A Neuroimaging Study of Preference for Strategic Uncertainty

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Abstract

We report the findings of an experimental study of preference for strategic uncertainty using neuroimaging. Participants decide whether to receive a specific amount for sure or enter either a matching pennies or a coordination game. We find that people have a general aversion to uncertainty arising in a competitive setting than in a cooperative setting and that this aversion is moderated by whether the uncertainty results from a randomized choice or a conscious choice of a strategic counterpart. Specifically, participants choose to play the coordination game with a conscious player more often than they did against a randomized player and reverse this pattern when playing matching pennies. Consistent with our behavioral findings, increased amygdala and orbital prefrontal cortex activation are associated with participants valuing matching pennies less than coordination when played against a conscious opponent and valuing coordination less than matching pennies when played against a die.

Keywords: experimental economics, neuroeconomics, strategic uncertainty, source preference, decision theory

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1. Introduction

Since time immemorial, uncertainty has been an inseparable part of our daily lives. Besides naturally occurring events, social interactions also constitute a significant source of uncertainty. We adopt the practice of referring to the latter as strategic uncertainty and the former as nonstrategic uncertainty. Real world examples of strategic uncertainty are endless, from anti-terrorism activities to playing pokers with friends, and from auditing tax returns to professional sports. Intriguingly, data from Wimbledon (Walker and Wooders 2001) and two major European soccer leagues (Chiappori et al. 2002) show that the notion of mixed-strategy equilibrium can be used to model how professional tennis players and soccer players randomize their serves and penalty kicks. At the same time, people's preference for strategic uncertainty arising from playing different games has not received much attention in the literature.

A fundamental tenet of decision making models, including expected utility theory, is that the value of a lottery is fully determined by its payoffs and associated probabilities. This implies that games with the same mixed-strategy equilibrium would be valued equally for players engaged in equilibrium play. We distinguish uncertainties which arise when the payoffs for the decision maker and her strategic counterpart are positively correlated from those which arise when their payoffs are negatively correlated. We refer to the former as cooperative and the latter as competitive. The present paper builds on previous research studying the neural correlates of decision making under nonstrategic uncertainty (e.g., Smith et al. 2002, Hsu et al. 2005, Huettel et al. 2006).

In his 1921 "Treatise on Probability", Keynes famously asked, "*If two probabilities are equal in degree, ought we, in choosing our course of action, to prefer that one which is based on a greater body of knowledge*? (Keynes 1921, p.313)" While the fundamental tenet would rule out precisely this possibility, Keynes illustrated his question with an example of the 2 urns (see Ellsberg 1961) in which one contains 50 red and 50 black balls while the other contains an unspecified combination of the two. A correct guess of the color of a ball drawn randomly from an urn will pay a fixed amount of money. When offered a choice of which of the urns to bet on, people overwhelmingly prefer the first over the second (see Camerer and Weber 1992 for a review). This observation that choices between prospects depend not only on the degree of uncertainty but also on how it arises was termed source preference in several papers (Fox and Tversky 1995, Tversky and Fox 1995, Tversky and Kahneman 1992, Tversky and Wakker 1995). For instance, Fox and Tversky (1995) found that participants were willing to pay more for a less than even bet on the temperature in San Francisco than one based on a better than even bet on the temperature in Istanbul.

There has not been much experimental research on the nature of preference for strategic uncertainty. An early paper is Camerer and Karjalainen's (1994) study which identified a general aversion to strategic uncertainty in the context of playing a matching pennies game. In a follow up study, Fox and Weber (2002) replicated this finding, but they observed the reverse pattern – an affinity for strategic uncertainty – when participants played the coordination game. In another study, Kühberger and Perner (2003) found that participants preferred to draw from an unknown urn prepared by a partner with positively correlated payoffs over a different unknown urn prepared by an opponent with negatively correlated payoffs. However, none of these studies allowed for the elicitation of participants' risk attitudes among these games. How a preference between playing coordination versus matching pennies may interact with whether the opponent chooses consciously or randomly remains unaddressed. We study these questions experimentally using a 2 (matching pennies vs. coordination) x 2 (conscious vs. randomized choice) design in conjunction with fMRI (functional magnetic resonance imaging) to extend current neuroimaging findings to decision making under strategic uncertainty. Moreover, our design incorporates the additional option of a sure amount to enable the elicitation of risk attitudes.

