

Risk seeking in naturalistic decision making from a signal detection perspective

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Abstract

Severe weather often requires protective action at low likelihood due to the seriousness of the consequences. However, people often fail to protect when it is warranted to do so, resulting in risk-seeking decisions, even in situations where reliable probabilistic information is present. This study applied signal detection theory to examine whether in these situations, risk-seeking decisions are due to biases in the subjective criterion for taking protective action or due to biases in the perceived likelihood of the weather event. Participants evaluated forecasts to decide whether to take protective action. Two manipulations were of primary interest. First, the economically optimal criterion (likelihood above which one should take protective action) was manipulated to reveal a centering effect. We found that the subjective criterion (likelihood above which one decides to take protective action) was shifted toward 50% regardless of whether the economically optimal criterion was above or below 50%. Second, the framing of the decision as a gain or loss shifted the subjective criterion toward risk-averse (gain) or risk-seeking (loss). However, decisions remained risk-seeking overall. This tendency was not due to a biased perception of likelihood which was unaffected by ^{both} ~~the~~ manipulations. Thus, we conclude that a bias in the subjective criterion, shiftable by the centering and framing effects, contributed to risk-seeking decisions in naturalistic decision tasks. Possible interpretations of these results are discussed along with potential interventions to reduce risk-seeking behavior.

Keywords: Severe Weather Warning; Signal Detection Theory; Risk Perception; Risk Seeking; Decision Criterion

the likelihood of severe weather was above an internal criterion that is higher than the economically optimal criterion (e.g., shelter only when the likelihood of a tornado is 50% or greater as opposed to the recommended 30%). This is referred to as their subjective criterion. Therefore, in the study reported here, we ask whether a higher than optimal subjective criterion, the likelihood above which one decides to take protective action, contributes to the observed risk-seeking tendency. We refer to this as the biased criterion hypothesis.

A high enough subjective criterion could counteract overestimated subjective likelihood and lead to risk-seeking decisions. For example, suppose the probability of the adverse event is 30% and the economically optimal criterion for choosing the safe option is 20%. A person might choose the risky option in this case even if their perceived likelihood is at, say, 40%, if their subjective criterion is at, say, 50%. Therefore, a biased subjective criterion could explain the combination of overestimated subjective likelihood and risk-seeking decisions. A similar explanation has been used for biases in the motivated reasoning literature. For instance, people require more evidence (higher criterion) to be convinced that their preferred conclusion is false compared to the nonpreferred conclusion (Kunda, 1990; Windschitl et al., 2010).

Signal Detection Theory and Decision Making

In the work presented here, a signal detection approach was used to identify the participants' subjective criterion so that it ^{can} ~~could~~ be compared to the optimal criterion. Signal detection theory, typically used to understand perceptual processes, concerns two psychological concepts: 1) Separate internal representations of the strength of the ^{relevant} stimulus and the background ^{relevant} in absence of the stimulus (two distributions in Figure 1), as well as 2) the subjective criterion

representing the strength of the internal representation of the stimulus required by the decision maker to identify it as present (red line in Figure 1; Macmillan & Creelman, 2005).

Both of the internal representations are assumed to be noisy and follow some distribution. Because of this noise, the same stimulus might be internally represented differently each time it occurs. The ability to differentiate internal representations of the stimulus present versus absent is the person's *sensitivity* in stimulus detection. Sensitivity is determined by the distance between the two distributions of the internal representation relative to their variability. The further apart the distributions or the less variability, the greater the sensitivity.

The placement of the subjective criterion ^{at the cut} ~~indicates~~ whether there is a decision bias towards reporting the presence or the absence of the stimulus. Under the same internal representation, a lower subjective criterion leads to an increase in both hits (reporting stimulus is present when it is) and false alarms (reporting stimulus is present when it is not). In contrast, a higher subjective criterion leads to a decrease in both outcomes. In short, a change in subjective criterion can lead to a behavioral change even if the internally represented distributions stay the same. ✓

Assuming stochastic internal representations such as those of signal detection theory is not new to decision theories (Busemeyer & Townsend, 1993; Thurstone, 1994; Wallin et al., 2018) and can account for situations in which one does not necessarily make the same decision based on the same external information. This means that, in the context of weather decision tasks, it can explain situations in which one does not take protective action every time the objective probability is above the economically optimal criterion. Furthermore, signal detection theory can be integrated with behavioral economics theories, such as prospect theory, to better understand decision-making processes ^{e.g.:} (Lynn et al., 2015). Indeed, signal detection theory has ✓

↳ Lynn, Schooler & Engstler, 2011

been applied to diagnostic decisions to identify the economically optimal criterion to increase outcome utility in many domains including medical diagnoses, weather forecasting, and school admissions (Swets et al., 2000). In weather forecasting research, signal detection theory ^{has been} ~~was also~~ ✓ used to distinguish sensitivity and criterion to understand how forecasters make forecasts under different circumstances (Harvey et al., 1992).

Random Likelihood Model

Signal detection theory was applied in this project by assuming a random likelihood model. As illustrated in Table 1, the four outcomes in naturalistic weather decision tasks can be aligned with the four outcomes in signal detection theory (hit, false alarm, miss, correct rejection; Ferrell & McGoe, 1980, Harvey et al., 1992). Here, ~~with a method~~ similar to Ferrell and McGoe (1980), the internal representation was the participant's subjective likelihood estimate of the weather event. The subjective criterion was the subjective likelihood above which the participant decided to take protective action. We assume ^d that the subjective likelihood of the weather event has variability. However, there was no need to assume a specific shape of distribution because subjective likelihood ratings were elicited directly from participants and used to estimate the internal representations. ✓

^{provided} We further assumed that participants' subjective likelihood varied over trials even when the same probabilistic forecast information was ~~provided~~. This assumption is consistent with previous studies using naturalistic decision-making tasks showing that subjective likelihood ratings made by the same participant differed on ~~different trials in which~~ ^{despite being provided} the same well calibrated probabilities were ~~provided~~ (Demnitz & Joslyn, 2020; Gulacsik et al., 2022; Qin et al., 2024). ✓

~~On the other hand,~~ our model assumed no variability in the subjective criterion, consistent with the typical application of signal detection theory (Macmillan & Creelman, 2005). ✓

In other words, we assumed that people chose the safe option whenever their subjective likelihood was above the same subjective criterion every time. This is a simplifying assumption, as ~~people might change their subjective criterion between decisions depending on~~ ^{he} ~~the~~ ^{might be influenced by factors such as} the outcome of previous trials (Demnitz & Joslyn, 2020). ✓

This model can be used to account for biased decision making in several ways that are illustrated in Figure 1. One is shifting the subjective criterion. Shifting the subjective criterion to the right of the optimal criterion can lead to a risk-seeking bias while a left-shifted criterion can lead to a risk-averse bias.

Another way is a change in the ^{part of the} ~~two~~ internal representation distributions on the right of the subjective criterion (hits and false alarms). Larger areas to the right, taking protective action more, represent a risk-averse ~~bias~~ ^{tendency} while smaller areas, taking protective action less, represent a risk-seeking ~~bias~~ ^{tendency}. Inflated subjective likelihood can also cause a shift to the right (in either one or both internal representations: stimulus present and/or absent) leading to a risk-averse ~~bias~~ ^{tendency}. On the other hand, a shift to the left can lead to a risk-seeking ~~bias~~ ^{tendency}.

A change in sensitivity can lead to a change in decisions that is not a bias. Lower sensitivity, an increase in the overlap between the two internal representations, leads to worse decisions compared to economically optimal. This is not a bias necessarily as long as it does not also cause an overall shift in the distributions. To determine whether the manipulations (see sections below) lead to biases as opposed to changes in the overlap of the distributions, we also conducted an analysis of sensitivity.

