstreich & Hsee, 2001). The present findings suggest that once emotional processes are triggered, however, they may introduce a similar, or even smaller magnitude of bias for judgments of more versus less aversive outcomes.

Aside from potentially modulating sensitivity to relevant probabilistic information, greater negativity was associated with a general increase in risk perception. This conflation of outcome severity and likelihood is indicative of an affect heuristic (Slovic et al., 2007) and was more pronounced for disease symptoms than treatment complications. We additionally observed that when relevant probabilities were unknown, the magnitude of the affect heuristic increased with age. This finding is consistent with evidence suggesting that age-related decline in controlled cognitive processes may be associated with a corresponding increase in affective and heuristic processes (Johnson, 1990; Mikels et al., 2010; Mutter & Pliske, 1994; Peters et al., 2000). Notably, however, an effect of age was not observed when participants could rely on objective probabilities to inform their judgments.

Lastly, and contrary to expectations, we did not find any indication that people relied on irrelevant information to estimate risks. One plausible explanation for the contrast between our findings and prior work showing that individuals often are anchored by irrelevant information (Tversky & Kahneman, 1974; Critcher & Gilovich, 2008; Englich, Mussweiler, & Strack, 2006) is that participants in our study were not explicitly instructed to pay attention to the anchor, unlike in many previous demonstrations of anchoring effects. For example, Tversky and Kahneman (1974) asked participants to estimate the percentage of African countries in the United Nations, first by indicating whether it was higher or lower than a random value obtained from spinning a wheel, and then to report a precise percentage. In comparison, we took a more implicit approach in which participants were presented with an irrelevant probability but were not forced to evaluate it in relation to the focal event. This may suggest that anchoring effects occur because people insufficiently adjust their estimates from previous evaluations (as posited by Tversky & Kahneman, 1974) and not necessarily as a result of passive exposure to irrelevant information.

In summary, our results suggest that the emergence of cognitive and affective biases during evaluations of disease- and treatment-related risks are moderated by the availability of relevant probabilistic estimates, as well as individual differences in age and gender. In addition to well-established effects of gender on risk perception and risk tolerance (Croson & Gneezy, 2009), the present findings indicate that sensitivity to probabilistic risk estimates may be subject to gender differences as well. Our data also suggest that the likelihood of conflating outcome severity with probability increases with age but can be ameliorated with objective estimates of risk. Identifying the individual and contextual factors that impact risk perception is a key step toward promoting life-saving decisions regarding preventative care. As controversies and hesitancy regarding vaccinations continue worldwide, understanding how age and gender impact health judgments can inform the development of more targeted strategies for communicating disease- and treatment-related risks.

Conclusions

The most effective approach for calibrating risk perception will depend on correctly identifying the source of potential distortions, including incomplete knowledge, inaccurate assumptions, and emotional responses. We elucidate the conditions under which estimates of risk are subject to cognitive heuristics by simultaneously examining the influence of demographic variables (gender, age), online affective evaluations (i.e., perceived negativity), the source of risk (disease vs. treatment), and the availability of relevant information. By being mindful of triggers and contexts that elicit biased evaluations, patients and doctors can begin equipping themselves with more sophisticated ways of evaluating and conveying risks, whether they are managing their personal health or navigating a global crisis.

Appendix 1: Measures

On each trial, participants read a description of potential adverse effects associated with declining and accepting a preventative treatment (see Appendix 2), as well as the estimated probability of experiencing one set of the outcomes (disease symptoms or treatment complications). The scenario remained visible on the screen while participants responded to a series of questions using sliding scales. Each scale had two verbal anchors and ranged from 0 to 100.