2. Modeling Approach

In a recent paper, Chew and Sagi (2008) offered an axiomatic model of source preference in terms of possibly distinct attitudes towards risks arising from different sources of uncertainty. Controlling for knowledge, source preference refers to the incidence of identically distributed risks arising from different sources of uncertainty being valued differently. The simplest source preference model corresponds to having possibly distinct SEU preferences (with different von Neumann-Morgenstern utility functions) for risks arising from different sources of uncertainty. For our experimental study, we hypothesize that participants possess such a source-dependent expected utility preference with possibly distinct utility functions u_{MS}, u_{MN}, u_{CS}, and u_{CN} under the matching pennies-strategic (MS), matching pennies-nonstrategic (MN), coordination-strategic (CS), and coordination-nonstrategic (CN) conditions respectively.

Given a specific utility function u, the expression for the *certainty equivalent* c of an even-chance lottery that pays a gain amount x or 0 is given by:

$$c = u^{-1}(u(x)/2), \tag{1}$$

assuming that $u(0) = 0$. The corresponding *risk premium* π is given by $x/2 - c$, so that risk aversion (affinity) corresponds to π being positive (negative). We can then model the phenomenon of participants being ambiguity averse with respect to matching pennies by requiring u_{MS} to be more concave than u_{MN} resulting in a lower certainty equivalent for MS than for MN. For our behavioral analysis in Section 4, we will make use of a constant relative risk aversion utility specification

$$u(x) = x^{k_{MS}+(k_{MN}-k_{MS})d_{MN}+(k_{CS}-k_{MS})d_{CS}+(k_{CN}-k_{MS})d_{CN}} \tag{2}$$

where $1 - k_{MS}$, $1 - k_{MN}$, $1 - k_{CS}$, and $1 - k_{CN}$ are the respective indices of relative risk aversion in the MS, MN, CS, and CN conditions while d_{MN}, d_{CS}, and d_{CN} are the dummies for MN, CS and CN respectively.

Hypotheses: Building on intuition linking ambiguity with strategic uncertainty and incorporating behavioral evidence from the literature, we posit the following:

H1: *People prefer playing a coordination game than playing matching pennies when both have the same mixed-strategy equilibrium.*

H2: (a) *People are more averse towards strategic uncertainty than nonstrategic uncertainty.*
(b) *Playing coordination strategically is preferred to playing nonstrategically*, while *playing matching pennies nonstrategically is preferred to playing strategically.*

The rank-dependent expected utility model (Quiggin, 1982) offers an alternative approach to modeling source preference (see Abdullaoui, Baillon, Placido, and Wakker 2010) by maintaining the same utility function and allowing the probability weighting function to depend on the underlying source of uncertainty. This approach was adopted in Hsu et al. (2005) which assumed a standard expected utility specification with a power utility function for unambiguous uncertainty and a rank-dependent expected utility specification with the same power probability utility function and an additional power probability weighting function for ambiguous uncertainty. Conceptually, it seems more appealing to adopt a source-dependent expected utility specification with the corresponding source-dependent risk aversion measures than to apply probability weighting to an even-chance lottery depending on which of four conditions obtains.

3. Experimental Design

Sixteen participants, recruited from a university in Hong Kong, were asked to make 48 sequential decisions on whether to enter to a game which might yield a higher but uncertain outcome or to receive a lower but certain amount. Being randomly matched with one of the sixteen opponents who were separately recruited, participants were informed that their payoffs in each game are jointly determined by their own choices and their opponents' choices. We have a 2 (*game*: coordination vs. matching pennies) x 2 (*uncertainty*: strategic vs. nonstrategic) within subject design (see Figure 1).

CS

	L	C	R
U	x, x	0, 0	y, y
D	0, 0	x, x	y, y

MS

	L	C	R
U	x, 0	0, x	y, y
D	0, x	x, 0	y, y

CN

	L	C	R
Odd	x, x	0, 0	y, y
Even	0, 0	x, x	y, y

MN

	L	C	R
Odd	x, 0	0, x	y, y
Even	0, x	x, 0	y, y

Figure 1. Examples of game matrices. Participants as column players are asked to choose between playing the game (L or C) and receiving the sure amount (R). Contrary to convention, the first payoff in each cell corresponds to the payoff of the column player.