In sum, the study reported here used the random likelihood model to examine two possible explanations for the tendency toward risk-seeking decisions described above: The biased criterion hypothesis, which is a bias in the subjective criterion, versus the biased likelihood hypothesis, which is a bias in the subjective likelihood.

Possible Psychological Mechanisms of Biases in Subjective Criterion

[Inconsistent with a "mechanism"]

We examined two possible psychological mechanisms that could lead to a shift in the subjective criterion away from the economically optimal criterion. The first is the centering effect, the tendency to bias judgements towards the center of the response range (also called central tendency bias; Poulton, 1979; Olkkonen et al., 2014). Originally observed in perceptual judgements (noise volume, distance, color perception), this effect has been observed in judgement and decision-making tasks such as the estimation of opposing bidders' bid in an auction (Poulton, 1979; Radvansky et al., 1995; Olkkonen et al., 2014). It is possible that a similar effect is present in the subjective criterion in decision-making tasks. It can be revealed by manipulating the economically optimal criterion. For instance, an economically optimal criterion at 20% might result in a subjective criterion above 20% closer to the midpoint of 50%, while an economically optimal criterion at 80% might lead to a subjective criterion below 80%, again, closer to 50%. In addition, ^a the centering effect might also be seen in subjective likelihood.

A second psychological mechanism that could bias the subjective criterion is ~~the~~ gain-loss framing ^{can occur} that is central to prospect theory (Tversky & Kahneman, 1979). Risk-seeking in the loss frame ^{can occur} might function by raising subjective criterion above optimal while risk-aversion in the gain frame ^{can occur} might be due to a lower subjective criterion than is economically optimal. This ^{can} ~~could~~ be revealed by manipulating the frame (loss/gain). These two psychological mechanisms are not mutually exclusive and might both contribute to a biased subjective criterion.

Overview of Analyses and Experiments

To begin, two previously published experiments from Qin et al., (2024) were reanalyzed ^{investigate} to ~~test~~ the random likelihood model and to detect possible framing and/or centering effects in subjective criterion or subjective likelihood. Then, two new naturalistic weather decision

these conditions were not the concern of the analysis reported here, they were combined. There were 83 participants from Experiment 1 and 85 from Experiment 2 in the reanalyses. *per participant* ✓

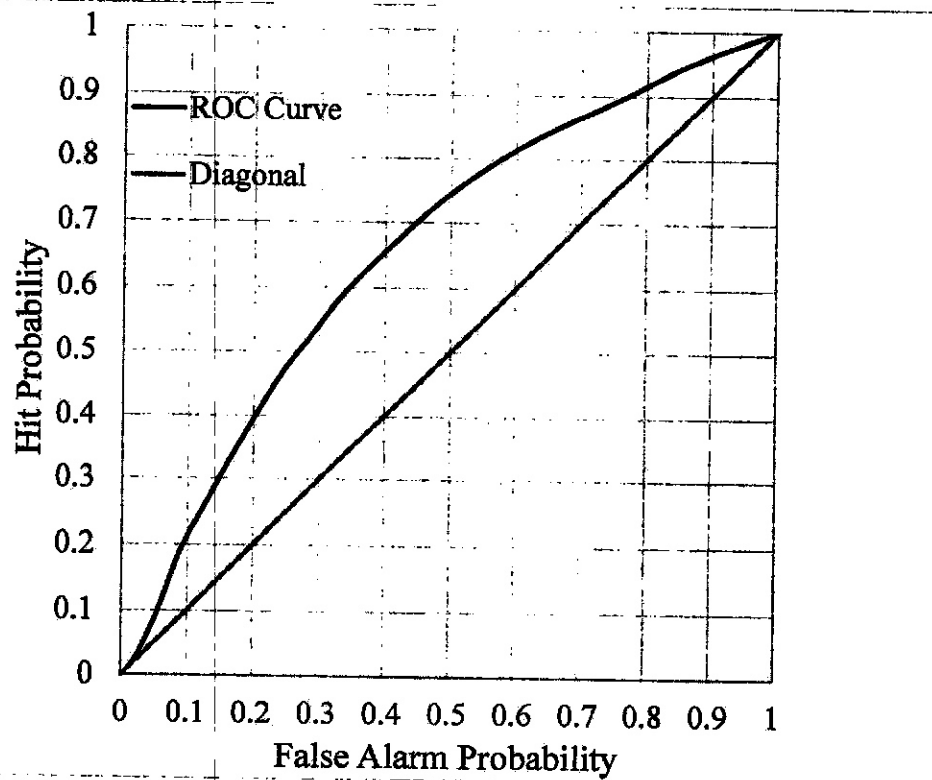
The procedure of the two experiments was identical. There were 68 trials ~~in total~~. On each trial, participants saw a tornado warning, rated how likely they thought a tornado would occur (likelihood ratings), and decided between the safe option and the risky option (binary decision). At the end of each trial, they were told whether the tornado occurred. As mentioned above, there was a point cost to shelter and a larger point penalty if participants failed to shelter and a tornado hit their location. Therefore, only losses were possible. Participants' goal was to lose as few points as possible by the end of the experiment.

The main difference between the two experiments was the cost of the safe option (see Table 2). In both experiments, the risky option had no cost but would incur a 1,000-point penalty *in itself* ✓ if a tornado hit. Participants could mitigate this loss completely by choosing the safe option for 90 points in Tornado Experiment 1 and 270 points in Tornado Experiment 2. *This yields an* ~~Therefore, the~~ economically optimal criterion ~~was~~ *of* 9% in Tornado Experiment 1 and 27% in Tornado Experiment 2. Another difference was that in Tornado Experiment 1, 23.5% of trials resulted in a tornado, while in Tornado Experiment 2 ~~the proportion~~ *it* was 38.2%.

Results

Three sets of analyses were conducted for each experiment. Analyses were conducted on mean subjective criterion and mean likelihood ratings to detect biases. In addition, sensitivity, operationalized as the area under curve in Receiver Operating Characteristic (ROC) plots, was analyzed. In order to test the assumption that subjective likelihood and subjective criteria jointly determined decisions, ROC plots were constructed from participants likelihood ratings and *to test that* decisions ~~on~~ *to test that* internal consistency ~~was~~ *it* (see Figure 2). T-tests were conducted comparing the

Figure 2
A Typical ROC Curve



Note. The y axis is the probability of a hit and the X axis is the probability of a false alarm. A lower criterion is indicated by an increase in the probability of both a hit and a false alarm, following the blue curve from bottom left to upper right.

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Subjective Criterion

The subjective criterion was estimated using each participant's likelihood ratings and proportion of trials on which they chose the safe option. The assumption was that participants chose the safe option whenever their subjective likelihood was higher than their subjective criterion. Thus, for each participant, a ~~percentage~~ ^{value} X% was determined such that the cumulative proportion of likelihood ratings falling between X% ~~of trials~~ ^{value} and 100% matched the proportion of trials on which the participant chose the safe option. The likelihood at the end point (X%) is referred to as the *subjective criterion*. For example, if a participant chose the safe option on 57% of the trials, a ~~number~~ ^{value} was located on their likelihood rating distribution such that 57% of the trials had a likelihood rating higher than that ~~number~~ ^{value} (Figure 3). This number, say 51% likelihood (the red line in Figure 3), was the subjective criterion for this participant. With this method, a subjective criterion was obtained for each participant, and a mean was calculated for each experiment.

as a function of
 In Figure 4, the mean subjective criterion for each experiment is shown as a blue dot ~~in relation~~ ^{for that experiment.} to the economically optimal criterion. An independent t-test revealed that the mean subjective criterion in Tornado Experiment 1 ($M = 31.0\%$, $SD = 18.6\%$) was significantly lower than in Tornado Experiment 2 ($M = 41.2\%$, $SD = 13.8\%$) with a difference of -10.2% (95% CI -15.2% , -5.3% ; $t(148.6) = 4.07$, $p < .001$, Hedge's $g = .62$). This suggests that the subjective criteria were influenced by the different economically optimal criteria in each experiment.

