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BRIEF REPORT

Emotion and Decision-Making Under Uncertainty: Physiological Arousal Predicts Increased Gambling During Ambiguity but Not Risk

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Uncertainty, which is ubiquitous in decision-making, can be fractionated into known probabilities (risk) and unknown probabilities (ambiguity). Although research has illustrated that individuals more often avoid decisions associated with ambiguity compared to risk, it remains unclear why ambiguity is perceived as more aversive. Here we examine the role of arousal in shaping the representation of value and subsequent choice under risky and ambiguous decisions. To investigate the relationship between arousal and decisions of uncertainty, we measure skin conductance response—a quantifiable measure reflecting sympathetic nervous system arousal—during choices to gamble under risk and ambiguity. To quantify the discrete influences of risk and ambiguity sensitivity and the subjective value of each option under consideration, we model fluctuating uncertainty, as well as the amount of money that can be gained by taking the gamble. Results reveal that although arousal tracks the subjective value of a lottery regardless of uncertainty type, arousal differentially contributes to the computation of value—that is, choice—depending on whether the uncertainty is risky or ambiguous: Enhanced arousal adaptively decreases risk-taking only when the lottery is highly risky but increases risk-taking when the probability of winning is ambiguous (even after controlling for subjective value). Together, this suggests that the role of arousal during decisions of uncertainty is modulatory and highly dependent on the context in which the decision is framed.

Keywords: decisions of uncertainty, emotional arousal response, risk and ambiguity, skin conductance response

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In people's everyday lives they regularly make choices where the outcomes are unknown. Imagine deciding whether to drive or take the bus to work, to confide in a coworker, or to invest in a new stock. These are all decisions under uncertainty that have been fruitfully deconstructed into distinct choice parameters (Kahneman & Tversky, 1984), highlighting the critical difference between decisions made under risk (i.e., known probabilities; Bernoulli, 1738/1954) from those made under ambiguity (i.e., unknown probabilities; Ellsberg, 1961; Knight, 1921). The fact that individuals routinely avoid outcomes associated with ambiguity is one indication that ambiguity is perceived as more aversive than risk (Becker & Brownson, 1964; Camerer & Weber, 1992; Slovic & Tversky, 1974). This has led some to argue that ambiguity is a more-profound form of uncertainty compared with risk, with a stronger impact on behavior (Ellsberg, 1961). But what shapes these discrete preferences and the observable aversion to ambiguity? Based on the hypothesis that the primary function of emotion is to highlight the relevance of stimuli and events in order to guide adaptive behavior (Frijda, 2007b), here we investigate how emotion—as assessed by physiological arousal—discretely contributes to decisions of risk and ambiguity.

Despite the fact that decision-making under risk and uncertainty is one of the more active and interdisciplinary research topics in judgment and decision-making, there are many psychological constructs believed to contribute to choice that continue to elude quantification. For example, in decomposing how decisions under uncertainty are made, traditional economic models have assumed that choices are the result of a rational analysis of possible options, where value is relatively stable and—one might hypothesize—distinct from emotion (Samuelson, 1938; Von Neumann & Mor-

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genstern, 1944). Yet simple observation of human behavior reveals clear bounds to the stability of preferences believed to accompany rationality (e.g., ambiguity aversion, gamblers' fallacy). Because these models treat emotion as epiphenomenal, they fail to capture the potential influence of emotion on decisions of uncertainty (Loewenstein, Weber, Hsee, & Welch, 2001), which may be an important cause of the instabilities of preferences widely observed to violate traditional theories.

In the last few decades, affective scientists have established that emotion—a discrete response to external or internal events resulting in a range of reactions including subjective feelings and bodily responses (Phelps, 2009; Scherer, 2000)—plays a role in the representation of value. Pioneering research revealed patients with affective deficits due to damage in the ventromedial prefrontal cortex were impaired on gambling tasks (Bechara, 2004; Bechara, Damasio, & Damasio, 2000; Damasio, 1994), experimentally demonstrating that emotion—broadly construed—influences decisions of uncertainty. In these studies, participants completed the Iowa gambling task (IGT), which requires choosing cards from multiple decks where each card represents a monetary reward or punishment (Bechara, Damasio, Tranel, & Damasio, 1997). Because decks vary in their payoff schedules, one must learn through trial and error which deck yields higher profits. Healthy individuals exhibit increased anticipatory skin conductance responses (SCRs)[1] when selecting cards from a "bad deck" compared to a more "advantageous deck," suggesting that increased arousal signals avoidance of the bad deck to promote adaptive choice. Although this illustrates that arousal during choice can become part of the computation of value, participants are learning about reward (gain) and punishment (loss) contingencies under ambiguous contexts where there is no explicitly stated risk. Research utilizing different tasks has continued to demonstrate a quantifiable role of arousal when outcomes are uncertain (Critchley, Mathias, & Dolan, 2001; Figner, Mackinlay, Wilkening, & Weber, 2009).

