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# Phineas gauged: decision-making and the human prefrontal cortex

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**Abstract**

Poor social judgment and decision-making abilities have often been attributed to people who have suffered injury to the ventromedial prefrontal cortex (VMPFC). However, few laboratory tests of decision-making have been conducted on these patients. The exception to this is the Iowa Gambling Task which has often, but not always, demonstrated differential performance between patients and controls. Results from patients with prefrontal cortex lesions on a novel test of decision-making are presented. Participants explored and chose from pairs of gambles that differed in their underlying distributions, primarily in the variance of their respective outcomes. In accordance with many findings from the behavioral decision-making literature, both young normal participants and older patient controls demonstrated a marked avoidance of risk and selected largely from secure, low variance gambles. In contrast, patients with ventromedial lesions were divided into two clear sub-groups. One group behaved similarly to normals, showing a risk-averse strategy. The other group displayed a distinctive risk-seeking behavior pattern, choosing predominantly from the high-variance, high-risk decks. This research demonstrates some of the advantages of using methods and theories from traditional decision-making research to study the behavior of patients, as well as the benefits of examining individual participants, and provides new insights into the nature of the decision-making deficit in patients with ventromedial prefrontal cortex lesions.
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## 1. Introduction

Since the accident that befell Phineas Gage in 1848 there has been much interest in the effects of prefrontal cortex lesions on human decision-making behavior. While employed as a railroad construction foreman, Gage accidentally patted down an explosive charge with a 109 cm long tamping rod, leading to an explosion which caused the fine pointed rod to pass through his head and inflict severe damage to his prefrontal cortex. This was the first well-documented case of a victim of brain injury who, having made an apparently miraculous recovery appeared on closer examination to be lacking something essential in his everyday judgment and decision-making capacities. A responsible, trusted employee prior to his accident, he underwent a remarkable personality change, becoming irresponsible, profane, and indifferent to the social conventions of the time. In his physician's memorable phrase, "Gage was no longer Gage" [9].

A careful interpretation of the path of the iron rod through Gage's skull has strongly implicated lesions to ventromedial cortex involving Brodmann areas (BAs) 8, 9, 10, 11, 12, 24, and 32 [3]. The behavioral changes exhibited by Gage have often been characterized as a deficit in social decision-making [14], and similar behavior has been observed in other patients who have suffered brain damage to the prefrontal cortex, in particular to the ventromedial areas of the frontal lobes.

In general, these patients with ventromedial prefrontal cortex (VMPFC) lesions exhibit normal cognitive abilities. Results from standard tests of memory and language aptitude are usually well within the normal range. However, as in Gage's case, the patients frequently demonstrate poor decision-making habits, and family members and friends often complain of something missing in the patient's post-injury personality. The patients are described by words and phrases like "socially incompetent", "decides against his best interest", "doesn't learn from his mistakes", and so on [5,6]. Although these are useful observations, it is difficult to convert them into firm behavioral concepts.

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Until quite recently, these descriptions were the only evidence available of a breakdown in the decision-making abilities of patients with VMPFC damage. There has been an increased interest in linking judgment and decision-making functions as tested in the laboratory with the underlying neural topography [7,8,17–19,21], however, the most extensive and intriguing research on decision-making relevant to the Gage case has been carried out by researchers at the University of Iowa (for a current summary, see [2]).

The Iowa Group introduced a Gambling Task that was designed to experimentally capture the deficits that have been anecdotally reported in patients with VMPFC damage. The Gambling Task involves the patient choosing from four decks of cards, the object of the game being to maximize his or her profits by choosing 'winning' cards from the decks. The decks are arranged so that two of them (A and B) have high winning payoffs but also high penalties, therefore overall these decks have a negative expected value (i.e. the players will lose if they play only these decks). Decks C and D have lower win payoffs, but even lower penalties, so overall these decks have a positive expected value. The basic finding reported is that normal and brain-damaged controls (patients with damage in areas other than the ventromedial prefrontal cortex), are drawn initially towards the riskier decks because of the larger payoffs, but ultimately shift to the safer, low payoff, decks (C and D). Patients with ventromedial damage on the other hand, continue to select primarily from the risky decks (A and B), and fail to respond to the high punishment schedule [2].

The primary conclusion drawn from the research at Iowa was that ventromedial patients exhibit "myopia for the future" in that they are insensitive to both uncertain potential gains and losses [2]. Another interpretation of the results is that these patients are somehow attracted to risk, that is, to the higher variance of the two disadvantageous decks. This 'risk-seeking' hypothesis has been tested in patients with both aneurysms of the anterior communicating artery (AcoA) [16] and frontal lobe lesions of various types [15] using a task involving placing bets on the location of a target. The results from these studies were mixed, with AcoA patients (who often exhibit similar types of emotional and judgmental deficiencies as seen in ventromedial patients) exhibiting increased risk-taking behavior, whilst patients with ventromedial lesions demonstrated no difference in risk-taking performance than did controls. However, the focal group of ventromedial patients had in general quite small, predominantly left-sided lesions, which distinguished them from the ventromedial patients used by Bechara and colleagues.

The goal of the present study therefore, is to build on the aforementioned findings by examining the risk attitudes of patients with lesions to the ventromedial prefrontal cortex. We have attempted to do this by using models and tasks previously developed and rigorously tested in the field of decision science. We are predominantly interested in the patients' and controls' attitudes towards risk (broadly defined as the variance of returns over time). To this end, the task we employed does not have a more advantageous or disadvantageous strategy, an important difference from the Iowa Gambling Task where the focus lay on the normatively correct or incorrect choices made by their participants.

The specific payoff distributions we employed were developed in traditional, behavioral research on risky decision-making. Risky decisions involve choosing one course of action from a set of two or more, where there is uncertainty (usually expressed as a numerical probability) about what consequences will occur contingent on the decision. These tasks require decision makers to integrate judgments under uncertainty with assessments of the personal value or utility of the consequences in order to choose the course of action that is most likely to achieve the decision maker's goals [4].

The classic laboratory risky decision-making tasks involve choices where subjects are offered monetary gambles of various types. A typical gamble might consist of two options: a "sure-thing" choice and a risky choice. For example, a subject might be offered the choice of either a sure US$ 50 or a chance to flip a coin, where "heads" means they receive US$ 100, but "tails" means they get nothing. Although both options in this example have the same positive expected value (US$ 50), the majority of participants take the safe option in this instance and select the sure US$ 50, which implies people are risk-averse where gains are concerned [10].