In addition, the mean subjective criterion in each experiment was directly compared to the economically optimal criterion in that experiment using one-sample t-tests. In both cases the mean subjective criterion was higher than the economically optimal criterion. In Tornado Experiment 1, the subjective criterion ($M = 31.0\%$) was significantly higher than the economically optimal criterion of 9% with a difference of 22% (95% CI 18.0% , 26.1% ; $t(82) = 10.77$, $p < .001$, Cohen's $d = 1.18$). In Tornado Experiment 2, the subjective criterion ($M = 41.2\%$) was also significantly higher than the economically optimal criterion of 27% with a difference of 14.2% (95% CI 11.4% , 17.1% ; $t(84) = 9.81$, $p < .001$, Cohen's $d = 1.03$). Thus, the subjective criterion was higher than the economically optimal criterion in both experiments, suggesting the subjective criterion was biased to result in risk-seeking decisions. Moreover, the bias was larger in the experiment with the lower economically optimal criterion.

Likelihood Ratings

In each experiment, one-sample t-tests were used to compare the mean likelihood rating (over all trials with differing probability levels) to the mean objective probability, operationalized as the proportion of trials in which a tornado occurred in that experiment¹. In both experiments

¹ This is equivalent to the mean objective probability which was reliable.

Receiver Operating Characteristic Plots

The ROC analysis was conducted to test the assumption of the random likelihood model that subjective likelihood and the subjective criterion jointly determine the decision. The graphs in Figure 6 were composed of two parts: 1) ROC curves 2) Points indicating the hit and false alarm rates of decisions in each experiment. For a similar approach see Harvey et al. (1992). The calculation of each is explained below. ✓

The ROC curves represent the relationship between the estimated hit and false alarm probabilities at hypothetical cut-off points. ^{of the distribution of likelihood ratings.} These cut-off points occur at 5% intervals on the likelihood rating distribution from 0% to 100% (similar to Ferrel & McGoeys, 1980). A hit was defined as a trial with a likelihood rating above the cut-off and a tornado. The hit probability was the proportion of tornado trials above that likelihood cut-off. A false alarm was a trial with a likelihood rating above the hypothetical cut-off and no tornado. The false alarm probability was the proportion of trials without a tornado above the likelihood cut-off. By varying the cut-off in 5% steps from 0% to 100%, a pair of hit and the false alarm probabilities was calculated at each step (20 total) and plotted as the ROC curve in Figure 6. As 68 trials per participant were too few data points to populate 20 steps to create participant level ROC curves, trials from all participants were combined to create a single ROC curve for each experiment.

Next, ~~a data point for each experiment~~ ^{representing the} based on participants' binary decisions ~~was~~ added to the appropriate ROC plot. It indicates the mean proportion of hits (the participant chose the safe option and the tornado occurred) and false alarms (participant chose the safe option and no tornado occurred) in that experiment.

The first goal of the ROC analysis was to test the internal consistency of the random likelihood model method of calculating the subjective criterion. If participants chose the safe

Discussion

In the reanalyses presented above, participants' subjective criterion was higher than the economically optimal criterion in both experiments, indicating a risk-seeking tendency. This analysis does not distinguish whether the bias was due to framing, centering or something else. Both experiments employed a loss frame which tends to lead to risk-seeking behavior. Neither tested a gain frame that would theoretically have produced a risk-averse bias. In addition, the subjective criterion in both experiments was elevated bringing them closer to 50%, consistent with the centering effect. However, neither tested a criterion that was higher than 50% which, according to centering, would have lowered the subjective criterion creating a risk-averse bias. Therefore, it is not possible to distinguish between these two explanations. Hence in the new experiments reported in the next section, the appropriate conditions were added to distinguish between the effects of gain-loss framing and centering.

The reanalysis presented above also suggests that the risk-seeking tendency observed in these two experiments was not due to biased subjective likelihood. The mean likelihood rating was significantly over- rather than underestimated and similar in both experiments. Nevertheless, the higher-than-optimal subjective criterion counteracted the overestimated likelihood ratings and led to risk-seeking decisions².

Finally, in the ROC plots of both experiments, the 95% confidence interval of the binary decision point overlapped with the ROC curve. This indicates that the proportion of hits and false alarms based on participants' binary decisions was consistent with the ROC curve of hits and false alarms based on likelihood ratings. This in turn suggests that the subjective criterion and

² Due to different trial compositions in the two experiments, one cannot draw conclusions about the effect of different economically optimal criterion on likelihood ratings.

Participants were first provided with instructions. In the task, henceforth called the *drought task*, participants played the role of an agricultural consultant who advised farmers on whether to plant a drought-resistant crop (safe option) or a regular crop (risky option) based on a drought forecast for the upcoming season. Participants were told that a potential drought might lead to a loss for farmers reflected in a point loss for participants, compared to non-drought seasons. They were then introduced to the point structure that tracked the outcomes of their decisions (see below).

that plant the regular crop ✓

Point Structure. The purpose of the point structure was to simulate real life decisions with consequences and to encourage participants to put forth their best effort (See Table 3). It also allowed us to establish and manipulate the optimal criterion. In all conditions participants were endowed with a starting balance of 20,000 points. There were three economically optimal criterion conditions (eoc): 25% (25eoc), 50% (50eoc), and 75% (75eoc). In all conditions the regular crop (risky option) cost 0 points but resulted in a loss of 400 points if there was a drought. The drought resistant crop (safe option) was available at a cost of 100, 200 and 300 points in the 25eoc, 50eoc, and 75eoc conditions, respectively resulting in three different optimal criterion (See table 3). The economically optimal criterion in each condition was the probability where the expected values of the two options broke even (e.g., in the 25eoc condition: $400 \times 25\%$ (risky option) = 100 (safe option)). At the end of the experiment participants were paid a monetary bonus commensurate with their ending point balance. Participants' goal was to lose as few points as possible.

The bonus payment structure was set up to make the bonus roughly equivalent in the three conditions. In the 25eoc condition, participants were paid \$1 for every 1,000 points in their balance above a payment threshold of 15,000 points. In the 50eoc condition, participants were

paid \$1 for every 2,000 points in their balance above 10,000 points. In the 75eoc condition, participants were paid \$1 for every 3,000 points in their balance above 5000 points. Payment thresholds were designed to discourage taking the simplistic approach of choosing the safe option in every single trial. For example, in the 25eoc condition, if they chose the safe option in all 50 trials, they would end up with 15,000 points ($20,000 - 50 * 100$).

Trial Structure. After reading the instructions, going through a practice trial, and answering two attention check questions (See Supplementary Materials), participants began the 50 experimental trials. Each trial comprised three screens. On the first screen, participants saw a forecast which described the drought probability for that trial (e.g., “The latest climate forecast indicates a 35% chance of drought in the upcoming season for farmer-client 1”). We refer to this as the *objective probability* because it was calibrated to be roughly reliable: The mean objective probability ($M = 36.5\%$) ^{roughly} matched the proportion of droughts across the 50 trials (36%). Objective probability had five within-subject levels: 20%, 35%, 50%, 65%, and 80% (see Supplementary Materials S2). Each level was also calibrated. The trial order was randomized for each participant. ✓

Participants then rated drought likelihood by moving the slider on a visual analog scale (VAS) with anchor points *impossible* and *certain* (likelihood rating). On the second screen, participants saw the same forecast again and chose the crop they wished to plant by pressing one of the two buttons (binary decision) labeled “Regular Crop: A loss of 0 points if there is no drought; A loss of 400 if there is a drought” (25eoc example) and “Drought Resistant Crop: A loss of 100 points regardless of drought.” Then, the third screen showed the outcome of the trial in terms of point deductions.

manipulation of the economically optimal criterion should not affect subjective likelihood or sensitivity.