However, because the unique contributions of risk and ambiguity are conflated in these tasks, it is unclear whether the arousal response steering individuals away from bad decks is associated with ambiguity or risk. Thus, the question remains: Which uncertainty type is mediating the observed relationship between arousal and choice? Although a recent study revealed a relationship between arousal and discrete aspects of risky decision-making, namely loss aversion (Sokol-Hessner et al., 2009), to date, research has yet to establish a relationship between arousal and risk attitudes. Accordingly, it may be that the psychological uncertainty of not knowing the probabilities of an outcome (ambiguity) evokes greater arousal than does risky uncertainty. If this were the case, one would expect to see a specific role for arousal in influencing the computation of value during decisions of ambiguity but not risk. To examine the relationship between arousal and discrete parameters associated with decisions containing unknown outcomes, we measured SCR—a quantifiable measure reflecting sympathetic nervous system arousal (but not valence; Lang, Greenwald, Bradley, & Hamm, 1993)—during choices to gamble under risky and ambiguous contexts.

Method

Participants

Forty-five participants were recruited from New York University. Informed consent was obtained in a manner approved by the University Committee on Activities Involving Human Subjects. Forty participants were included in the analysis (25 female, mean age = 23.6 years, ±3.6 *SD*; see online Supplemental Material for details). Participants were paid an initial $10 and any additional monetary bonus accrued during the task (up to $125).

Task

In order to characterize the unique role of arousal in risky and ambiguous decisions, participants performed a task (Levy, Snell, Nelson, Rustichini, & Glimcher, 2010; Tymula et al., 2012) comprised of 31 gambles with known probabilities (risky trials; see Figure 1A) and 31 gambles with unknown probabilities (ambiguous trials; see Figure 1B). On each trial, participants had the option to choose the safe option with a sure payout of $5 or take the gamble—where each gamble had varying degrees of risk, ambiguity, and monetary value (between $5 and $125). Each lottery was either risky or ambiguous, allowing us to assess an individual's sensitivity to these distinct uncertainty types. The magnitude of the potential win (money) and the probability of winning (risk and ambiguity levels) were randomly varied and matched across trial types, such that both risk and ambiguity could independently influence choice.

For instance, a risky trial might juxtapose the option of $5 for sure (available on every trial) against a gamble with 50% chance of winning $50 or $0 (see Figure 1A). In this example, there are 50 blue chips and 50 red chips and the winning amount happens to be associated with the red chips. For risky trials, outcome probabilities were fully stated, with varying winning probabilities of 25%, 50%, and 75% (see Figure 1C). On ambiguous trials, outcome probabilities were partially obscured by a gray bar with varying levels of occlusion (24%, 50%, and 74%; see Figure 1C: Although increasing occluder size reduces information about the contents of the "bag of chips," raising the level of ambiguity, the true objective winning probability is always 50%). To measure arousal, we recorded SCR while participants viewed the lottery and made their decision (10.5 s window; see Figure 1D). Because raw SCRs were positively skewed, SCRs were normalized by taking the square root of each response (Dawson, Schell, & Filion, 2007). As in Levy et al. (2010), at the conclusion of the experiment, one trial was selected for realization in an entirely incentive compatible manner.

[1] Historically, the terms *skin conductance response* and *arousal* have been used interchangeably to describe emotion. There is robust research mapping the relationship between autonomic sympathetic activity and arousal. However, the arousal response indexes multiple aspects of emotion and has been linked to fear, anger, and happiness, depending on the context, as well as other cognitive processes such as cognitive load. Here we refer to skin conductance response as arousal (but see Boucsein, 1992; Lempert & Phelps, 2014; and Power & Dalgleish, 2008, for a comprehensive discussion of arousal's role in measuring emotion).