In each condition, participants are asked to make 12 binary choices between playing a game with another participant (the opponent) and receiving a sure amount (see Figure 2). There are 12 sure amounts equally spaced between 20% and 80% of the gain amount which is randomly drawn between HK$80 and 120 (US$1 ≈ HK$7.8). This procedure enables us to estimate and compare participants' risk attitudes from their choices in the four conditions. The sequence of 48 trials is completely randomized. In each trial, participants respond by a button press with an MRI-compatible button box. In the strategic treatment, participants either see a matching pennies game or a coordination game. In the nonstrategic conditions, the opponents' decisions are delegated to a die. The appearance of the three columns is counterbalanced (see Figure 1). To randomize over the two actions with equal probabilities, an odd (even) number from the roll of a die yields the U (D) action. All uncertainties are resolved immediately after scanning. Participants collect their payoff in cash from one randomly selected trial plus a show up fee of HK$50 towards the end of the experiment which takes approximately one hour. On average, each participant earned about HK$100.

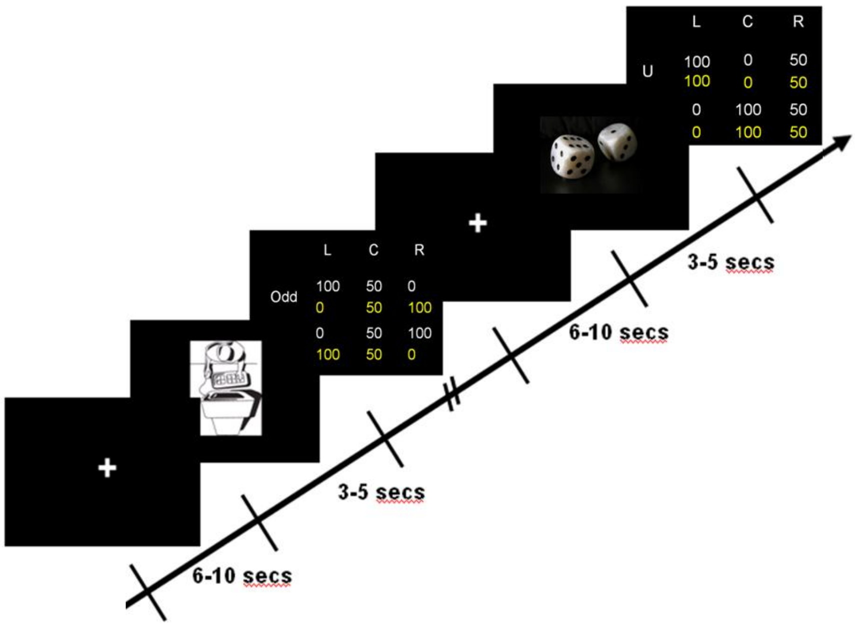


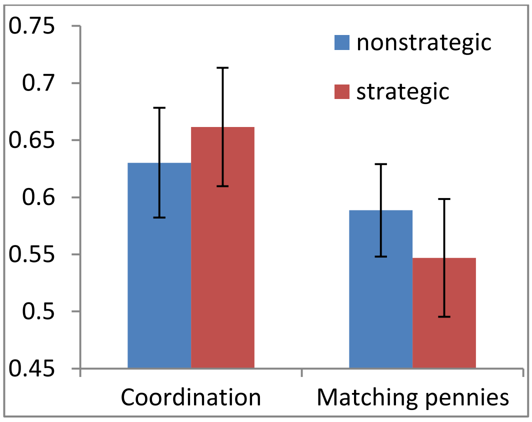
Figure 2. Timeline of the experiment. The strategic (represented by the picture of a human working on the computer) and the nonstrategic (represented by the picture of a die) is cued for 3-5 seconds. Then participants made their decisions by pressing the corresponding buttons of a button box. It is followed by a fixation of 6-10 seconds.

4. Results

Behavioral results

An overall flavor of the observed decision making behavior can be gleamed from Figure 3 displaying the relative frequencies of playing the game in the four conditions of MS, MN, CS, and CN. Participants played coordination game with human opponents more often than they did against a die.