The same set of dependent measures as those used in the reanalyses reported above were analyzed in Experiment 1. These included the subjective criterion and ^{mean} likelihood ratings. As the trial compositions were kept the same across the conditions, an analysis of sensitivity (area under the ROC curve) was conducted to examine whether sensitivity changed due to the manipulation. For all dependent variables, a series of ANOVAs and t-tests were conducted. Holm-Bonferroni Method was used for planned and post hoc t-tests as well as planned pairwise comparisons under omnibus ANOVAs. Tukey method was used for post hoc pairwise comparisons under omnibus ANOVAs. All tests were two-tailed where applicable. ✓

Subjective Criterion

In Figure 7, the subjective criterion for 25eoc, 50eoc, and 75eoc conditions is shown as blue dots. The mean subjective criterion was 35.0% (SD = 13.3%) in the 25eoc condition, 48.4% (SD = 15.9%) in the 50eoc condition, and 58.1% (SD = 15.3%) in the 75eoc condition. An ANOVA on the subjective criterion with economically optimal criterion (25eoc, 50eoc, and 75eoc) as the independent variable showed a main effect ($F(2,154) = 32.53, p < .001, \eta_p^2 = .30$), suggesting that participants' subjective criterion increased with the economically optimal criterion. In planned pairwise comparisons the 50eoc condition had a significantly higher subjective criterion than the 25eoc condition with a difference of 13.4% (95% CI 7.6%, 19.2%; $t(154) = 4.54, p < .001$, corrected alpha = .025, Hedge's $g = 0.91$). The 75eoc condition had a significantly higher subjective criterion than the 50eoc condition with a difference of 9.7% (95% CI 4.0%, 15.5%; $t(154) = 3.30, p = .001$, corrected alpha = .05, Hedge's $g = 0.62$).

see

In addition, the pattern of self-reported criterion (Supplementary Materials S3) was consistent with that of the subjective criterion, although the self-reported criterion was pulled towards 50% to a greater extent than the subjective criterion in the 25eoc condition. In addition, the pattern of the proportion of safe option choices was also consistent with the estimated subjective criterion. The proportion of safe choices was lower than economically optimal proportion (risk-seeking) in the 25eoc condition, not different from economically optimal (risk-neutral) in the 50eoc condition, and higher than economically optimal (risk-averse) in the 75eoc condition.

Likelihood Ratings

Figure 8 shows mean likelihood ratings by eoc condition as a function of objective probabilities. To determine whether the centering effect was observed in perceived likelihood, an ANOVA was conducted on mean likelihood ratings collapsed over objective probability levels with the economically optimal criterion manipulation as the independent variable (25eoc, 50eoc, and 75eoc). It failed to reach significance ($F(2,154) = 0.81$, $p = .45$, $\eta_p^2 = .01$). Mean likelihood ratings were similar across conditions (25eoc: 37.1%, SD = 7.0%; 50eoc: 39.3%, SD = 11.9%; 75eoc: 37.8%; SD = 7.1%).

To assess likelihood rating accuracy, post hoc one-sample t-tests compared the mean likelihood rating in each eoc condition with the proportion of drought trials (36%). None of the three differences reached significance (25eoc: 1.1%, 95% CI -0.8%, 3.0%; $t(53) = 1.16$, $p = .25$, Cohen's $d = 0.16$); 50eoc: 4.3%, 95% CI -0.1%, 6.7%; $t(48) = 1.94$, $p = .06$, corrected alpha = .017, Cohen's $d = 0.28$); 75eoc: 1.8%, 95% CI -0.1%, 3.8%; $t(53) = 1.88$, $p = .07$, corrected alpha = .025, Cohen's $d = 0.25$). This suggests that the likelihood ratings were fairly accurate,

unaffected by the manipulation of economically optimal criterion and each closely follows the objective probability. ~~In summary, as shown~~ In summary, as shown ~~In addition, as seen in Figure 8,~~ the three conditions had similar mean likelihood rating patterns. Likelihood ratings were slightly overestimated at all objective probability levels except for 35%. ✓

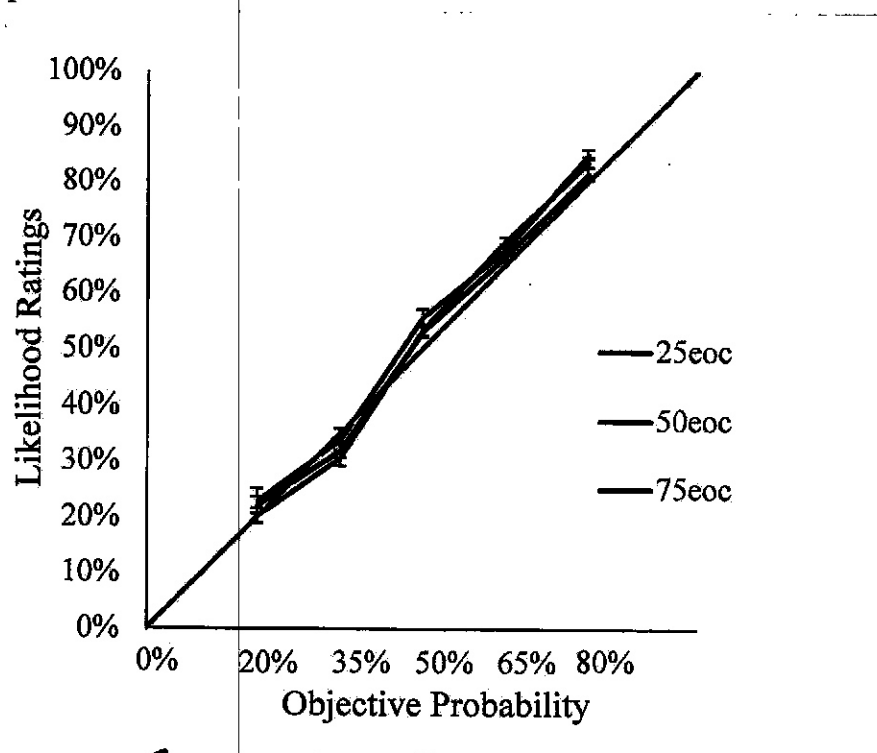
ROC Plots and Sensitivity

Figure 9 shows ROC plots for the 25eoc, 50eoc, and 75eoc conditions. ~~Notice that the~~ Notice that the dots representing the mean binary decisions fell on the ROC curve in all three conditions, validating the assumption of our analyses that decisions were indeed based on subjective likelihood and subjective criterion.

In addition, the ROC curves of the three conditions were similar, indicating that all conditions had similar sensitivity (area under the curve). The mean percent area under ROC curve was 71.2% (SD = 5.0%) in the 25eoc condition, 70.3% (SD = 5.5%) in the 50eoc condition, and 70.6% (SD = 5.4%) in the 75eoc condition. An ANOVA on the mean percent area under curve, with the economically optimal criterion as the independent variable (25eoc, 50eoc, and 75eoc) failed to reach significance ($F(2,154) = .043$, $p = .65$, $\eta_p^2 = .01$). This suggests that the economically optimal criterion manipulation had no observed effect on the sensitivity.

Figure 8

Mean Likelihood Ratings by eoc condition, as a Function of Objective Probability in Experiment 1



were similar.



Note. ~~the similar patterns~~ between lines representing different eoc conditions. Also ~~note~~ that, when comparing the lines representing eoc conditions with the identity line, there is no centering effect (lower end is much higher than identity while the higher end is much lower). Error bars show standard errors of the mean.