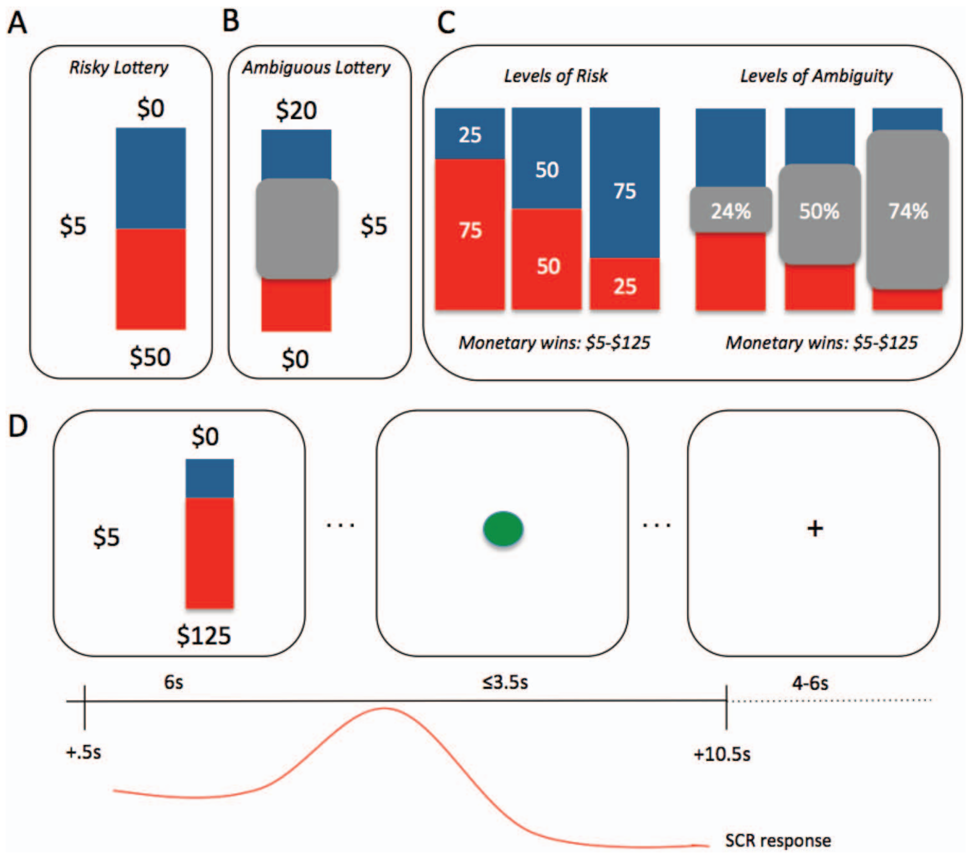

Figure 1. Experimental design. Participants completed a computerized lottery task where each lottery depicted a stack of 100 red and blue poker chips that corresponded to actual payout bags in the testing lab. On each trial, participants could choose between receiving $5 for sure and taking a gamble. Panel A: An example of a risky trial that contained 50/50 odds of winning $50 (i.e., 50% risky gamble). Panel B: An example of an ambiguous trial where 50% of the chips are occluded (i.e., 50% ambiguity). In this case, the participant could gamble for $20 or take the sure $5. Panel C: Risky trials were always presented as 25% (high risk), 50%, or 75% (low risk) probability of winning. During ambiguity trials, the probabilities were occluded to varying degrees (three levels were used) ranging from 24% to 74%. The monetary wins were always counterbalanced between red and blue chips and were matched across risky and ambiguous trials. Panel D: Each trial consisted of a fixed lottery presentation for 6 s. Once a green dot appeared, the participant could key in a response to indicate playing the lottery or taking the safe bet. Skin conductance response (SCR) was recorded for 10.5 s, starting .5 s after the lottery presentation onset. See the online article for the color version of this figure.

Results

Gambling Behavior as a Function of Uncertainty Type

Choice behavior was initially analyzed by averaging the number of times a gamble was taken under both uncertainty types and for each level of risk and ambiguity. As expected, as the gamble became riskier and the chances of winning declined (25% risk), participants were less likely to gamble (see Figure 2A). To examine whether ambiguity has an effect on behavior (Glimcher, 2008; Levy et al., 2010; Tymula et al., 2012), we explored the rates at which participants selected the gamble during ambiguous compared to purely risky lotteries. It is important to note that in this experimental design (as in Ellsberg, 1961), even though the increasing occluder size reduces information about the outcome odds, the objective-winning probability is always 50%. Confirming that ambiguous uncertainty is more aversive than risk (Slovic & Tversky, 1974), all ambiguous trials were treated as if the winning probability were less than 50%, with participants taking even fewer gambles as the ambiguity level increased (see Figure 2B).