This pattern is reversed when playing matching pennies with participants preferring the die to playing with a human opponent.



	MS	MN	CN
MN	1.92		
CN	3.55*	2.59	
CS	8.86***	4.00**	0.45

Figure 3. (*Top panel*) Relative frequencies of playing the game in the four conditions. (*Bottom panel*) Chi-square (1) statistics in the tests comparing among the four conditions from logit regression (*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$).

We present the result of logit regression using choice of sure amount as dependent variable (equals 1 when the sure amount is chosen, and equals 0 otherwise), and the gain amount x, the proportion of the sure amount over the gain amount, and the two dummy variables for game and strategic uncertainty as independent variables (variance clustered by participants). The main effect between the coordination game and matching pennies is significant ($z = 3.08$, $p < 0.005$), supporting H1, but the main effect for strategic versus nonstrategic uncertainty is not significant ($z = 0.29$, $p > 0.7$), not supporting H2a.

We run another logit regression with choice as the dependent variable and the gain amount, the proportion of sure amount over the gain amount, and the dummies d_{CN}, d_{MN} and d_{CS} from equation (2), as independent variables (variance clustered by participants). This analysis reveals that H1 is partially supported. While the probability of choosing between coordination game and matching pennies under strategic uncertainty is significantly different ($p < 0.005$), the corresponding comparison under nonstrategic uncertainty is not significantly different ($p > 0.1$). H2(b) is weakly supported – the probability of choosing CS is marginally different from that of choosing CN ($p < 0.1$) but the probability of choosing MN is not significantly different from that of choosing MS (see Figure 3).

Finally, we study the effect of strategic uncertainty on decision makers risk preferences by estimating participants' risk attitudes using a source-dependent expected utility specification as in equation (2) with $1 - k_{MS}$, $1 - k_{MN}$, $1 - k_{CS}$, and $1 - k_{CN}$ as respective indices of relative risk aversion in the MS, MN, CS, and CN conditions. The choice probability of playing a game is given by

$$\Phi[(\frac{1}{2}x^{k_{MS}+(k_{MN}-k_{MS})d_{MN}+(k_{CS}-k_{MS})d_{CS}+(k_{CN}-k_{MS})d_{CN}} - c^{k_{MS}+(k_{MN}-k_{MS})d_{MN}+(k_{CS}-k_{MS})d_{CS}+(k_{CN}-k_{MS})d_{CN}})/\mu]$$

where μ is a measure of how noisy subjects' choices is, x and c are respectively the gain amount and the sure amount in each trial. This estimation is done in *Stata 10.0* with program code developed in Harrison and Rutstrom (2008) with the Luce error (variance clustered by participant). Parameters for each participant's risk attitudes in the four conditions are estimated with their choices in the fMRI study. In each trial, risk premium of the gamble is calculated as in equation (1).

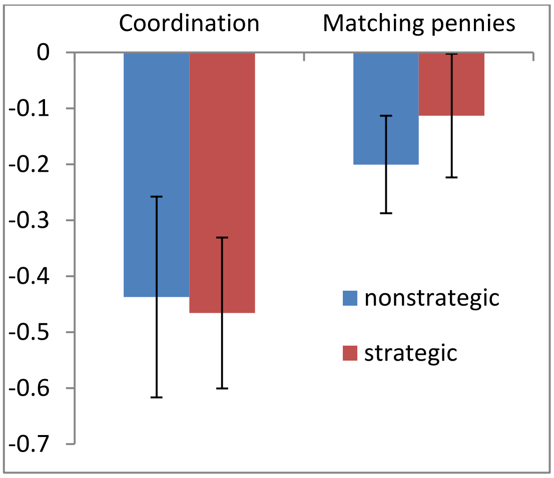


Figure 4. Estimated relative risk aversion indices in the four conditions.

Notice that the relative risk aversion indices are uniformly negative suggesting that participants are risk seeking in all conditions. Participants are less risk seeking under MS than under CS or under CN ($p < 0.05$), and marginally so under MN ($p < 0.06$). Other comparisons are not significant ($p > 0.1$).