Based on preferences among these gambles, the risk propensity of normal subjects can be established, and many different theoretical measures of risk attitudes have been employed to answer this question. Indeed, the use of multi-outcome gambles is a common technique to elicit reliable preferences within the field of judgment and decision-making [20,22].While all of these theories and their associated measures provide methods to estimate and interpret the functions relating objective outcome values and subjective values, we chose a particular theoretical framework that provides additional useful parameter-based measures of individual decision-making habits. Security/potential aspiration (S/P-A) theory [11–13] includes measures of decision weight and utility functions plus an estimate of "level of aspiration," an outcome with a special significance in choice among risky alternatives. S/P-A theory is composed of two-factors, a security/potential factor and an aspiration level factor. The security/potential factor is a dispositional variable that reflects an individual's tendency to be risk-averse (security) or risk-seeking (potential), independent of the given situation. Security motivation (risk aversion) is by far the most common pattern, hence the surprise at the performance of the Iowa patients who appear to be motivated by a desire for potential as opposed to security. The aspiration level factor is a situational variable that reflects the fact that risk-seekers may play safe some of the time and risk-avoiders will occasionally take chances when necessary. Aspiration level therefore reflects the environment's immediate opportunities (what can be obtained) as well as its constraints (what is needed).

The primary method Lopes and Oden use to elicit risk preferences involves presenting subjects with choices between multi-outcome lotteries (each multi-outcome lottery is analogous to one of the card decks in the Iowa Gambling Task). In a typical experiment, participants are shown pairs of these lotteries in all possible combinations and asked which they would prefer to play. Pair-preference data can then be used to infer a preference ordering across the entire set of stimulus lotteries. Usually, all of the lotteries used have identical expected values, which allows for an exploration of preferences for various risky payoff distributions.

This method provides several measures of risk-taking propensities: direct measures of the percent of trials on which a subject chooses a more risky response alternative; and parameter estimates of value and decision weight functions (that can be interpreted as risk-seeking versus security-conscious orientations). The primary parameter of interest for our purposes is the security versus potential orientation of the decision-maker (this parameter is termed $w$). If $w = 1$ then the decision-maker is said to be strictly security-minded, whilst $w = 0$ would indicate strict potential-mindedness. If the parameter value lies between 0 and 1, we can conclude that the decision-maker is cautiously hopeful with a mix of security and potential, where the greater the deviation from 0.50 the greater the degree of one factor or the other. We also explore a set of attentional parameters which estimate the degree to which attention to outcomes diminishes as the evaluation procedure proceeds upward from losses to gains (this parameter is $q_s$) and to the degree to which attention diminishes as the evaluation proceeds downwards, from gains to losses ($q_p$).

If a disturbance in risk attitudes is present, we would expect to see increased risk-seeking behavior in patients with ventromedial prefrontal cortex lesions compared to both patients with lesions in other cortical regions, and to the control group (i.e. a lower $w$-value in the VMPFC group). This result can be decomposed, using the individual subject parameter estimates, to determine if this behavior should be attributed to either differential valuation (e.g. an insensitivity to losses), to differential weighting of risks versus gains (e.g. a risky decision weighting policy), or to something else. This use of the participants' value and decision weight functions allows a more precise analysis of the patients' attitudes towards risk than was possible in previous studies.

## 2. Methods

### 2.1. Participants

Four groups of participants were examined in this study. The primary group of interest was a group of nine patients with orbitofrontal lesions (VMPFC group). VMPFC lesions were defined as damage to any of Brodmann areas 10, 11, 12, 13, 14, and 25 (no patients in our sample had damage to areas 13, 14, or 25). Another group of four patients had prefrontal cortex lesions that did not incorporate VMPFC Brodmann areas (FLL group). Fig. 1 shows the lesioned brain locations of each of the patients as taken from their CT scans (as most of the patients have metal in their heads MRI images cannot be acquired). The lesioned regions are denoted by the darkened areas in the templates. Table 1 gives the demographic particulars of the participants, and Table 2 details the precise lesion locations. It should be noted that patient G.S. is legally blind due to damage sustained at the time of his lesion, therefore the task was administered to him verbally by the experimenter. However, there was no evidence of any difference in performance between G.S. and the other three patients identified as part of the 'Safe' cluster.

Also tested were two normal control groups: (1) 17 age-matched normal controls (NC-NIH group) and (2) 63 psychology undergraduates from the University of Colorado (NC-CU group) who completed the experiment for course credit.

Table 1
Demographic details for the 13 frontal lobe patients studied. VM-1 is the 'safe' group, VM-2 the 'risky'

| | Group | Age | Sex | Handedness | Years of education | VIQ | PIQ | FIQ | Lesion etiology |
|---|---|---|---|---|---|---|---|---|---|
| G.S. | VM-1 | 52 | M | R | 17 | – | – | – | PHI[a] |
| G.W. | VM-1 | 51 | M | R | 14 | 103 | 104 | 103 | PHI |
| J.H. | VM-1 | 52 | M | R | 14 | 131 | 105 | 120 | Stroke |
| S.G. | VM-1 | 69 | M | R | 13 | 73 | 79 | 74 | Stroke |
| B.S. | VM-2 | 54 | M | R | 14 | 85 | 81 | 82 | PHI |
| E.A. | VM-2 | 44 | F | R | 18 | 86 | 90 | 87 | Tumor |
| M.E. | VM-2 | 51 | M | R | 14 | 94 | 100 | 97 | PHI |
| M.Y. | VM-2 | 56 | M | R | 12 | 94 | 111 | 102 | PHI |
| W.B. | VM-2 | 50 | M | R | 11 | 82 | 83 | 80 | PHI |
| A.R. | FLL | 65 | M | R | 16 | 133 | 132 | 136 | PHI |
| D.A. | FLL | 52 | M | R | 14 | 99 | 124 | 110 | PHI |
| E.H. | FLL | 52 | M | R | 14 | 103 | 94 | 99 | PHI |
| M.K. | FLL | 53 | M | R | 13 | 95 | 105 | 99 | PHI |

[a] Penetrating head injury.

### 2.2. Apparatus

The task was programmed in Hypercard and implemented on Apple computers.