Emotional Arousal and Subjective Value

To explore the relationship between arousal and the *subjective value* (SV) of a given lottery, we modeled the SV for each gamble under consideration as a function of the fluctuating amount of risk and ambiguity across trials, as well as the amount of money that could be gained. Although there are a number of models that account for decisions under ambiguity, Gilboa and Schmeidler's (1989) *maxmin utility model* provides a simple and widely used model anchoring parameters for best and worst case scenarios,

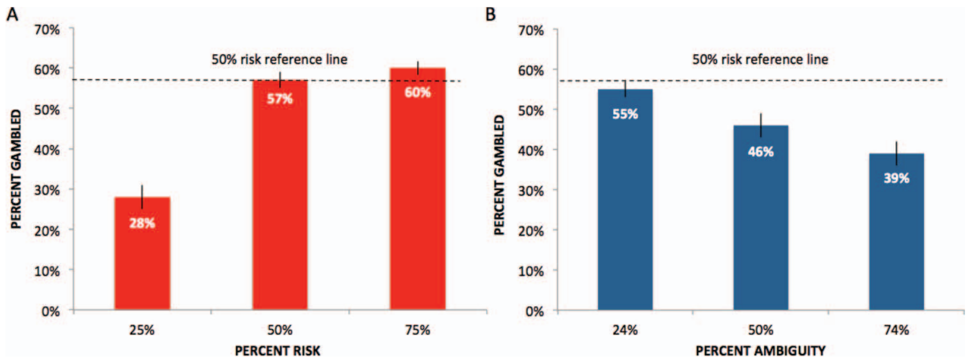

Figure 2. Behavioral results. Panel A: Participants gambled the most when the trial contained known probabilities (risk) and there was a high probability (75%) of winning. As the lottery became riskier (25% chance of winning), participants were less likely to gamble, reducing their gambling rates to 28%. Panel B: Ambiguous uncertainty is perceived as more aversive than risky uncertainty: Trials that contained highly ambiguous trials (i.e., 50% and 74% ambiguity) were treated as if the winning probability were less than 50%. Gambling rates at 50% risk is indicated by the dotted reference line. See the online article for the color version of this figure.

where one parameter indicates risk sensitivity (α) and the second parameter indicates ambiguity sensitivity (β). This "utility function" takes into account the effect of ambiguity on perceived winning probability as

$$SV(p, A, v) = \left(p - \beta \times \frac{A}{2}\right) \times v^{\alpha}$$

where for each trial, SV is calculated as a function of the lottery's objective winning probability (P), level of ambiguity (A), and monetary value (v), accounting for each individual's risk (α) and ambiguity (β) attitudes, which are obtained from the behavioral fit of the model. Figure 3 illustrates the distribution of participants' risk and ambiguity attitudes, revealing these attitudes are not correlated (Pearson's two-tailed correlation $r = -.22$, $p = .19$, $R^2 = .045$). Classically used by Luce (1959), as well as by Holt and Laury (2002), these attitudes are derived by fitting choice data using the maximum likelihood with the following probabilistic choice function:

$$\mathrm{P}(\textit{chose lottery}) = \frac{1}{1 + e^{\gamma(SV_F - SV_V)}}$$

where SV_F and SV_V are the subjective values of the fixed (F) and variable (V) options, respectively, and γ is the slope of the logistic function, which is a participant-specific parameter (see the online