Perceived negativity and likelihood of disease symptoms

- As mentioned above, choosing NOT TO *[get a flu shot]* can cause some negative effects (*[sore throat, fever, pneumonia, severe body aches, difficulty breathing]*). How bad do you think these negative effects are? (0 = Not bad at all, 100 = Extremely bad)
- How likely do you think it is that you would experience these negative effects? (0 = Not likely at all, 100 = Extremely likely)

Perceived negativity and likelihood of treatment complications

- As mentioned above, choosing TO *[get a flu shot]* can also cause some negative effects (*[soreness, weakness, difficulty performing tasks, allergic reaction, difficulty breathing]*). How bad do you think these negative effects are? (0 = Not bad at all, 100 = Extremely bad)
- How likely do you think it is that you would experience these negative effects? (0 = Not likely at all, 100 = Extremely likely)

*Note: Italicized text in brackets varied by scenario

Appendix 2: Medical Scenarios

Flu: You find out that millions of people are likely to get sick from the flu this year. If you get the flu, you may experience a number of unpleasant symptoms, such as sore throat and fever. It could even turn into pneumonia, which can cause severe body aches and difficulty breathing. You will greatly reduce your chance of catching the flu if you get a flu shot, but there are risks involved in getting the injection. Specifically, there may be soreness at the injection site. You may also experience weakness in your arms, making it difficult to perform normal tasks. You may also have allergic reactions to the shot, and experience negative symptoms such as difficulty breathing.

Breast cancer:* You just found out that you have a gene that puts you at high risk for developing breast cancer. If you get cancer, it can lead to a number of negative consequences, including difficulty breathing, severe pain, and even death. You may have to remove your breasts as treatment or else have chemotherapy. If you choose to have preventative surgery where the doctor removes both breasts, you will significantly reduce your chances of getting cancer, but there are risks associated with the procedure. Specifically, there could be potential complications, such as an infection during or after the surgical operation. You may have a reaction to the anesthesia, which can result in death in some cases. Some women also suffer from depression and anxiety because of concerns with body image.

Prostate cancer:* You just found out that you have a gene that puts you at high risk for developing prostate cancer. If you get cancer, it can lead to a number of negative consequences, including difficulty breathing, severe pain, and even death. You may have to remove your prostate as treatment or else have chemotherapy. If you choose to have preventative surgery where the doctor removes your prostate, you will significantly reduce your chances of getting cancer, but there are risks associated with the procedure. Specifically, there could be potential complications, such as an infection during or after the surgical operation. You may have a reaction to the anesthesia, which can result in death in some cases. Some men also suffer from depression and anxiety due to the loss of reproductive ability.

Leukemia: Your recent blood test suggests that you might have leukemia—a cancer of the white blood cells. If you have leukemia, it can lead to serious medical problems ranging from fever to death. You may have to have chemotherapy as a treatment, which can cause hair loss and lead to infections. If you choose to get a bone marrow puncture test, you will know whether you have leukemia before it can become more serious, giving you a higher chance of curing the disease, but there are risks involved in the procedure. Specifically, getting the bone marrow puncture test means that the doctors will use a large needle to puncture your spine to extract spinal fluids, which can cause sharp pain at the puncture site when the needle penetrates your bone. It may involve serious complications, such as bleeding and infection at the biopsy site. Some people experience long-lasting pain at the site after the procedure.

Hearing disorder: You have noticed that your hearing is not as good as it used to be, and so you have gone to see a hearing specialist. If you do nothing, your hearing may continue to deteriorate over time and you may eventually lose your hearing completely. Losing your hearing could hinder your ability to communicate, affect your job performance, and make you less sensitive to signs of danger. You will greatly improve your hearing if you choose to wear hearing aids, but there are some potentially unpleasant experiences associated with wearing hearing aids. Specifically, hearing aids amplify all sounds so you may hear irritating background noises and your own voice may sound too loud. It can take several months to adjust to the hearing aids, and hearing ability will not be restored to previous levels even with hearing aids. Some people are also concerned that wearing hearing aids will make them look old.