### 2.3. Deck distributions

All decks had identical expected values, that is, the average gain from all decks was the same (+10 points per card), and therefore over time we should expect a similar number of points gained irrespective of which decks were chosen. The decks differed in their underlying distributions, ranging from the NoLoss deck, where participants could never lose points but were unlikely to win many (maximum win of 20 points), to the Long-Shot deck, where there was a small probability of winning 150 points but also a reasonable chance of losing (up to 50 points). The distribution of the decks is summarized in Fig. 2, and Table 3 gives the statistical characteristics of the decks. The decks were randomly arranged in the experimental display, but for ease of exposition we have ordered them here (1 through 5) from low-variance to high-variance. As can be seen, the decks primarily differed in two factors, one being the respective variances and another being the proportion of cards in each deck that yielded a positive outcome. Traditionally, a 'sure-thing' option is offered in tasks of this kind, however we were concerned that one deck with a single value would look quite different from the other four (all of which contain a range of possible outcomes). We did include a deck that never incurs losses "NoLoss"

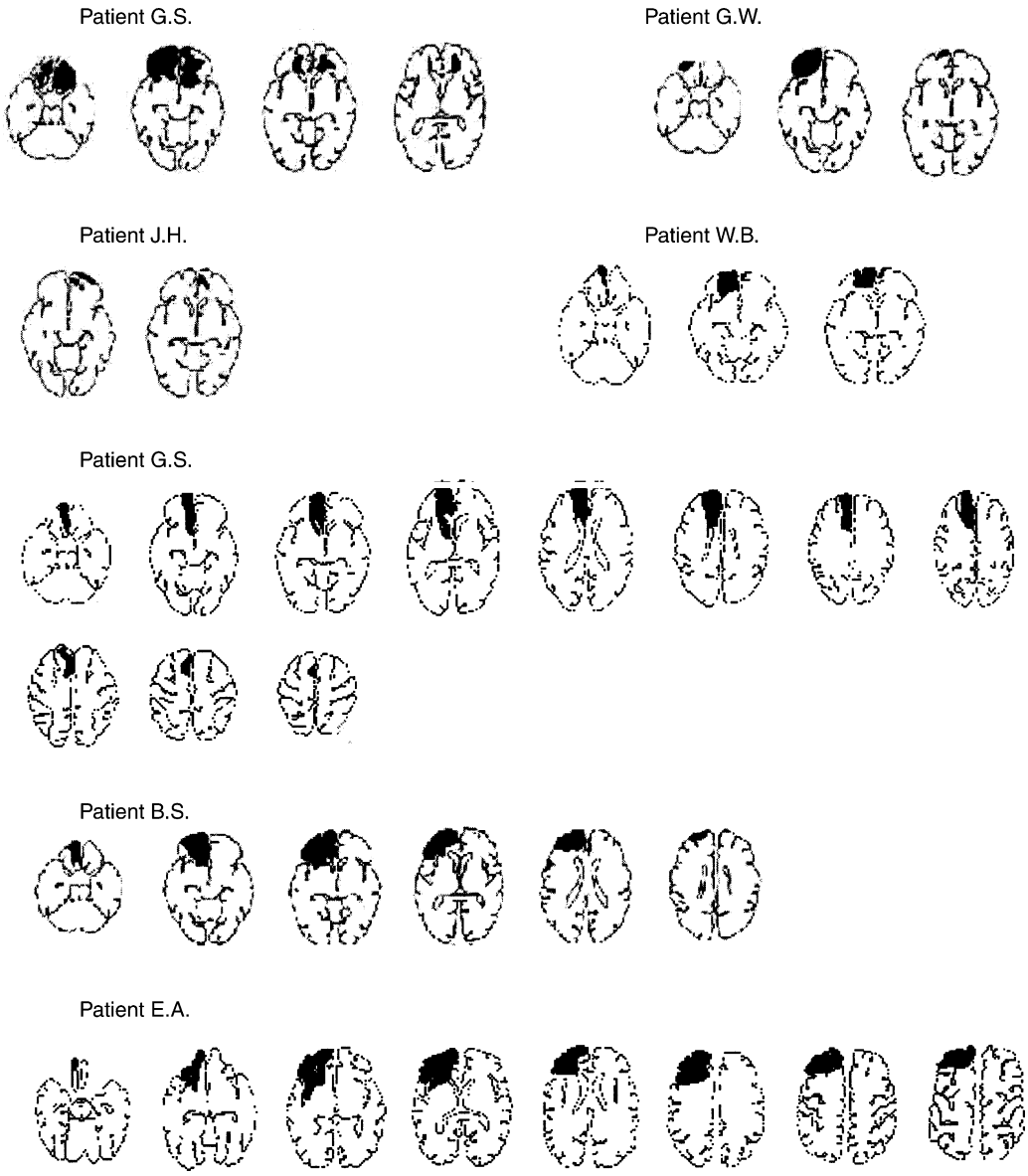


Fig. 1. Lesioned areas of all 13 patients with frontal damage.