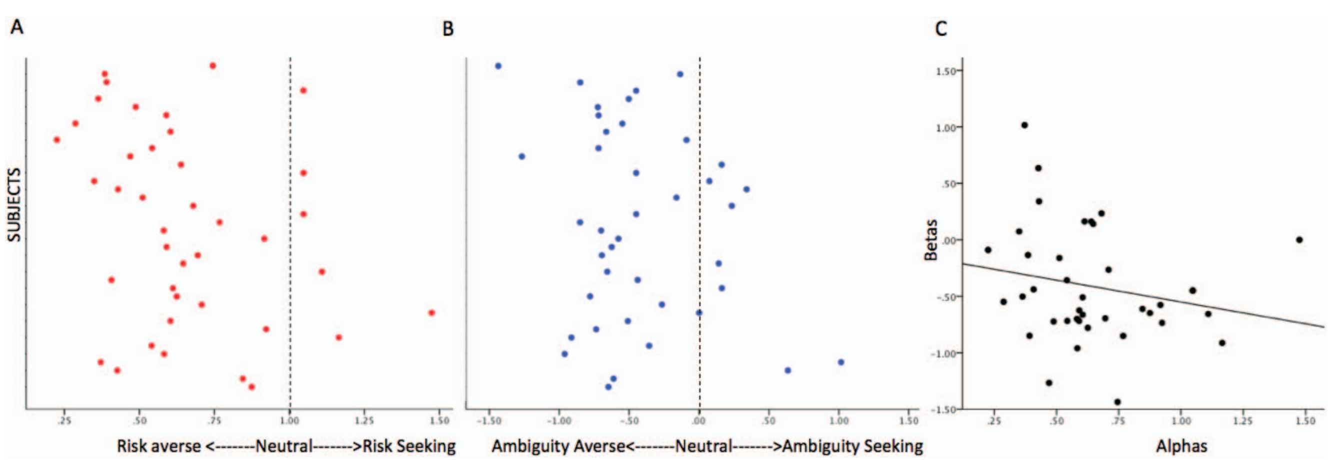

Figure 3. Risk and ambiguity parameters. Participants' risk attitudes (α; see Panel A) and ambiguity attitudes (β; see Panel B) as derived from the model (see Table S5 in the online supplemental material for full descriptive statistics of model parameters). An $\alpha > 1$ indicates a person is risk-seeking and more likely to gamble on risky trials, whereas an $\alpha < 1$ indicates a person is risk averse and less likely to gamble on risky trials ($\alpha = 1$ indicates risk is neutral). A $\beta > 0$ indicates a person is ambiguity averse and less likely to gamble on ambiguous trials, whereas a $\beta < 0$ indicates a person is ambiguity seeking and likely to gamble during ambiguous lotteries. For illustration purposes, betas have been inverted to align on the same scale (aversion seeking) as risk attitudes. Panel C: We found no relationship at the population level between risk and ambiguity attitudes ($p > .1$), replicating previous work (Levy, Snell, Nelson, Rustichini, & Glimcher, 2010). See the online article for the color version of this figure.

Supplemental Material for model fits and percentage of choices correctly predicted by model [Table S5], as well as other possible models that could account for behavior [Table S6]). This utility function captures the relative value a participant places on ambiguous versus risky lotteries, which allowed us to decompose the subjective value of each lottery and explore its discrete relationship with the arousal response.

To examine this relationship between SV and physiological arousal (SCR), we ran a trial-by-trial hierarchal linear regression (we report maximal models for all analyses; Barr, Levy, Scheepers, & Tily, 2013) modeling arousal as a function of every trial's SV given a participant's risk and ambiguity attitudes obtained from the model. This captured the relationship between arousal and SV, irrespective of uncertainty type (see Table 1). Results revealed a main effect of SV, indicating that greater subjective value predicts greater arousal. Independent regressions were run for each uncertainty type, revealing that under both risk and ambiguity, greater SV similarly predicts increased arousal (post–estimation tests revealed that risk and ambiguity coefficients were not significant from another; $p > .1$).

Emotional Arousal and Choice

Given this positive relationship between subjectively valuing a lottery and the arousal response—and that subjective value robustly (and unsurprisingly) predicted taking the gamble in both risky and ambiguous contexts (see Table S4 and Figure S2 in the online supplemental material)—we further hypothesized there should also be a relationship between choosing to gamble and arousal level. To explore this, we first tested whether higher arousal predicts gambles during risky and ambiguous lotteries. Although we observed no overall relationship between arousal and gambling, results revealed discrete and divergent relationships between arousal and gambling depending on whether the trial was risky or ambiguous (see Table 2). Under risk, enhanced arousal predicted taking the safe option, and this was solely attributed to high-risk trials, where there was only a small chance of winning (see Figure 4A and Table 3). In other words, although no relationship between arousal and choice during gambles with medium to low levels of risk was observed, for gambles with low odds of winning, higher arousal predicted *less* gambling.