Brain imaging results

Participants' risk attitudes in each condition are estimated from their choices (see appendix for more details). In each trial, the condition-specific risk premium of playing the game is computed as $x/2 - c$ as defined in equation (1). Notice that the negative of risk premium increases with the value of playing the game. As displayed in Figure 4, at the perceptual epoch, the caudate head encodes the value associated with the decision whether to enter a game ($p < 0.05$, small volume corrected, SVC).

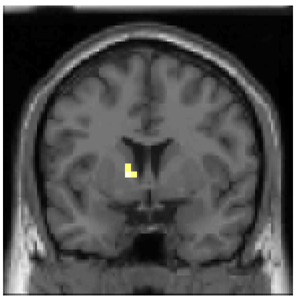


Figure 4. The coronal view of the brain (y = 4) shows that the activation of caudate head ($p < 0.05$, SVC centered at the peak voxels, x = -8, y = 12, z = 6, of the caudate head found in Tobler et al. 2007) correlates negatively with risk premium.

We classify the 48 trials by the four conditions. Our main purpose is to investigate brain regions which show interaction between the nature of the strategic uncertainty and whether the motive was the opponent was cooperative or competitive, i.e., the contrast of [(MS – MN) – (CS – CN)]. We find that at the decision epoch, the left amygdala and left orbital prefrontal cortex (OFC) show such an interaction ($p < 0.01$ and 0.005, SVC, respectively, see Figure 5).

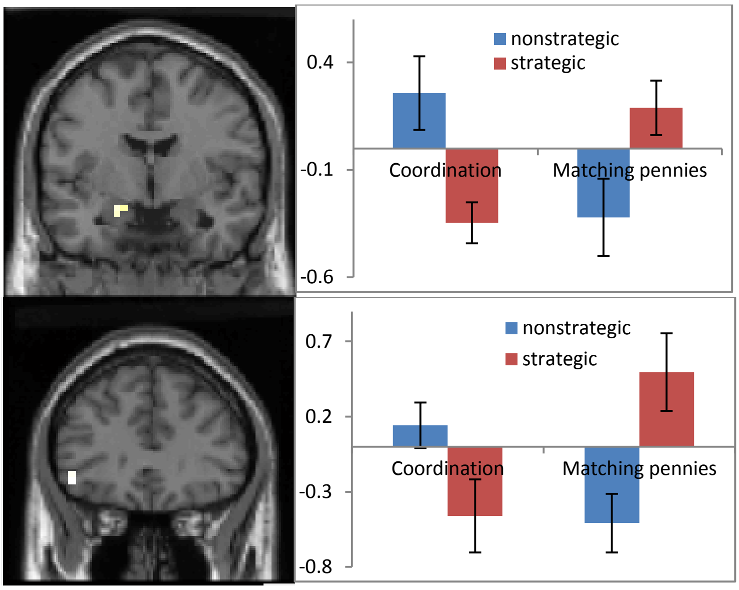


Figure 5. (*Top left*) The coronal view of the brain (y = -4) shows that the left amygdala ($p < 0.01$, SVC centered at the peak voxel, x = -21, y = -6, z = -18, of the amygdala found in Hsu et al. 2005). (Top right) Plot of the activations of the peak voxel (x = -20, y = -8, z = -20) by the four conditions. Error bars represent one standard error. (*Bottom left*) The coronal view of the brain (y = 32) shows that the left OFC ($p < 0.005$, SVC centered at the peak voxel, x = -54, y = 36, z = -6, of the left OFC found in Hsu et al. 2005). (Bottom right) Plot of the activations of the peak voxel (x = -48, y = 32, z = -8) by the four conditions.

Increased amygdala and OFC activation are associated with participants' valuing less the matching pennies game when played against a conscious opponent and valuing less the coordination game when played against a die. Previous research found that both regions were associated with ambiguity aversion (Hsu et al. 2005). In the current study, we find that activities in these two regions reflect not only the perceived ambiguity of the situation (in our case the strategic vs. nonstrategic uncertainty), but also the moderation of the motive underpinning how uncertainty arises. As displayed in tables 1 and 2, in both regions, all binary comparisons between the conditions are significant ($p < 0.05$), except between CN and MS, and between CS and MN. In particular, the simple effects between nonstrategic and strategic conditions in both games are significant ($p < 0.05$).