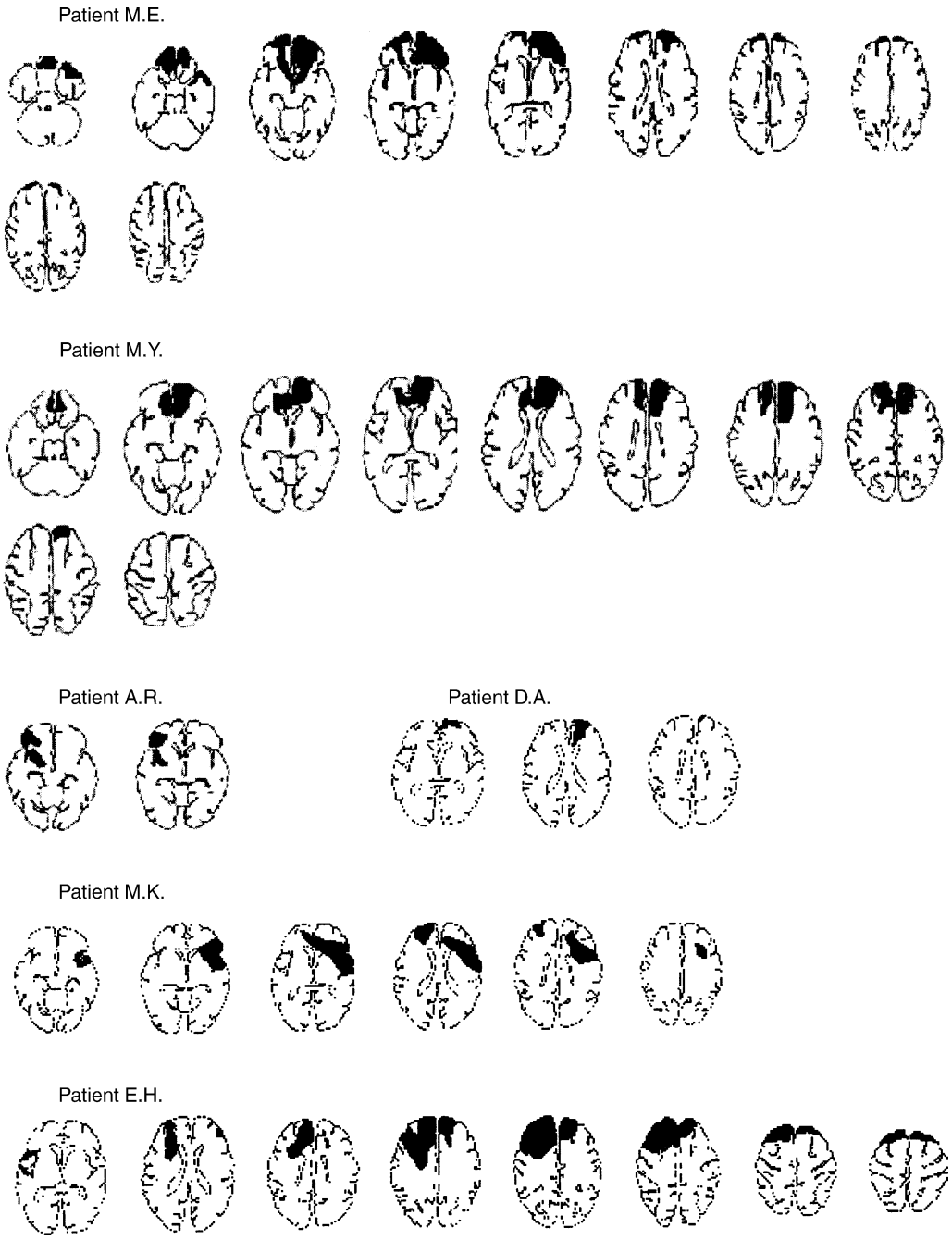


Fig. 1. (*Continued*).

which we believe serves as a reasonable proxy for a certain gain.

Each deck contained 25 possible outcomes. When a deck was selected, one of these 25 outcomes (represented by the vertical tally-marks in Fig. 2) was randomly picked to be the payoff for that turn. Once this value was displayed, it could not be shown again until all the remaining values in that distribution had been output. This ensured that participants saw a representative sample of values from each deck.

### 2.4. Procedure

The task took the form of a gambling game, the objective being to maximize the number of points won. Participants were informed that they would be engaged in a task which would involve making choices between different decks of cards in an effort to win as many points as possible. They were not however given any information regarding the distributions of the various decks, or indeed even that there were any difference between the decks. They sat in front of

Table 2
Brodmann area lesion location for all 13 frontal lobe patients studied

| | VMPFC | | DLPFC | | | | | Other | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 11/12 | 8 | 9 | 44 | 45 | 46 | 4 | 6 | 21 | 22 | 24 | 32 | 38 | 41/42 |
| G.S. | LR | LR | – | – | – | LR | – | – | – | – | – | LR | LR | – | – |
| G.W. | L | L | – | – | – | L | – | – | – | – | – | – | – | – | – |
| J.H. | R | R | – | R | – | – | R | R | – | – | – | R | R | – | – |
| S.G. | L | L | L | L | – | – | – | L | L | – | – | L | L | – | – |
| B.S. | L | L | – | L | L | L | L | – | L | – | – | L | L | – | – |
| E.A. | L | L | L | L | L | L | L | L | L | – | – | L | L | – | – |
| M.E. | LR | LR | LR | LR | – | R | LR | – | – | R | – | R | LR | R | – |
| M.Y. | R | LR | LR | LR | – | – | R | – | LR | – | – | LR | LR | – | – |
| W.B. | LR | LR | – | – | LR | – | LR | – | LR | – | – | R | – | – | – |
| A.R. | – | – | – | – | – | L | L | – | – | – | – | – | – | – | – |
| D.A. | – | – | – | R | – | – | – | – | – | – | – | R | R | – | – |
| E.H. | – | – | LR | L | LR | – | L | LR | LR | – | – | – | LR | – | L |
| M.K. | – | – | – | – | – | R | L | – | R | – | LR | LR | LR | – | – |

L: left side lesion, R: right side lesion.

Table 3
Statistical details of the decks

| | Deck 1 'NoLoss' | Deck 2 'Peaked' | Deck 3 'Equal-Small' | Deck 4 'Equal-Big' | Deck 5 'Long-Shot' |
|---|---|---|---|---|---|
| Mean | 10 | 10 | 10 | 10 | 10 |
| Range | 14 | 100 | 100 | 180 | 200 |
| S.D. | 4.1 | 20.41 | 33.85 | 62.85 | 70.95 |
| Cards winning (%) | 100 | 80 | 60 | 60 | 40 |

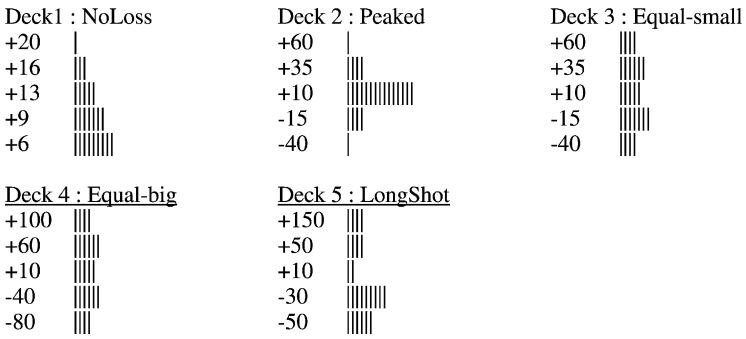


Fig. 2. Distributions of the five decks used. Each vertical tally mark represents a single outcome in the distribution. Each deck had a total of 25 outcomes.

a computer screen to play the game. On the screen were five decks, labeled A through E, arranged face-down in a circular pattern. Each deck was randomly assigned a particular position in the circle across participants. On each turn, two of the decks were highlighted. Using the mouse, the participant selected (clicked) one of the two decks to play. The card then "turned over" on the screen, revealing the number of points won or lost on that trial (the participants played for points, not real money). This number was then added to (or subtracted from) the running total displayed at the bottom of the screen. After a brief pause, another pair of decks was highlighted and the participant made another choice.

Each possible pair of decks (there were 10 possible pairs, pair order being irrelevant) was shown 20 times each, for a total of 200 trials. The order of these trials was randomized for each participant.

## 3. Results

Four groups of subjects were studied: two different normal control groups, patients with lesions in ventromedial prefrontal cortex, and patients with lesions in the prefrontal cortex that excluded the ventromedial region.

### 3.1. Demographic data and cognitive tests

Demographic information was collected for the NIH normal controls and the two frontal patient groups. ANOVAs showed no group differences for age ($F_{(2,27)} = 0.27$, $P > 0.05$) nor years of education ($F_{(2,26)} = 0.28$, $P > 0.05$) between the groups.