Discussion

Experiment 1 tested two predictions based on the hypothesis that risk-seeking is due to a shift in subjective criterion and that it shows a centering effect: 1) the subjective criterion shifts away from the optimal criterion towards 50%; 2) Likelihood ratings are unaffected by the change in criterion. Supporting the first prediction, the subjective criterion was between 25% and 50% in the 25eoc condition (a shift up towards 50%), and between 50% and 75% in the 75eoc condition (a shift down towards 50%). Meanwhile there was little shift in the 50eoc condition. These results were corroborated by analyses of self-reported criterion and the proportion of trials choosing the safe option in which similar patterns were observed. Thus, ~~in this loss-framed task~~ ✓ when compared with the optimal criterion, participants were risk-seeking in the 25eoc condition, risk-neutral in the 50eoc condition, and risk-averse in the 75eoc condition. In addition, as predicted by the biased criterion hypothesis, there was no evidence that manipulating the economically optimal criterion affected the likelihood ratings, ruling ^{out the} biased subjective likelihood ~~as~~ ✓ an explanation for participants biased choices.

Next, the ROC plots (Figure 9) supported the method for calculating participants' subjective criterion. The binary decisions plots were consistent with the ROC curves in each condition, suggesting that the subjective criterion and the subjective likelihood were the sole determinants of the binary decisions. Moreover, sensitivity was unaffected by manipulating the economically optimal criterion.

In summary, Experiment 1 yielded support for the hypothesis that manipulating the economically optimal criterion impacts the subjective criterion but not subjective likelihood or the sensitivity.

Experiment 2

Design

Experiment 1 used a 2 x 2 x 6 mixed design. There were two between-groups independent variables: Economically optimal criterion with two levels: 25eoc, and 50eoc and gain-loss framing with two levels: Gain and loss frame. There was one within-group independent variable: objective probability of a drought with five levels: 20%, 35%, 50%, 65% and 80%.

Results

Analysis Overview

As with Experiment 1, we expected the results to indicate a biased subjective criterion due to gain-loss framing and/or centering effects. The effect of framing is supported if there is a higher subjective criterion in the loss than in the gain frame condition, signaling a greater risk-seeking tendency. As with Experiment 1, the centering effect should shift the subjective criterion in the 25eoc condition up towards 50% while having no effect on the subjective criterion in the 50eoc condition. No interaction between these two effects was expected as their mechanisms are theoretically independent. Neither manipulation was expected to affect likelihood ratings or sensitivity. All tests were two-tailed where applicable.

Subjective Criterion

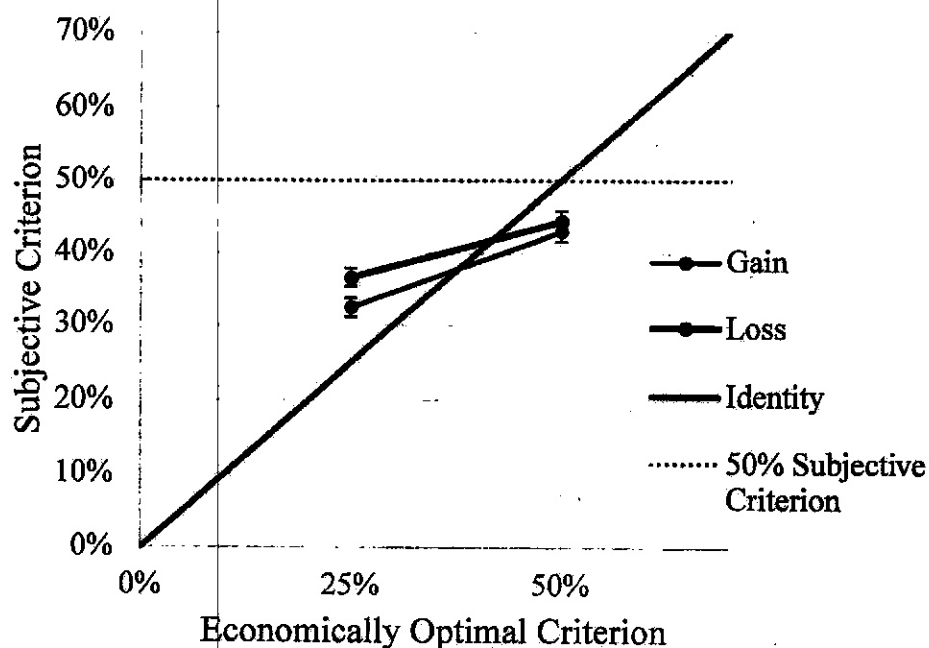
Panel A of
 Figure 10 shows the subjective criterion for the four conditions. An ANOVA on the subjective criterion with the gain-loss framing (gain frame, loss frame) and economically optimal criterion (25eoc, 50eoc) revealed a main effect of the gain-loss framing manipulation such that in the loss frame ($M = 40.6\%$, $SD = 15.9\%$) the subjective criterion was 2.7% higher than in the gain frame ($M = 37.9\%$, $SD = 16.9\%$) as predicted by prospect theory ($F(1, 554) = 4.38$, $p = .037$, $\eta_p^2 = .01$). There was also a main effect of manipulating the economically optimal

In summary, both manipulations affected the subjective criterion and they did not significantly interact with one another. While the subjective criterion in the 25eoc condition was higher than the economically optimal criterion as predicted, the subjective criterion in the 50eoc condition was unexpectedly lower than the economically optimal criterion.

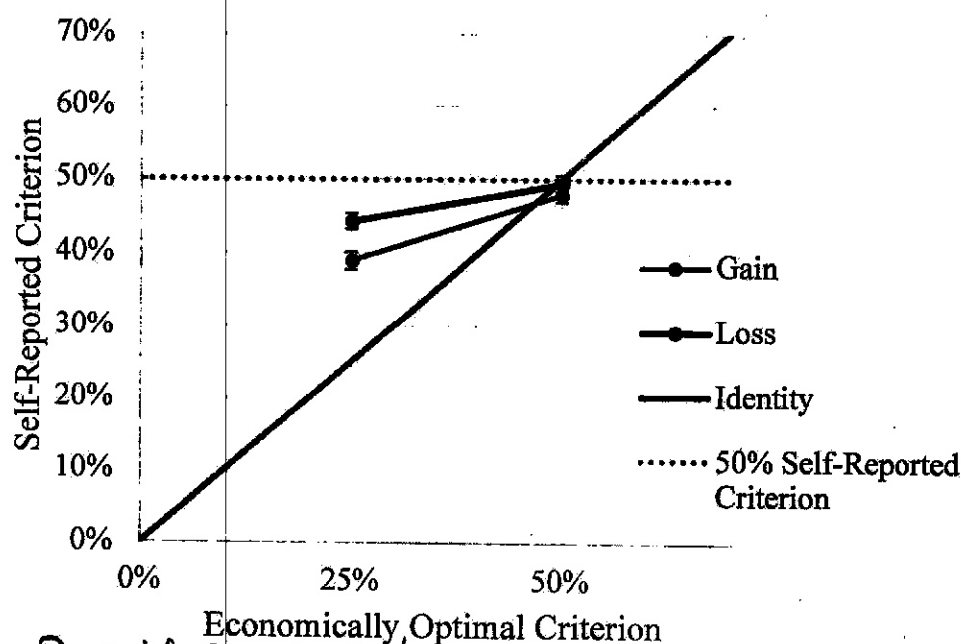
In addition, like Experiment 1, the pattern of self-reported criterion (See Figure 10) and proportion choosing the safe option was consistent with the pattern of results for the subjective criterion (Supplementary Material S4).