Table 1
$SCR_{i,t} = \beta_0 + \beta_1 Subjective\ Value_{i,t}$

Dependent variable and coefficient β	Estimate (*SE*)	*t*	*p*
All SCR			
Intercept	.47 (.06)	7.28	<.001***
All SV	.0009 (.19)	2.84	.004**
Risk SCR			
Intercept	.47 (.07)	7.15	<.001***
Risk SV	.0006 (.0003)	2.00	.04*
Ambiguity SCR			
Intercept	.48 (.07)	7.36	<.001***
Ambiguity SV	.002 (.001)	1.80	.067†

Note. SCR ~ SV, where SV is indexed by subject (i) and trial (t). Independent regressions are also reported for risk and ambiguity trials. SCR = skin conductance response; SV = subjective value.
† $p < .1$. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 2
$Choice_{i,t} = \beta_0 + \beta_1 SCR_{i,t} \times \beta_2 Uncertainty\ Type_{i,t}$

Dependent variable and coefficient β	Estimate (*SE*)	*t*	*p*
Choice			
Intercept	.03 (.13)	.35	.72
SCR	−.22 (.13)	−1.68	.09
Uncertainty type	−.29 (.13)	−2.22	.02*
SCR × Uncertainty Type	.45 (.16)	−2.90	.004**

Note. Choice ~ SCR × Uncertainty Type, where SCR is indexed by subject and trial and where uncertainty type is an indicator variable for risk (0) and ambiguity (1). Choice is coded as safe (0) and gamble (1). SCR = skin conductance response.
* $p < .05$. ** $p < .01$.

In contrast, during ambiguous trials, enhanced arousal predicted the likelihood that an individual would take the gamble (see Figure 4B and Table 4), indicating when the probability of the outcome is unknown, heightened arousal *increases* gambling rates. Reaction time tests exploring whether this effect could be explained by ambiguous choices' being more cognitively demanding revealed no such evidence (see the online Supplemental Material). To further unpack why increased arousal amplifies willingness to gamble during ambiguity but not risk, we investigated the relationship between all three variables of interest: subjective value, choice, and arousal.

Emotional Arousal, Subjective Value, and Choice

To further isolate the role of arousal in guiding choices to gamble as a function of risk and ambiguity, we used residuals from the regression (SV ~ SCR; see Table 1) to predict the probability of taking the gamble, which controls for the subjective value of each lottery. This enabled us to test the direct influence of arousal on gambling, irrespective of the effects of subjective value. Results revealed increased arousal predicts gambling only when the probabilities are unknown (see Table 5 and Figure 4B), with no discernable relationship between arousal and choice under risk (see the online Supplemental Material for multilevel mediation analysis confirming this relationship).

Discussion

Although both risk and ambiguity are ubiquitous in decision-making, until now, differentiating the specific role of arousal's function during different types of uncertainty has not been demonstrated. Here we find diverging functional roles for arousal and its contribution to the computation of value depending on whether the decision contains purely risky uncertainty or both risky and ambiguous uncertainty. First, individuals gamble more on risky trials than ambiguous trials, confirming that ambiguity is more aversive than risk. Second, irrespective of uncertainty type, arousal tracks the subjective value of the lottery. Third, arousal plays a specific role in influencing decisions under risk: Higher arousal is tightly coupled with choosing the safe option, such that gambling *decreases,* but only when the risk is high and there is little chance of winning. That arousal does not seem to broadly contribute to the representation of value during risky uncertainty suggests a more-limited role for arousal in the valuation of risk. In contrast, when