Wechsler Adult Intelligence Scale (WAIS)-III scores were obtained for the two frontal patient groups, with the

exception of one patient in the VMPFC group for whom IQ information was not available (patient G.S., who is legally blind). Predicted WAIS-R scores were obtained for the NIH normal controls using the National Adult Reading Test (NART). An ANOVA revealed differences between the groups ($F_{(2,26)} = 7.5$, $P < 0.05$). The NIH-NC and FLL groups were not different from each other (mean difference= 0.3, $P > 0.05$). Both the NIH normal controls and the non-VMPFC frontal group, however, had higher IQ scores than the VMPFC group (mean difference = 17.9, $P < 0.02$ and mean difference = 18.2, $P < 0.01$, respectively).

The participants in the present experiment had no foreknowledge as to the nature of the deck distributions, and hence there was initially a purely exploratory phase where choices were made more or less at random. To prevent these initial exploratory choices from obscuring the reliable preferences of the participants in the analysis, we estimated preferences by examining in detail the final 50 picks (from a total of 200) by each participant. This number was selected as the best compromise between ensuring enough data were used to calculate choice preferences, while allowing a reasonable number of selections to allow participants to learn the underlying distributions. A number of alternate scoring schemes were also examined (such as looking at the final 5 picks from each of the 10 pairs), and there were no discernable differences among these scoring methods. Participants were measured on their preference for each of the five decks by calculating the proportion of the time they selected a particular deck when that deck appeared in a paired choice. Of specific interest was whether they selected a deck more often than we would expect purely by chance (i.e. 50% of the time). Therefore, selection percentages in excess of 50% indicate a preference for a particular deck, while percentages below 50% would demonstrate the avoidance of a deck. Table 4 shows the mean selection proportions for all groups across the five decks.

These data are in the form of proportions and so a log-odds transformation of the data was computed. However, since the vast majority of the values lie between 0.2 and 0.8 this transformation had little effect and hence the results reported are based on the untransformed data.

### 3.2. Point totals

As expected, there were no significant differences between the four groups on this measure ($F_{(3,89)} = 0.48$, $P > 0.05$).

### 3.3. Normal controls

Normal controls showed significant preferences (both positive and negative) for four of the five decks (see Fig. 3). Participants in both normal control groups (NC-CU and NC-NIH) chose Deck 1 (NoLoss) more often than would be expected by chance (CU: $t_{(1,62)} = 5.8$, $P < 0.001$; NIH: $t_{(1,16)} = 2.9$, $P < 0.01$). Both groups also preferred Deck 2 (Peaked) more often than would be expected, though this was only significant for the NIH group (CU: $t_{(1,62)} = 1.8$, $P = 0.07$, NIH: $t_{(1,16)} = 2.6$, $P < 0.02$). Decks 1 and 2 are the two lowest-variance decks. Cards from Decks 3 (Equal-Small) and 5 (Long-Shot) were chosen less than would be expected by chance (Deck 3—CU: $t_{(1,62)} = -2.6$, $P < 0.02$, NIH: $t_{(1,16)} = -2.2$, $P < 0.05$; Deck 5—CU: $t_{(1,62)} = -3.6$, $P < 0.001$, NIH: $t_{(1,16)} = -3.5$, $P < 0.01$). Both groups chose Deck 4 (Equal-Big) slightly less than 50% of the time it was a possible choice, but this difference was not significant.

Further, there were no significant differences in preferences between the two normal control groups (NIH and CU) on any of the decks, despite distinct differences in the age and education levels of these groups. Because these groups' performances did not differ, we collapsed the two groups into one single normal control group (NCs) and will refer to them as such for the remainder of this discussion.

### 3.4. FLL patients (no VMPFC damage)

The four FLL patients without VMPFC damage demonstrated a similar pattern of performance to normal controls (see Fig. 4), and indeed did not differ from NCs on any of the decks (Deck 1:$F_{(2,81)} = 0.5$, $P > 0.05$; Deck 2: $F_{(2,81)} = 1.5$, $P > 0.05$; Deck 3: $F_{(2,81)} = 1.4$, $P > 0.05$; Deck 4: $F_{(2,81)} = 0.1$, $P > 0.05$; Deck 5: $F_{(2,81)} = 1.4$, $P > 0.05$). While there were only four patients in this group, Decks 1 and 2 were preferred, and chosen 81 and 61% of the time, respectively (Deck 1 was selected above chance levels at a marginally significant rate: $t_{(1,3)} = 2.7$, $P = 0.07$). Decks 3 and 5 were generally avoided, with 27 and 29% selection rates, respectively (Deck 3 was marginally significantly below chance: $t_{(1,3)} = -2.3$, $P = 0.09$), and Deck 4 was once more neutral (chosen 47% of the time). Again, these selection percentages are measured against a chance level of 50%.

Table 4
Group mean (S.D.) selection proportions for each of the five decks

| Group | Deck 1 | Deck 2 | Deck 3 | Deck 4 | Deck 5 |
|---|---|---|---|---|---|
| NC-CU | 0.68 (0.03) | 0.55 (0.03) | 0.44 (0.02) | 0.46 (0.03) | 0.40 (0.03) |
| NC-NIH | 0.69 (0.06) | 0.64 (0.05) | 0.42 (0.04) | 0.47 (0.02) | 0.31 (0.05) |
| FLL-other | 0.81 (0.11) | 0.61 (0.10) | 0.27 (0.10) | 0.48 (0.02) | 0.29 (0.10) |
| VMPFC | 0.49 (0.07) | 0.49 (0.07) | 0.48 (0.12) | 0.57 (0.08) | 0.48 (0.09) |

Chance is 0.50.

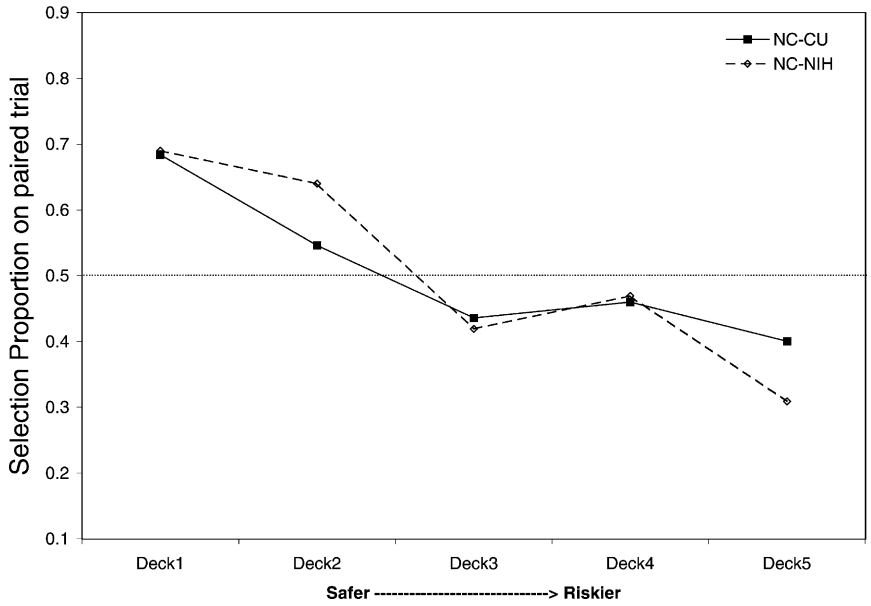


Fig. 3. Mean selection percentages across decks for the two normal control groups.