Panel 10

Figure 10
Subjective and Self-Reported Criterion in the Four Conditions of Experiment 2



3. A. Subjective Criterion Result



B. Self Reported Criterion

Note. The y axis represents the subjective criterion (panel A) or the self-reported criterion (panel B) while the x axis represents the economically optimal criterion. The grey diagonal line represents when the subjective criterion is the same as the economically optimal criterion. The grey dashed line represents a subjective criterion of 50%. Error bars show standard errors of the mean.

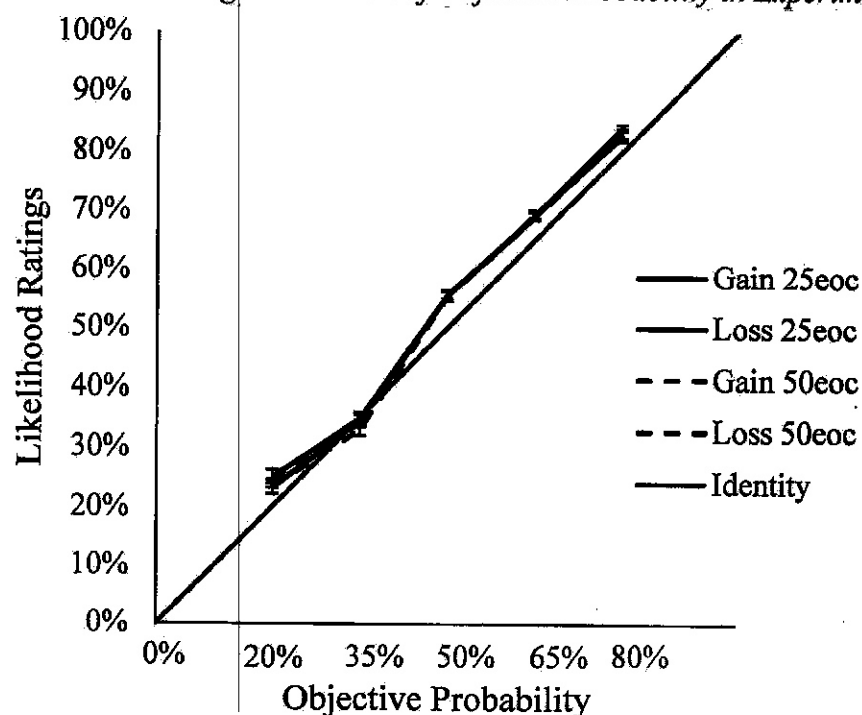
Likelihood Ratings

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Figure 11 shows mean likelihood ratings as a function of objective probabilities in the four conditions. An ANOVA on the mean likelihood ratings collapsed over objective probability levels with the gain-loss framing and economically optimal criterion manipulation (25eoc, 50eoc, and 75eoc) as the independent variables, revealed that mean likelihood ratings were similar across conditions. The difference in mean likelihood ratings in the gain ($M = 39.9\%$, $SD = 10.0\%$) and in the loss frame ($M = 40.0\%$, $SD = 10.3\%$) conditions failed to reach significance ($F(1, 554) = .017$, $p = .68$, $\eta_p^2 < .001$). Similarly, the difference in mean likelihood ratings in the 25eoc ($M = 40.1\%$, $SD = 9.2\%$) and 50eoc ($M = 39.8\%$, $SD = 10.9\%$) conditions failed to reach significance ($F(1, 554) = 0.23$, $p = .64$, $\eta_p^2 < .001$). The interaction failed to reach significance ($F(1, 554) = 0.36$, $p = .55$, $\eta_p^2 < .001$).

In addition, four post hoc one-sample t-tests compared the mean likelihood rating in each condition to the proportion of drought trials (36%). In all conditions, the mean likelihood rating was slightly but significantly higher than 36%. Thus, likelihood ratings were overestimated compared to the proportion of drought trials and unaffected by either the gain-loss framing or the economically optimal criterion manipulation.

Figure 11
Likelihood Ratings a Function of Objective Probability in Experiment 2



Note. The likelihood ratings increased with objective probability levels but were unaffected by the manipulation of eoc or framing. Note the similar patterns between lines representing different eoc and framing conditions. Also ~~note that~~, when comparing the lines representing eoc conditions with the identity line, there is no centering effect. Error bars show standard errors of the mean.

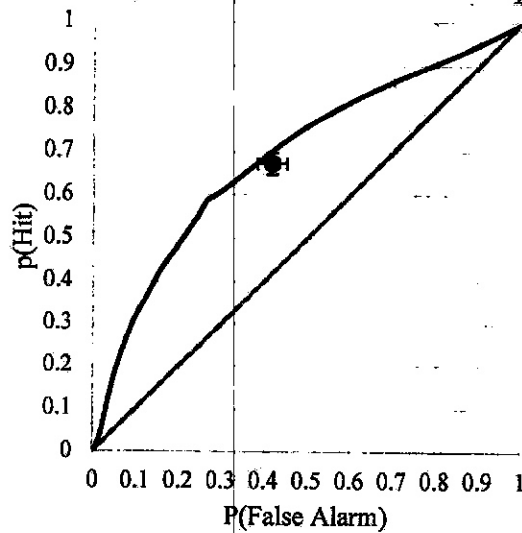
ROC Plots and Sensitivity

The next analysis examined sensitivity, as measured by the area under the ROC curve.

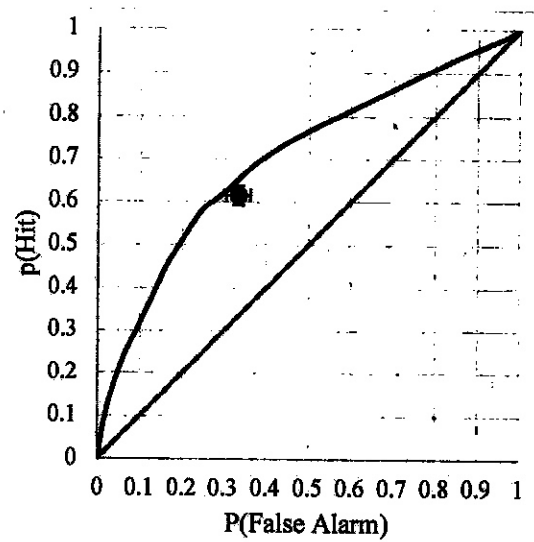
95, 114, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845, 846, 847, 848, 849, 850, 851, 852, 853, 854, 855, 856, 857, 858, 859, 860, 861, 862, 863, 864, 865, 866, 867, 868, 869, 870, 871, 872, 873, 874, 875, 876, 877, 878, 879, 880, 881, 882, 883, 884, 885, 886, 887, 888, 889, 890, 891, 892, 893, 894, 895, 896, 897, 898, 899, 900, 901, 902, 903, 904, 905, 906, 907, 908, 909, 910, 911, 912, 913, 914, 915, 916, 917, 918, 919, 920, 921, 922, 923, 924, 925, 926, 927, 928, 929, 930, 931, 932, 933, 934, 935, 936, 937, 938, 939, 940, 941, 942, 943, 944, 945, 946, 947, 948, 949, 950, 951, 952, 953, 954, 955, 956, 957, 958, 959, 960, 961, 962, 963, 964, 965, 966, 967, 968, 969, 970, 971, 972, 973, 974, 975, 976, 977, 978, 979, 980, 981, 982, 983, 984, 985, 986, 987, 988, 989, 990, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000

See Figure 12. In an ANOVA on the mean percent area under the curve with the gain-loss framing (gain frame, loss frame) and economically optimal criterion (25eoc, 50eoc) as the independent variables, neither the main effect of gain-loss framing ($F(1, 554) = 0.51, p = .47, \eta_p^2 < .001$) nor that of economically optimal criterion reached significance ($F(1, 554) = 1.93, p = .17, \eta_p^2 < .01$). The interaction also failed to reach significance ($F(1, 554) = 0.94, p = .33, \eta_p^2 < .01$). This suggests that sensitivity was not affected by the manipulation of gain-loss framing or economically optimal criterion. The mean percent Area under ROC curve was 70.0% (SD = 8.1%) in the 25eoc gain, 71.1% (SD = 5.2%) in the 25eoc loss, 69.8% (SD = 7.6%) in the 50eoc gain, and 69.6% (SD = 6.9%) in the 50eoc loss condition. In addition, the 95% confidence interval of binary decisions overlapped with the ROC curves in all but the 50eoc gain frame condition suggesting that participants' decisions can be explained by the combination of subjective likelihood and subjective criterion.