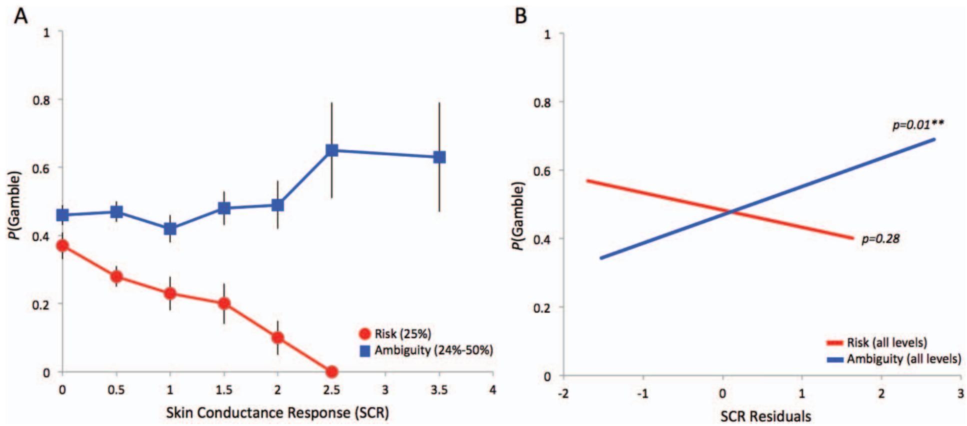

Figure 4. Panel A: Higher arousal predicts attenuated gambling during highly risky trials where there is low odds of winning the lottery (25%). In contrast, higher arousal during low (25%) and medium (50%) levels of ambiguous uncertainty (levels collapsed) results in increased gambling. Panel B: Relationship between arousal and choice, controlling for subjective value of a lottery, indicates that arousal predicts greater gambling behavior under ambiguous conditions but has no predictive power during risky conditions. See the online article for the color version of this figure.

uncertainty has a qualitatively different nature and the probability of winning is unknown, enhanced arousal plays a broad role in *increasing* gambling. Even after controlling for the subjective value of the lottery, this high arousal–increased gambling relationship during ambiguous uncertainty persists. Dovetailing with previous research (Phelps, Lempert, & Sokol-Hessner, 2014), this suggests that arousal should not be treated as a unitary construct in risky decision-making. Rather, arousal makes divergent contributions toward the representation of value when the decision space contains known or unknown uncertainty.

SCRs are an objective sign of psychological and physiological arousal (Pribram & Mcguinness, 1975), which are known to correlate with a myriad of environmental stimuli, including novelty, pleasantness, unpleasantness, and value (Frijda, 2007a; Otto, Knox, Markman, & Love, 2014; Scherer, 1984; Scherer & Peper, 2001). Given this, SCR is assumed to be a multicomponent nonvalenced signal that is highly adaptive, primed to detect stimuli that are critical for the survival and wellbeing of the organism (Frijda, 2007b; ÖHman, 1986). Thus, it is not surprising that we found that arousal indexes more than one aspect of the decision space. Previously, however, the relationship between arousal and choice has been described almost exclusively within the context of risk and was presumed to have a linear relationship in predicting attenuated gambling (Bechara, 2004; Bechara et al., 1997). Yet in prior research (i.e., the IGT; Bechara et al., 1997), risk and ambiguity, as well as the potential for both monetary losses and gains are all covariates, making it difficult to determine the specific role of arousal in guiding choice. In our task, the only difference between deciding on a risky versus an ambiguous outcome was the amount of *perceived* uncertainty—all other components of the task were held constant. In contrast to previous work, once these aspects of the decision space were controlled for, we observed a limited role for arousal in guiding risky choices: Therefore, heightened arousal predicts attenuated gambling only when one *knows* the chance of winning is very low. The opposite relationship is observed when the outcomes of winning are *unknown*: Increased arousal predicts increased gambling during ambiguous uncertainty.

Our finding that increasing arousal correlates with the subjective value of the lottery—irrespective of context—illustrates that arousal is highly responsive to value (Frijda, 2007b; Zink, Pagnoni, Martin-Skurski, Chappelow, & Berns, 2004). This aligns with research demonstrating that heightened arousal facilitates

Table 3
$Choice_{i,t} = \beta_0 + \beta_1 SCR_{i,t}(Risk25\%_{i,t}) + \beta_2 SCR_{i,t}(Risk50\%_{i,t}) + \beta_3 SCR_{i,t}(Risk75\%_{i,t})$

Dependent variable and coefficient β	Estimate (*SE*)	*t*	*p*
Choice			
Intercept	.10 (.09)	1.11	.26
SCR × Risk 25%	−2.06 (.32)	−6.37	<.001***
SCR × Risk 50%	.14 (.16)	.87	.38
SCR × Risk 75%	.25 (.16)	.10	.10

Note. SCR ~ SCR × Risk Level, where SCR and risk level are indexed by subject (*i*) and trial (*t*) and each level of risk level is an indicator variable. SCR = skin conductance response.
*** $p < .001$.