### 3.5. FLL patients (VMPFC damage)

As a group, these nine patients exhibited no overall preferences in their choices (see Fig. 4). All decks were chosen at levels very similar to chance (Deck 1: 49%, Deck 2: 49%, Deck 3: 48%, Deck 4: 57%, Deck 5: 48%). None of these percentages were significantly different from chance (Deck 1: $t_{(1,8)} = -0.1$, $P > 0.05$; Deck 2: $t_{(1,8)} = -0.1$, $P > 0.05$; Deck 3: $t_{(1,8)} = -0.6$, $P > 0.05$; Deck 4: $t_{(1,8)} = 0.9$, $P > 0.05$; Deck 5: $t_{(1,8)} = -0.3$, $P > 0.05$). On closer examination however, the individual patients did appear to show distinct patterns of performance. A cluster analysis was performed to examine this, revealing two distinct patient groups: one cluster with four patients, and another group containing five (see Fig. 5).

### 3.6. VMPFC group 1—safe

One cluster of four VMPFC patients (patients G.W., G.S., J.H., and S.G.) performed very similarly to many of the normals and the non-VMPFC group. Overall they showed a preference for Decks 1 and 2, were neutral towards Deck 3,

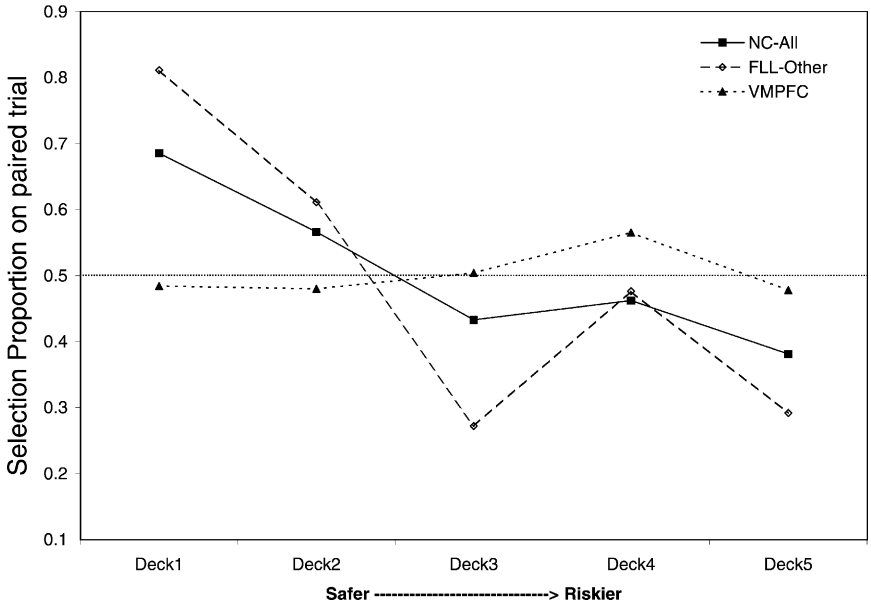


Fig. 4. Mean selection percentages across decks for normal controls, frontal patients without VM lesions, and VMPFC lesion patients.

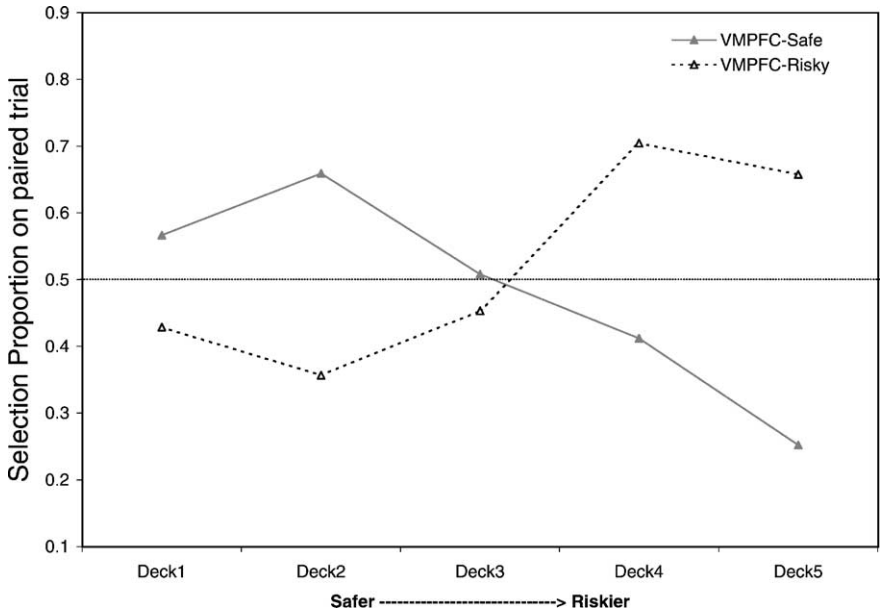


Fig. 5. Mean selection percentages across decks for two VMPFC sub-groups.

and had an aversion towards Decks 4 and 5 (see Table 5 for details).

### 3.7. VMPFC group 2—risky

Interestingly, the five VMPFC patients in the second cluster (patients E.A., M.E., M.Y., W.B., and B.S.) showed a pattern of performance almost exactly opposite to that of the first cluster, demonstrating a marked preference for the riskier decks and an aversion to the safer decks (again, see Table 5). Also striking was that all five of these patients exhibited very similar patterns of choice.

### 3.8. Demographic data and cognitive tests of the two VMPFC groups

The two identified VMPFC groups did not differ on either age ($t_{(1,8)} = -1.1$, $P > 0.05$) or level of education ($t_{(1,8)} = -0.4$, $P > 0.05$). IQ tests were administered to eight of the nine patient participants (patient G.S. is legally blind and did not complete the test), with no significant difference in IQ between the two VMPFC groups ($t_{(1,7)} = -0.8$, $P > 0.05$).