GI disease: You experienced some unexpected weight loss recently. If you do nothing, you may fail to detect damage or disease in your upper gastrointestinal tract, which can cause infections, as well as difficulty swallowing. You may also have to make radical dietary changes when a condition is finally discovered. If you allow the doctor to insert a camera into your stomach, it will likely reveal the cause for your weight loss and allow you to be treated, but there are risks involved with the procedure. Specifically, you will not be able to move around or breathe normally during the 5- to 6-min procedure. There is also a risk of the camera scratching parts of your digestive system. Some people vomit and have difficulty swallowing after the operation.

Toe injury: A heavy item fell on your toe and damaged the flesh around it. If you do nothing, you have a chance of developing a serious infection, which could lead to bleeding, lasting pain in your toe, and difficulty walking. If the infection is bad enough, you may even end up having to remove your toe as treatment. If you choose to have your nail removed, you will significantly reduce your chance of spreading the infection, but there are risks involved with the treatment. Specifically, the surgery might damage the surrounding tissue so your nail may either fail to grow back or grow back abnormally, which could prevent you from walking normally. Existing infections might also spread to nearby tissues during the surgery. Some people feel a lot of pain after the anesthesia wears off.

Chickenpox: Imagine that you are a parent and are trying to decide whether to give your baby the optional chicken pox vaccine. If you do nothing, your child might get chicken pox at some point. If your child gets the chicken pox, he/she may get blisters and ulcers on their skin and experience fever and fatigue. If you choose to give your baby the vaccine, his/her chances of getting chicken pox drops significantly, but there are risks involved with getting the vaccine. Specifically, getting this vaccine could result in your baby experiencing adverse effects, such as headaches and a fever. Your baby may also have an allergic reaction to the shot, causing symptoms, such as nausea. Some babies also get rashes at the vaccination site.

Immune disorder: Imagine that you are hospitalized with an immune system disorder that has weakened your immune system and have learned that there is a different hospital in another city that has more expertise treating your condition.

If you choose not to transfer, you may need to have many uncomfortable medical tests and try numerous ineffective treatments while the doctors try to figure out the right treatment. Meanwhile, your condition could become worse, eventually leading to further complications. You will significantly speed up your recovery by transferring to the new hospital where better resources are available, but there are risks involved in the process. Specifically, it means that you would have to leave the isolation ward and expose yourself to viruses and bacteria, putting yourself at risk of infection and even death due to your weak immune system. You may feel uncomfortable leaving the isolation ward after living in a protected environment for so long. Some people also get accidentally injured during such transfers.

Wisdom teeth: You are currently growing wisdom teeth. If you choose not to have them removed, impacted wisdom teeth can cause bleeding and infection in the surrounding tissue and squeeze adjacent healthy teeth, leading them to become crooked and causing damage to surrounding areas. If you choose to have your wisdom teeth removed, you will no longer have to worry about them causing health issues, but the procedure is unpleasant and carries some risk. Specifically, getting your wisdom teeth removed involves potentially painful surgery. Damage to your jawbone, nearby teeth, and nerves can occur during the operation. Some people experience a lot of pain after the anesthesia wears off.

Coronary heart disease: You are experiencing chest pain as a result of a waxy substance, called plaque, reducing the supply of oxygen-rich blood to your heart muscle. If you choose to do nothing, the condition may worsen and you may have frequent difficulty breathing. You also may experience heart failure or an arrhythmia (irregular heart rate), which can cause your heart to stop beating. If you choose to have heart bypass surgery, you will be able to restore a healthy blood-oxygen supply again, but there are risks involved in the surgery. Specifically, because doctors need to operate on your heart, they will need to temporarily stop it, which carries some risks, as they may not be able to restart it in some cases. There could be complications, such as internal bleeding and kidney failure, during the surgery. Some people also experience short-term memory loss after the surgery.

*Participants were given either the breast or prostate cancer scenario depending on their reported gender.

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Data Availability Datasets analyzed for the current study are available from the corresponding author on reasonable request.

Declarations

Conflicts of Interest The authors declare no conflicts of interest.

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