Table 4
$Choice_{i,t} = \beta_0 + \beta_1 SCR_{i,t}(Amb25\%_{i,t}) + \beta_2 SCR_{i,t}(Amb50\%_{i,t}) + \beta_3 SCR_{i,t}(Amb75\%_{i,t})$

Dependent variable and coefficient β	Estimate (*SE*)	*t*	*p*
Choice			
Intercept	−.27 (.13)	−2.08	.03*
SCR × Amb 25%	.54 (.17)	3.09	.002**
SCR × Amb 50%	.32 (.16)	1.90	.05*
SCR × Amb 75%	−.08 (.17)	−.45	.64

Note. SCR ~ SCR × Ambiguity Level, where SCR and Ambiguity level are indexed by subject (*i*) and trial (*t*) and each level of ambiguity is an indicator variable. SCR = skin conductance response; Amb = ambiguity.
* $p < .05$. ** $p < .01$.

Table 5
Choice$_{i,t}$ = $\beta_0 + \beta_1$*SCR Residuals*$_{i,t} \times \beta_2$*Uncertainty Type*$_{i,t}$

Dependent variable and coefficient β	Estimate (*SE*)	*t*	*p*
All choice			
Intercept	−.10 (.08)	−1.27	.20
SCR_{resid} × Uncertainty Type	.35 (.15)	2.40	.016*
Risk choice			
Intercept	−.07 (.08)	−.93	.35
Risk SCR_{resid}	−.21 (.19)	−1.08	.28
Ambiguity choice			
Intercept	−.14 (.11)	−1.3	.19
Ambiguity SCR_{resid}	.36 (.15)	2.4	.01*

Note. Choice ~ SCR Residuals × Uncertainty Type, where the SCR residuals are taken from the independent risk and ambiguity regressions reported in Table 1, indexed by subject (*i*) and trial (*t*). Uncertainty type is an indicator variable for risk (0) and ambiguity (1). Regressions are also run separately for risk and ambiguity. SCR = skin conductance response; resid = residuals.
* $p < .05$.

detection of potentially important environmental events and information (Zink et al., 2004); in this case, lotteries that bear higher subjective values are more likely to reap higher payouts. However, because the role of value is to provide a metric for the decision maker in weighing various options for choice, the subjective value of the lottery should determine whether an individual decides to take the gamble, irrespective of whether the context is risky or ambiguous.[2] Interestingly though, once subjective value (an SCR-free model-based estimate of choice propensity) was controlled for, we found arousal predicted greater gambling only during ambiguity but not risk.

Why might arousal motivate gambling only when there is great uncertainty about the probability of winning? During conditions of ambiguous uncertainty, an individual must make more inferences about the state of the decision space in order to predict possible outcomes. When there is explicit information about outcome probabilities—as there is in risk—individuals can make better informed decisions to optimize their payouts. For example, knowing there is a 75% chance of winning $125 indicates that the odds are in one's favor to win a large payout. However, when the uncertainty of winning is ambiguous and there is little knowledge of whether one's choice will reap the desired outcome, individuals must effectively guess which option will lead to the best outcome. In these noisy environments, teasing apart the value of the possible outcomes becomes more difficult, and thus the body reacts with an amplified arousal response. Simply put, unlike during highly risky situations, where enhanced arousal plays a clear and specific role in signaling adaptive choice, ambiguous uncertainty poses an obstacle for effective decision-making—because there is a perception of inadequate knowledge about possible outcomes. Simply put, arousal appears to play a clear adaptive role when there is sufficient knowledge about the outcomes, but when there is insufficient knowledge, arousal enhances the value representation of the possible outcome, which is either adaptive or maladaptive depending on the parameters of the decision space.

Here we illustrate that arousal contributes to the calculation of value during choice in a way not captured by the traditional arousal-free models. However, arousal's role is modulatory in nature (Phelps et al., 2014), varying depending on the context in which the decision is framed. Under risky and ambiguous contexts, arousal has divergent effects in shaping one's perceptions of uncertainty. Questions remain: If arousal differentially guides choices depending on the type of uncertainty, then pharmacologically blunting arousal responses (Sokol-Hessner et al., 2015) or employing emotion-regulation techniques to regulate the arousal response (Sokol-Hessner et al., 2009) could result in divergent behavior, enhancing highly risky choices and possibly diminishing ambiguous choices. Future work can help further tease apart how emotional arousal contributes to the representation of value during decision-making.

[2] Indeed, the fact that one derives subjective value by analyzing choice makes this almost tautologically true.

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