### 3.9. S/P-A parameters

The S/P-A parameters were fitted using the solver function of Microsoft Excel. Solver iteratively fits curves and adjusts specified free parameters to optimize the fit of a model to data. In this instance we defined 'fit' as minimizing of root-mean-squared-deviation (R.M.S.D.). For more information on the details of the parameter estimation procedure, see [13]. In fitting the parameters, we focussed on the two VMPFC groups, the FLL-other group, and the NIH-NC (normal control) group.

We first attempted to fit one set of parameter estimates per group, using the mean choice proportions for each of the 10 pairs. In a slight departure from the method used previously, for the parameter estimation we took the last 10 selections for each pair, and calculated the mean pairwise choice proportions accordingly. The best-fitting parameter values are given in Table 6. Of note is the fact that only the VMPFC-risky group had a mean $w$ of less than 0.5, indicating a generally potential-minded behavior. The other three groups all had $w > 0.5$, which can be interpreted as a security-minded orientation.

Table 5
Mean (S.D.) selection proportions for the sub-groups identified within the patient and matched control groups

| Group | Deck 1 | Deck 2 | Deck 3 | Deck 4 | Deck 5 |
|---|---|---|---|---|---|
| VMPFC-safe | 0.57 (0.14) | 0.66 (0.04) | 0.51 (0.04) | 0.41 (0.11) | 0.25 (0.06) |
| VMPFC-risky | 0.43 (0.07) | 0.36 (0.09) | 0.45 (0.07) | 0.71 (0.08) | 0.66 (0.08) |
| NC-NIH-safe | 0.77 (0.05) | 0.68 (0.05) | 0.39 (0.04) | 0.40 (0.06) | 0.25 (0.05) |
| NC-NIH-risky | 0.31 (0.10) | 0.47 (0.14) | 0.57 (0.05) | 0.80 (0.17) | 0.59 (0.08) |

Table 6
Fitted S/P-A parameter values for each of the groups

| Group | $w$ | $q_s$ | $q_p$ | R.M.S.D. |
|---|---|---|---|---|
| VMPFC-risky | 0.39 | 10.04 | 2.31 | 0.055 |
| VMPFC-safe | 0.72 | 0.02 | 0.08 | 0.046 |
| FLL-other | 0.69 | 0.16 | 0.66 | 0.038 |
| NC-NIH | 0.62 | 0.98 | 0.45 | 0.027 |

Parameter values were also fitted for each participant individually. An ANOVA indicated an overall main effect ($F_{(3,26)} = 3.27$, $P < 0.05$), and subsequent comparisons showed that the VMPFC-risky group scored significantly lower on the security-potential parameter ($w$) than the three other groups independently; while none of these three groups differed from each other.

### *3.10. Anatomical differences between the two VMPFC groups*

The two VMPFC groups did not differ significantly in terms of brain volume lost due to their respective lesions ($t_{(1,6)} = 1.1$, $P > 0.05$), nor were there any obvious laterality differences between the groups. The etiology of the lesions in each group were also very similar (penetrating head injury). We speculate on possible anatomical distinctions between the groups in the discussion.

### *3.11. NIH-NC—two groups*

A further analysis was conducted on the 17 NIH normal controls in an attempt to see if cluster analyses could also discriminate different patterns of performance within this group. Again, two groups were differentiated in the analysis, a large group containing 14 participants and a smaller one with the remaining 3 participants. Similar clusters were found for the CU-NC group, but we will focus here on the NIH control group, as this provides a better indication of the performance of normal age- and education-matched participants. The large group of 14 demonstrated the pattern observed in the control groups, preference for the safe decks, avoidance of the risky decks. However, the second group again showed an almost opposite pattern, this time favoring the risky decks at the expense of the safer alternatives (see Table 5 for details). These two groups did not differ on any of the demographic variables, age ($t_{(1,15)} = 0.36$, $P > 0.05$), level of education ($t_{(1,15)} = -0.04$, $P > 0.05$), or NART assessed IQ score ($t_{(1,15)} = -0.08$, $P > 0.05$).

## 4. Discussion

In general, normal controls showed a marked avoidance of the higher variance decks and preferred to play from the low variance Decks 1 and 2. This is in accordance with many findings from behavioral research in judgment and decision-making, which have shown people to generally avoid risk and high-variance situations when gains are involved, as was the case here. Further, the two different normal control groups (University of Colorado undergraduates and NIH normal controls) exhibited very similar performance in terms of their preferred and avoided decks. FLL patients with no VMPFC damage exhibited similar qualitative preferences to the normal controls. This is also in accordance with many previous findings using gambling-type tasks, which typically find no difference between patients without VMPFC damage and controls [2].

The Iowa Gambling Task has focused attention on the role of the ventromedial prefrontal cortex in decision-making, and has provided some initial empirical clues about the behavioral deficits exhibited by these patients. Our task varied from the Iowa Gambling Task by concentrating our attention on the risk preferences exhibited by the patients. The Iowa Gambling Task has normatively good (advantageous) and bad (disadvantageous) outcomes, encouraging a strategy whereby participants seek out the best return over time. By equating the expected values of the decks in our task, we were seeking to understand the role of variance in the obtained outcomes. Patients were originally reported to be indifferent (risk-insensitive) when choosing between both the disadvantageous (choosing between A and B) and the advantageous decks, that is, between decks with different risk but the same return [1]. However, the present study has demonstrated that important differences in risk attitudes do exist between ventromedial patients and controls, and additionally suggests that the utilization of tasks based on established findings from the decision-making literature can lead to more refined conclusions regarding the nature of the decision-making deficit in ventromedial, and other, patient groups.

At first glance patients with VMPFC damage appeared to show no preferences whatsoever. Upon more detailed analyses however, two distinct patterns of performance emerged. One group (VMPFC-safe) performed largely as the normals did, showing a clear risk-avoidance strategy. In contrast, the other group (VMPFC-risky) showed a disinclination to choose from the low-risk and low-variance decks, preferring to select from high-reward, high-punishment decks. These results are new and important. The VMPFC-risky group's performance is suggestive of the performance of the VMPFC patients in the original Iowa studies, and prompts the speculative hypothesis that perhaps the "poor choices" they make in that task can be traced to an increased taste for risk and variance. It should be noted that all decks in the present study had the same number of unique values (five in each), and so we cannot account for the findings by positing that the patients simply prefer more variety in their outcomes. The choice preferences of the patient group seem sensitive to the specific values themselves. In addition, the present results may suggest an interpretation of the minor differences between early and later observations of the Iowa Group. Early

results implied that the VMPFC patients were attracted to the high variance decks, while later results were more consistent with a "no preference", "myopia to future events" conclusion (e.g. Fig. 2 in [2]), opening the possibility that different mixtures of sub-types of VMPFC patients were sampled in the different studies. At a minimum, we submit that the present Gambling Task provides good resolution in identifying preferences for uncertain prospects which vary in riskiness, in both patient and normal populations, and that this factor is an important one in attempting to describe deficiencies in the broad construct of decision-making.