	MS	MN	CN
MN	2.4319**		
CN	0.3228	2.4279**	
CS	3.22****	0.125	2.9482***

Table 1. t-statistics in the tests comparing the brain activations in the left amygdala among the four conditions (*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$, ****$p < 0.005$).

	MS	MN	CN
MN	2.956***		
CN	1.1799	2.4427**	
CS	2.8331***	0.1517	2.2739**

Table 2. t-statistics in the tests comparing the brain activations in the left OFC among the four conditions (*p < 0.1, **p < 0.05, ***p < 0.01).

5. Discussion and Conclusion

Decision making models generally assume that lotteries with the same distributions of outcomes and probabilities are valued the same regardless of how the underlying uncertainty arises. It follows that accepting an objective lottery would be valued as much as playing a game whose mixed-strategy equilibrium has the same stochastic payoffs as the lottery. Our design enables us to pin down the possibly distinct risk attitudes for the strategic vs. nonstrategic uncertainty in the coordination vs. competitive setting. Interestingly, we find that participants on average are risk seeking in all four conditions suggesting an overall affinity for uncertainty arising from human interactions. Our design encompasses both Camerer and Karjarlainen (1994) and Fox and Weber (2002) as well as delivers a novel finding of a general preference for playing the coordination game over matching pennies, in addition to replicating their respective findings.

Our observation of participants exhibiting a preference between playing coordination and playing matching pennies suggests a possible social preference motive – preference for ex post equity – which relates to the principle of shared destiny in the literature on the measurement of inequality for stochastic incomes (see, e.g., Ben-Porath et al. 1997, Gajdos, Weymark, and Zoli, 2010, Chew and Sagi 2011) – preferring positive correlations between individuals' stochastic incomes when they have the same mean incomes. This principle receives partial support in the present finding of playing coordination being preferred to playing matching pennies only when the opponent is making conscious choice. There remains the question of what may account for the relative decline in appeal of the coordination game when played against a randomized player.

In an earlier study, Charness (2000) reported that participants in an experimental labor market game were more disposed to reciprocate a good wage offer when it was consciously determined by the employer than when it was set randomly. He attributed the decrease in responsiveness towards random wage offers to the idea of *responsibility alleviation* – employers were held accountable less when wage offers were made randomly. Subsequently, Dana et al. (2007) observed a tendency for players in the dictator game to give less when their actions might be attributed to some random device such as a coin flip. The responsibility alleviation hypothesis offers an account for why subjects value the cooperative outcome in the coordination game more and value the competitive outcome in the matching pennies game less when they result from the other player's conscious choice. Our finding of the interaction – CS being chosen significantly more often than MS but not for CN over MN –

supports the responsibility alleviation hypothesis rather than the social preference account of an overall preference for playing coordination over playing matching pennies.

Beyond behavioral findings, our analysis of the underlying neuroimaging data shows that the interaction between the form of the game and the nature of strategic uncertainty is associated with activities in the amygdala and OFC. This suggests a neurobiological basis for the asymmetric effect of strategic versus randomized choice and its interaction with whether the setting is competitive or cooperative. Specifically, the increase in amygdala and OFC activity is associated with participants' degree of risk aversion in both the strategic-competitive versus nonstrategic-competitive and the strategic-cooperative versus the nonstrategic-cooperative comparisons. Post hoc analysis reveals that these comparisons yield statistically significant differences (see tables 1 and 2). In particular, we observe significant differences in activations between strategic and nonstrategic uncertainties in both games.

The role of the amygdala in modulating vigilance and fear response was first discovered in conjunction with faces with fearful and normal expressions. (see Whalen 1998 for a review). In relation to the association between amygdala activations with ambiguity aversion reported in Hsu et al. (2005), Charness, Karni and Levin (2012) interpreted this using the suspicion hypothesis (Yates and Zukowski 1975) – participants may think the unknown urn has been put together against them – inducing an amygdala response. On a related note, Amaral (2002) offered the ideas that fear in social contexts may be linked to different brain regions than fear of inanimate objects. Dolan (2007) further suggested the amygdala's encoding of emotional information may depend on the specific social situation. This is corroborated by the finding in De Martino et al. (2007) that activation of the amygdala depends both on how a decision is framed – gain oriented versus loss oriented – besides the choices themselves. In our case, the attitude towards strategic uncertainty is moderated by the social contexts of whether the setting is competitive or cooperative and whether uncertainty arises from conscious or randomized choice. In particular, under competition, amygdala is more activated for strategic uncertainty than for nonstrategic uncertainty while the reverse holds under cooperation. In view of Hsu et al.'s (2005) finding, our results support the idea that attitude towards strategic uncertainty is an extension of attitude towards ambiguity based on exogenous events.