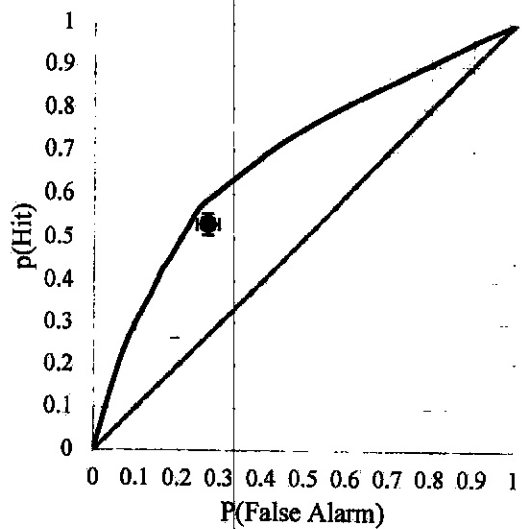
Figure 12
ROC Plot for the Four Conditions in Experiment 2



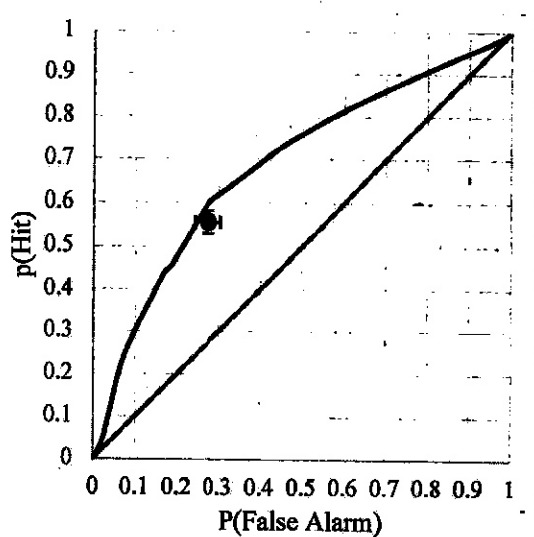
A) 25eoc Gain Condition



B) 25eoc Loss Condition



C) 50eoc Gain Condition



D) 50eoc Loss Condition

Note. The y axis represents the probability of hits. The x axis represents the probability of false alarms. The orange dot indicates the proportion of hits and false alarms for each experiment based binary decisions. Error bars show standard errors of the mean.

Discussion

Experiment 2 tested the hypotheses that two mechanisms lead to a biased criterion but not biased subjective likelihood: 1) Centering, in which the subjective criterion migrates toward the center of the range (50%). 2) Gain-loss framing, in which the subjective criterion tends to be higher in the loss than in the gain frame. Both effects were observed and did not significantly interact with one another. Nor did they impact likelihood ratings.

The mean subjective criterion was higher than 25% in the 25eoc condition suggesting movement toward the center (50%). The difference between the subjective criterion and the economically optimal criterion was greater in the 25eoc condition than in the 50eoc condition where little movement was expected. Interestingly, the subjective criterion in the 50eoc condition was slightly but significantly lower than 50%. This is corroborated by the proportion of safe choices in the 50eoc condition, where participants tended to be risk-averse (Supplementary Materials S3). This result was also consistent with the trend in proportion of safe choices observed in Experiment 1. This could mean either that the center was slightly lower than 50%, or other factors shifted the subjective criterion down. ✓

There was also evidence of a framing effect. The subjective criterion in the loss frame condition was significantly higher than that in the gain frame condition. This resulted in participants choosing the safe option less often and showing a risk-seeking decision bias in the loss compared to the gain frame.

It is also interesting that the effect sizes for the two manipulations differed in the 25eoc condition which is most similar to real world situations for which precautions are warranted for low-probability high-impact weather events. Gain-loss framing shifted the subjective criterion by 4.2% in the 25eoc condition while the centering effect shifted the subjective criterion to 9.5%

above 25%. Therefore, at the 25% economically optimal criterion, the centering effect had a larger impact on the subjective criterion than the gain-loss framing effect, which may have implications for applied communication interventions.

Consistent with Experiment 1, the likelihood ratings were not affected by manipulating economically optimal criterion. This experiment also found that the likelihood ratings were not affected by gain-loss framing. In addition, they were overestimated in all conditions compared to the objective probabilities as shown in Figure 11. However, this small amount of overestimation, which should lead to risk aversion all else being equal, was not enough to overpower the centering and framing effects on subjective criterion leading to risk seeking. This is also consistent with Experiment 1 and prior research that suggests that biased subjective likelihood did not contribute to the risk-seeking behavior observed in the loss frame.

In the ROC plots, the binary decisions (summarized by proportion of hits and false alarms in decisions) were consistent with the respective ROC curves (from likelihood ratings conditionalized by drought occurrence) in almost all conditions, suggesting that decisions were jointly determined by subjective likelihood and subjective criterion. In the 50eoc gain frame condition alone, which was not tested in previous experiments, the binary decisions were below the ROC curve. This is the only inconsistency in the ROC analysis observed across both experiments. It is unknown whether this inconsistency was a statistical false negative or whether there were some unknown effects on participants' behavior in this condition. In addition, the sensitivity was not affected by either manipulation.

General Discussion

In naturalistic task requiring decision-making under risk, people often make decisions that incur more risk than is normatively optimal. The research reported here used a novel signal detection theory approach to examine some of the psychological reasons for this phenomenon.

Summary of Results

Using participants' decisions and subjective likelihood ratings for an adverse weather event, we estimated their subjective criterion for taking a protective action. There were four main results.

1) Manipulating both economically optimal criterion and gain-loss frame significantly affected the subjective criterion but not subjective likelihood. Thus, these results are consistent with the hypothesis that risk-seeking is due to a biased subjective criterion and reject the hypothesis of a biased subjective likelihood.

2) Experiment 1 demonstrated, for that first time, that manipulating the economically optimal criteria revealed a centering effect on the subjective criterion. Specifically, the subjective criterion moved toward 50% relative to the economically optimal criterion. This occurred whether the economically optimal criterion was above or below 50%.

3) In Experiment 2, the manipulation of framing resulted in a shift of the subjective criterion that was consistent with greater risk-seeking with a loss compared to a gain frame. The framing effect was smaller than the centering effect in the key conditions that required protective action at the ^{low} a likelihood of an adverse event (25%).

4) The internal consistency of the proposed random likelihood model was verified in both the reanalysis of previously published experiments and the two new experiments. This supports the key assumptions of the random likelihood model.

lower than 50%. In Experiment 1, the subjective criterion in the 75 economically optimal criterion condition shifted downward to a greater extent than the subjective criterion shifted upward in the 25 economically optimal criterion condition. In Experiment 2, the subjective ~~criterion~~ ^{and off} in both the gain and loss frame 50 economically optimal criterion conditions were significantly lower than 50%, at 43% and 44%, respectively. One possible explanation is that participants' preconceived notion of severe weather events was that the potential harm is much greater than the cost of protection to take action. Therefore, they adopted a criterion that was slightly lower than 50% as such a criterion was consistent with their preconceived notion.