The two groups of VMPFC patients, though demonstrating clear distinctions in behavioral performance, do not differ in any obvious way in terms of their lesion locations. There is no significant difference in volume loss or any distinct laterality disparity. The absence of a clear difference precludes definitive statements, however it is worthwhile speculating briefly about possible anatomical distinctions between the groups. There does seem to be some qualitative differences with respect to lesions outside the ventromedial area, specifically to the dorsolateral prefrontal cortex (DLPFC). The risky VMPFC group appears to have more damage to areas of DLPFC (Brodmann areas 8, 9, 44, 45, 46) than the safe group, with left DLPFC implicated, particularly BA46. It should be noted, however, that three of the four patients with frontal lobe damage outside the ventromedial area (FLL-other group) also have damage to left BA46, though these patients show no appreciable risky behavior. Hence the difference between the two VMPFC groups cannot be wholly accounted for by DLPFC damage, though the results are suggestive of a VMPFC–DLPFC interaction whereby impairment to both of these areas may lead to an increased probability of risky behavior. Another area of damage more apparent in the risky group are the frontal poles, which are bilaterally damaged in patients exhibiting risky behavior. However, one patient in the safe group also shows bilateral frontal pole damage, so the role of the frontal polar region in estimating risk remains unclear. While these possible differences are certainly speculative at this point, they may provide hypotheses to test in future studies with VMPFC patients.

One additional benefit of our new lottery preference task is that it supports theoretically meaningful parameter estimates and interpretations. In the present application, the values of the $q_s$ and $q_p$ parameters for the experimental groups suggest that the observed risk preference differences may be explained as differential attention to aspects of the gambles by different groups of participants. The potential-minded group pays increased attention to what can be gained, while the security-minded groups focus attention on the amounts that can be lost. An immediate implication is that direct measures of attention allocation would reflect the operations of this mechanism and provide a micro-behavioral picture of the observed group differences.

We also believe that the present methods provide much more leverage to study differences between individuals sampled from a single, possibly heterogeneous, population. Especially notable is our discovery of two sub-types on the risk-preference dimension in both the sample of control subjects and the sample of VMPFC subjects. The distinctiveness of the clusters implies that the differences are more than a matter of degree. But, the appearance of potential-oriented participants in both patient and control samples suggests that we may be observing extremes in a normally occurring distribution of risk-attitudes. Our findings underscore the importance of examining individual subjects, even within a group of research participants that is expected to be homogeneous.

In general, we believe the present research demonstrates some of the advantages of using methods and theories from traditional decision-making research to study the behavior of patients and other special populations. The experimental task was sensitive to subtle differences in behavior, the results were clear-cut and reliable, and the development of a specific theoretical interpretation was relatively straightforward.

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## References

[1] Bechara A, Damasio AR, Damasio H, Anderson SW. Insensitivity to future consequences following damage to human prefrontal cortex. Cognition 1994;50:7–15.
[2] Bechara A, Tranel D, Damasio H. Characterization of the decision-making deficit of patients with ventromedial prefrontal cortex lesions. Brain 2000;123:2189–202.
[3] Damasio H, Grabowski T, Frank R, Galaburda AM, Damasio AR. The return of Phineas Gage: clues about the brain from the skull of a famous patient. Science 1994;264:1102–5.
[4] Dawes RM. Behavioral decision-making and judgment. In: Gilbert DT, Fiske ST, Lindzey G, editors. The handbook of social psychology, vol. 1. New York: McGraw-Hill; 1998. p. 497–548.
[5] Dimitrov M, Phipps M, Zahn TP, Grafman J. A thoroughly modern Gage. Neurocase 1999;5:345–54.
[6] Dimitrov M, Grafman J, Hollnagel C. The effects of frontal lobe damage on everyday problem solving. Cortex 1996;32:357–66.
[7] Godefroy O, Rousseaux M. Binary choice in patients with prefrontal or posterior brain damage. A relative judgement theory analysis. Neuropsychologia 1996;34:1029–38.
[8] Godefroy O, Rousseaux M. Novel decision-making in patients with prefrontal or posterior brain damage. Neurology 1997;49:695–701.
[9] Harlow JM. Recovery from the passage of an iron bar through the head. Publications of the Massachusetts Medical Society 1868;2:327–46.
[10] Kahneman D, Tversky A. Prospect theory: an analysis of decision under risk. Econometrica 1979;47:263–91.
[11] Lopes LL. Between hope and fear: the psychology of risk. Advances in Experimental Social Psychology 1987;20:255–95.
[12] Lopes LL. Algebra and process in the modeling of risky choice. In: Busemeyer J, Hastie R, Medin DL, editors. Decision making from

a cognitive perspective, vol. 32. San Diego (CA): Academic Press; 1995. p. 177–220.
[13] Lopes LL, Oden GC. The role of aspiration level in risky choice: a comparison of cumulative prospect theory and S/P-A theory. Journal of Mathematical Psychology 1999;43:286–313.
[14] Macmillan M. An odd kind of fame: stories of Phineas Gage. Cambridge (MA): MIT Press; 2000.
[15] Manes F, Sahakin B, Clark L, Rogers R, Antoun N, Aitken M, et al. Decision-making processes following damage to the prefrontal cortex. Brain 2002;125:624–39.
[16] Mavaddat N, Kirkpatrick PJ, Rogers RD, Sahakin BJ. Deficits in decision-making with aneurysms of the anterior communicating artery. Brain 2000;123:2109–17.
[17] Nichols MJ, Newsome WT. The neurobiology of cognition. Nature 1999;402:C35–8.
[18] Paulus MP, Hozack N, Zauscher B, McDowell JE, Frank L, Brown GG, et al. Prefrontal, parietal, and temporal cortex networks underlie decision-making in the presence of uncertainty. NeuroImage 2001;13:91–100.
[19] Schall JD. Decision making: from sensory evidence to a motor command. Current Biology 2000;10:R404–6.
[20] Schneider SL, Lopes LL. Reflections on preferences under risk: who and when may suggest why. Journal of Experimental Psychology: Human Perception and Performance 1986;12:535–48.
[21] Shizgal P, Conover K. On the neural computation of utility. Current Directions in Psychological Science 1996;5:37–43.
[22] Slovic P, Lichtenstein S. Importance of variance preferences in gambling decisions. Journal of Experimental Psychology 1968;78: 646–54.