Given that the social preference hypothesis can partially account for the observed preference for playing the coordination game over matching pennies, one may anticipate activation in brain regions such as the insula and the anterior cingulate cortex based on prior findings of their being associated with fairness preference and inequity aversion (Sanfey et al. 2003; Hsu et al. 2008). This implication does not find support in our brain imaging results. Instead, our finding, specifically the pattern of amygdala and OFC activation, is compatible with the implication of the responsibility alleviation hypothesis and suggests that there may be a shared neurobiological mechanism underpinning both attitude towards strategic uncertainty and attitude towards ambiguity based on exogenous events.

When making decisions, managers need to bear in mind that the risk preference of different stakeholders may depend on differences in the decision contexts. Our results underscore the value of paying attention at differences between strategic and nonstrategic uncertainty that could impact decision making in business settings. One example concerns how firms price their products, especially the ones with highly fluctuating costs. When consumers perceive the company to have cooperative motive, the firm may be perceived more favorably for either a price increase or decrease, whereas when consumers perceive the company to have competitive motive, the firm may want to attribute any price fluctuations to exogenous events (e.g., uncertainty about the costs of raw materials). Investors' aversion to strategic uncertainty in the competitive setting of the stock market may partly account for persistence of the equity premium.

Our findings may shed light on the increasingly important industry of recreational gaming in the economy (The Economist 2005). As opposed to investors, who are generally risk averse, gamblers tend to exhibit risk affinity towards different gaming products involving both strategic and nonstrategic uncertainty. Naturally, they may value games differently depending on how uncertainty arises. Moreover, one's enjoyment of interactive gambling may also be moderated by their perception of the motive of the other players, whether it is competitive among them (as in poker) or cooperative against the house (as in blackjack). In a sample of 440 pathological gamblers, participants who were older and female tended to stay away from playing strategic games and go for nonstrategic ones based on exogenous uncertainty (Odlaug et al. 2011).

In his seminal work, Keynes (1936, p. 159) wrote, "*It is usually agreed that casinos should, in the public interest, be inaccessible and expensive. And perhaps the same is true of stock exchanges*." Keynes' observation underpins the incidence of a recreational motive akin to gambling for some who are engaged in stock trading (Dorn and Sengmueller 2009). It comes as little surprise that day traders, who exhibit risk affinity by engaging in high frequency small-stake trades, could concurrently be risk averse in their decisions concerning insurance purchase (Jadlow and Mowen 2010). Our results suggest that some gamblers may find appeal in small-stake risks arising from the stock market which involves strategic interaction among a far larger group of players than in casinos. This observation of consumers being less averse to hazards due to natural causes but more averse to those traceable to human failings suggests a fresh perspective for policy makers in the insurance context. In this regard, Kunreuther et al (1978) reported how people tend to under insure against natural disasters such as earthquakes and hurricanes even when such insurance is subsidized. At the same time, they may insure against specific hazards, e.g., travel and flight insurance, even when the premium is excessive (Eisner and Strotz, 1961; Johnson, Hershey, and Kunreuther, 1993).

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Appendix

Image Acquisition

fMRI was performed on a Philips Achiva 3T whole body MRI at the Jockey Club MRI Engineering Centre, Hong Kong with an 8 channel quadrature birdcage head coil. A sagittal spin echo localizer image was acquired initially. fMRI is performed in the transverse plane, parallel to the anterior–posterior commisura (AC-PC) line. A 35-slice set of fMRI images is acquired with the following scan parameters: TR = 2000 ms; TE = 30 ms; flip angle = 90°; matrix = 64 x 64; field of view = 22 cm x 22 cm; slice thickness = 4.0 mm, without inter-slice gap. Anatomical whole brain MRI is acquired using a T1-weighted turbo spin echo (TSE) sequence with TR 2000 ms and TE 10 ms with IR delay 800 ms. Around 200 fMRI volume images, depending on participants' response time, were collected during each run. The first four fMRI volume images of each run are discarded to insure steady state magnetization.