A potential mechanism for the centering effect is anchoring and adjustment (Kahneman, 2003). When people estimate an unknown quantity, they sometimes start with a number recently encountered and then adjust away from that anchor to make their estimate. The adjustment is often insufficient. In the case of the centering effect observed in the experiments reported here, it is possible that the center of the range of possible probabilities (50%) was an anchor from which adjustment was insufficient. Alternatively, it might be that participants intentionally shifted the subjective criterion toward the center of the likelihood range to avoid extreme decisions. This is similar to the compromise effect observed in decision making (Simonson, 1989).

The centering effect did not appear in subjective likelihood in the reanalyses or new experiments reported here. Perceptual studies suggest that when good information regarding the correct response is available, the centering effect is reduced (Radvansky et al., 1995). In the current experiments, reliable probabilistic information was provided in each forecast, perhaps overpowering the influence of centering on subjective likelihood. Indeed, in control conditions of previous studies in which probabilities were not provided, effects consistent with centering were observed such that the mean likelihood ratings were close to 50% (Demnitz & Joslyn, 2020; Qin

[cut this or also mention in prev sections?] ⁶²

et al., 2024). However, when probabilities were provided, the centering effect on subjective likelihood disappeared.

The Gain-Loss Framing Effect

In Experiment 2, framing was manipulated. Consistent with prospect theory (Kahneman & Tversky, 1979), the subjective criterion was higher, that is more risk-seeking, for a loss compared to a gain. However, with a 25% economically optimal criterion in the gain frame, the subjective criterion was also risk-seeking, although less so than with a loss. Similar patterns were observed in the shift in self-reported criterion and the proportion of trials choosing the safe option, corroborating this analysis. This suggests that a shift in the subjective criterion mediates risk-averse tendencies observed here.

However, the effect size of gain-loss framing in this study was small (only 3% difference at 25% economically optimal criterion) in comparison to classic experiments in prospect theory. For example, in the disease problem (Tversky & Kahneman, 1981), in a loss frame a quarter of participants chose the safe over the risky option while in a gain frame three quarters chose the safe over the risky option. There are two potential explanations. First, the multi-trial nature of the experiments reported here might have led participants to consider the big picture as opposed to one trial at a time (narrow framing) when making decisions. When considering a series of risky decisions together instead of each trial independently, people are better able to consider the long term strategies that underly an appreciation of expected value (Thaler, 1999) and are less susceptible to the effects of gain-loss framing as a result. An alternative explanation is that in classic prospect theory experiments, the expected values of the safe and risky options were the same or similar. In the experiments reported here, the expected value of the risky option might

differ drastically from that of the safe option and varied trial by trial. Therefore, it was possible that the gain-loss framing effect became less salient when the expected values varied widely.

Random Likelihood Model

This work introduces a new application of signal detection theory, the random likelihood model. It is based on the assumption that subjective likelihood and a subjective criterion alone determined participants' decisions. Our approach is different from previous applications of signal detection theory in two ways. First, it introduces variability into the representation of likelihood rather than utility. This is realized in the current experiments by varying likelihood from trial to trial and holding the cost of the safe choice constant. Second, rather than assuming a normal distribution for the internal representation of likelihood, we use the observed distribution of the likelihood ratings *combined with the* ~~along side~~ binary decisions to estimate the subjective criterion. This is viable for these decision-making tasks in which participants found it relatively easy to report aspects of their decision.

this model
To validate ~~these assumptions~~, ROC plots were calculated from likelihood ratings conditionalized by whether or not there was a drought. In 6 out of 7 cases the participants' binary decisions (proportion of hits and false alarms in decisions) were consistent with the ROC curve based on the likelihood ratings. This supports the validity of this approach which isolates the effects of subjective criterion from that of subjective likelihood. In addition, for future research using this method, the subjective criterion would remain unaffected by trial structure, allowing for comparison between studies with different trial compositions.

Potential Behavioral Interventions

*Not clear
- Cut*

An abundance of previous research investigating naturalistic decisions suggests that people are risk-seeking for losses, especially when the economically optimal criterion is low (Baker, 1995; Joslyn & LeClerc, 2013; Atreya et al., 2015; LeClerc & Joslyn, 2015; Qin et al., 2024). The current experiments revealed that in such situations, risk-seeking decisions are mediated by a higher-than-optimal subjective criterion. ~~In real life situations, a response is often required to protect against adverse weather events that have a low probability of occurrence (low economically optimal criterion) because of the potential for severe consequences.~~ Therefore, one important implication of the findings of the current experiments is that behavioral interventions to lower the subjective criterion might help to reduce risky decisions. Based on the gain-loss framing effect, changing the frame of the situation is a straightforward intervention, but framing might not make sense in some real-world situations (e.g., framing taking shelter as a gain).

On the other hand, there are several possible interventions that take advantage of the centering effect. Here, this effect was observed in the subjective criterion but not subjective likelihood for which the objective probability was provided. Therefore, communicating the relevant optimal criterion to participants might reduce the centering effect in subjective criterion as well. For instance, participants might be told “you should choose the safe option when the probability of a severe weather event is higher than 25%.” The effectiveness of directly supplying both economically optimal criterion information and probabilistic information has not been tested, although some evidence suggests that providing explicit advice to protect whenever the optimal criterion is exceeded improves decisions, as long as the event probability is also provided (Joslyn & LeClerc, 2012). Alternatively, it might help to simply bring attention to the criterion by asking participants to estimate the economically optimal probability for taking action when they have sufficient information to do so (Cheng et al., 2012). However, this might not be

feasible in some real-life scenarios because the potential loss might be difficult to quantify and might differ depending on individual circumstances.

Another possible intervention to adjust participants' subjective criterion is to manipulate what they perceive as the center of the range of possible likelihoods. For example, the forecast could provide a visualized ruler showing a range of likelihoods from 0% to 50% and indicating a specific point as the likelihood of a given weather event, e.g., 15%. This might cause users to constrict their perceived range of possible subjective criteria to 0%-50%, making 25% the value toward which estimates would shift toward because of the centering effect. Future studies should test these and other interventions to reduce the subjective criterion and risk-seeking choices.

Limitations and Future Directions

Theoretically, the placement of the subjective criterion should be based on the utility as well as the likelihood of the options. The reanalyses and two new experiments reported here focused on likelihood alone. Consider several examples of this focus. The objective probability of weather events was manipulated from trial to trial while utility was held constant. Participants reported a likelihood rating on every trial but never reported utility. Therefore likelihood ratings but not utility were used to calculate the subjective criterion. Future research might shift the focus to utility to determine ^{its} the ^{the} impact on subjective criterion. ✓

For instance, a possible future direction is to incorporate the expected utility (perceived efficacy in risk communications; Rogers, 1975) of protective actions into the model as a variable that can have stochastic distributions. The experiments reported above assumed perfect efficacy of protective actions. This is rarely the case in real world situations. According to protection

Constraints on Generality

The new experiments and the reanalyses used an online US nationwide sample that was fairly representative in terms of age, gender, race. However, since the sample was recruited from Prolific, the education level is expected to be slightly higher than a representative sample (see Prolific, 2025). For that reason, the results might not extend to those with lower levels of education. Nonetheless, as the sample was fairly representative in age, gender, race, so we consider it suitable for generalizing to the US population.

Conclusion

This study used a random likelihood model based on signal detection theory to better understand the risk-seeking tendency in naturalistic weather decisions with reliable probabilistic information. The random likelihood model ^{allows one to estimate} ~~and its approach to calculate~~ the subjective criterion ^{upon which a decision is based} ~~can be used to compare different decision-making under risk studies with different trial~~ compositions. ^{More importantly,} the findings suggest that, in real life situations where the likelihood of the severe weather is low but the potential damage is great, people's risk-seeking tendency is likely due to an inflated subjective criterion instead of underestimated subjective likelihood. Therefore, the subjective criterion is an important psychological construct to target in behavioral interventions that aim to promote protective actions.