Image Processing

Post-processing of fMRI data is done using Statistical Parametric Map (SPM2) software package (Wellcome Department of Cognitive Neurology, Institute of Neurology, Queen Square, UK), running on Matlab (Version 7.1; Math Works Inc., Natick, MA, USA). Each fMRI image volume is realigned to the first image of the time series to correct for head movements during the fMRI acquisition. The time series volumes are registered to the brain template adopted by the International Consortium for Brain Mapping (ICBM) (Mazziotta et al., 1995); spatial normalization into Montreal Neurological Institutes coordinates (resampled 4mm x 4mm x 4mm). The spatially normalized EPI volumes are smoothed by an 8 mm fullwidth-half-maximum Gaussian kernel. Physiological noise is filtered using a window function that corresponds to a homodynamic impulse response function (HRF).

Imaging Data Analysis

Statistical analysis is conducted at two levels. 48 trials are classified into four conditions. Individual task-related activation is evaluated. Significant hemodynamic changes for each condition are examined using the general linear model using two models: 1) a boxcar functions convoluted with a hemodynamic response function (decision epoch), and 2) event-related design at the onset of the presentation of the game (perceptual epoch). Statistical parametric maps for each contrast of the t-statistics are calculated on a voxel-by-voxel basis. Brain activity correlated with the trial-by-trial EV and risk premium of playing the game is evaluated by parametric modulation. Autocorrelation of the hemodynamic responses was modeled as an AR(1) process. The contrast images are obtained from single-participant analysis and are entered into the group analysis. To make inferences at a group level, individual data are summarized and incorporated into a random effects model (which estimates the error variance for each condition across participants) and is implemented for group analysis. An ANOVA is applied to determine group activation for the interaction effect between the nature of uncertainty and whether the motive was competitive or cooperative, i.e., the contrast of [(MS − MN) − (CS − CN)]. Significant clusters of activation are determined using the conjoint expected probability distribution of the height ($p < 0.005$, uncorrected) and extent threshold (5 voxels). We apply SVC to our caudate head finding by centering a 10mm spheres centered at the peak voxels, x = -8, y = 12, z = 6, of the caudate head found in Tobler et al. (2007). Similarly, SVC is applied to our left amygdala finding at the peak voxel, x = -21, y = -6, z = -18, and our left OFC finding at the peak voxel, x = -54, y = 36, z = -6, both reported in Hsu et al. (2005).

Results

Brain Region	MNI coordinates			Cluster size (*k*)	*T*
dlPFC	32	24	40	46	5.17
Inferior Frontal Gyrus	32	24	-28	23	4.74
Sub-Gyral	-24	4	44	16	4.66
vmPFC	28	36	0	25	4.23
Caudate	0	8	0	10	4.22
dlPFC	36	0	44	19	3.83
Precentral Gyrus	-20	-24	48	10	3.63

Table A1 Regions showing negative correlation with the risk premium at the perceptual epoch ($p < 0.005$, $k \geq 10$).

Brain Region	MNI coordinates			Cluster size (*k*)	*t*
Thalamus	12	-24	0	75	4.73
vmPFC	-24	32	-8	71	4.35
Thalamus	-28	-28	0	20	4.26
Sub-Gyral	-28	-8	28	8	4.17
vmPFC	24	40	-8	43	4
Insula	-48	8	0	5	3.75
Superior Temporal Gyrus	44	-36	12	5	3.74
Amygdala	-20	-8	-20	18	3.7
dlPFC	-48	32	-8	7	3.64
Parahippocampal Gyrus	8	-20	-16	6	3.57
Putamen	32	-16	-4	5	3.29

Table A2 Regions associated with increased activation responding to valuing less the matching pennies game when played against a conscious opponent and the coordination game when played against the dice (i.e., the contrast of [(MS – MN) – (CS – CN)]) at the decision epoch ($p < 0.001$, $k \geq 5$).