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Causes of social reward differences encoded in human brain

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Vostroknutov A, Tobler PN, Rustichini A. Causes of social reward differences encoded in human brain. *J Neurophysiol* 107: 1403–1412, 2012. First published December 7, 2011; doi:10.1152/jn.00298.2011.—Rewards may be due to skill, effort, and luck, and the social perception of inequality in rewards among individuals may depend on what produced the inequality. Rewards due to skill produce a conflict: higher outcomes of others in this case are considered deserved, and this counters incentives to reduce inequality. However, they also signal superior skill and for this reason induce strong negative affect in those who perform less, which increases the incentive to reduce the inequality. The neurobiological mechanisms underlying evaluation of rewards due to skill, effort, and luck are still unknown. We scanned brain activity of subjects as they perceived monetary rewards caused by skill, effort, or luck. Subjects could subtract from others. Subtraction was larger, everything else being equal, in luck but increased more as the difference in outcomes grew in skill. Similarly, reward-related activation in medial orbitofrontal cortex was more sensitive to the difference in relative outcomes in skill trials. Orbitofrontal activation reflecting comparative reward advantage predicted by how much subjects reduced unfavorable reward inequality later on in the trial. Thus medial orbitofrontal cortex activity reflects the causes of reward and predicts actions that reduce inequality.

rewards coding; merit; skill-luck

OUTCOMES OF INDIVIDUALS PERFORMING a task may vary because of skill, effort, and luck. Individuals high in skill and more willing to produce effort usually perform better and earn more rewards. The social perception of the inequality in outcomes may depend on what produced it. We study this social perception and its consequences in behavior and brain activation. We do so by building on extensive literature on brain processing of rewards and of relative rewards, adding one dimension: the cause of the reward and in particular the role of skill and luck in determining outcomes. As we examine the effects on behavior and patterns of brain activation, we expect to find mechanisms in action that are by now familiar in relative reward processing. What will this new dimension add? We rely on two widely accepted principles in the philosophical and game-theoretic literature, which determine how we respond to causes of inequality in outcomes: the signaling and merit principle.

The merit principle (Feinberg 1963; Kleinig 1971; Lamont 1994; Macleod 2005; Moriarty 2002) states that an individual deserves a reward when it is responsible for it. Following this principle, individuals are less inclined and feel less justified to reduce inequalities of outcomes when they are due to skill and effort rather than luck. There is experimental evidence that subjects follow this principle (Hoffman et al. 2008; Hoffman and Spitzer 1982, 1985; Konow 2003). The signaling principle states that when a difference in outcome is observed in a skill task, the better performance will be attributed at least in part to skill and not only effort. If we have no prior information on *individuals A* and *B* and are informed that *A* performed better than *B* in a skill task, we should, and typically will, think that *A* is in some measure more skillful than *B* in that task. This opinion will be stronger, and the perceived difference larger, the larger the difference in the outcomes. If instead we know that *A* won a coin flip, our opinion of *A* and *B*'s skill will not change, no matter how large the win is. The signaling principle has a foundation in biology and in economics ("honest signaling"; Spence 1974; Zahavi 1975).

The interaction of the signaling and merit principles creates a tension that is operating in our experiment. Three subjects played 12 trials of both a skill and a luck game. At the end of each trial, all subjects first saw his own score and then the score of all other players. They then had in every trial the opportunity to reduce the payment of others. Whether they did was never communicated to the other subjects, so there was neither opportunity nor reason for retaliation in later trials. We make two predictions. First, individuals will be more inclined, everything else being equal, to reduce inequalities in outcomes when they are due to luck (merit principle). Second, the psychological impact (joy in the winner, disappointment in the loser) will increase with the size of the difference in outcomes in a skill task because the outcome will be considered as a signal to all observers of a superior skill of the winner or of an inferior skill of the loser (signaling principle). When large enough, the temptation to reduce inequality in a skill task might outweigh the merit principle, and individuals might overall feel more inclined to reduce inequality in skill games with large differences in outcomes. This temptation is not an attempt to hide or garble the signal but rather an expression of the negative affective impact of the perceived difference. These effects should be observable in behavior, in self-reports on emotions, and in brain activations.

Our results are consistent with these predictions. Behavior in skill and luck games differed substantially; the difference in outcomes mattered more in skill than in luck games. The probability that subjects reduced the payment of others was, everything else being equal, higher in a luck game; but that probability was more sensitive to the size of the difference between the performance of others and that of the subject in the skill game: larger probability of subtracting for a larger difference. Neurally, we anticipate activity in orbitofrontal cortex

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(OFC) because it has been implicated in processing the value of outcomes (O'Doherty 2007). However, it is unknown whether these regions would show the predicted larger sensitivity to outcomes arising from skill compared with luck. We found that this is indeed the case. The degree of enhancement of outcome-related OFC activation by skill over luck predicted the degree to which participants subsequently reduced differences in reward distribution. Another structure involved in the processing of rewards, the striatum, is also sensitive to the difference between skill and luck but at the moment of the subtraction decision.

MATERIALS AND METHODS

Experimental design. Three subjects participated in each session, one inside the scanner and two outside. Each session consisted of 24 trials. In each trial (Fig. 1*A*), the three subjects played the same game against a computer. The game was either a game of skill or a game of luck. In the game of skill, subject and computer were moving one after the other, sequentially, changing the position of a common marker on a board. The player who moved the marker to a specified position won. The game is the graphical representation of the following game: 2 players face 2 piles of coins, each pile with a number of coins between 1 and 5. They take turns and remove as many coins as they want from 1, and only 1, pile. The player who takes away the last coin wins. Winning depended on the ability to foresee correctly future moves of the computer. Subject and computer alternated in moving first. The initial positions were the same for all three subjects in the experimental session and for all of the sessions. Half of the positions were winning positions for the subject, and half for the computer. The game is the same (except for the graphical presentation) as the Hit 15 game in Burks et al. (2009). See the supplementary material available online at the *Journal of Neurophysiology* web site for a detailed description and a picture of the board. Better performance in this game is a reliable signal of better cognitive skills. For example, in the data of Burks et al. (2009), the correlation between the score in Raven's Progressive Matrices and the score in the skill game (Hit 15) is 0.411 with $P < 0.00001$. In the game of luck, the subject had to guess the future random choice of a number, between 1 and 12, made with equal probability by the computer: thus the probability of winning was independent of subject's choice, and the score only depended on luck. Subjects were informed that the opponent in the two games was a computer program and not either of the other two subjects.

There was no other difference among the tasks of the three subjects. Parameters in the design were chosen to ensure that the probability distribution of individual monetary rewards in the two games was similar. The initial monetary outcome in any given game depended only on the skilled performance or luck of the individual player and thus was independent of the action or efforts of the others. At the end

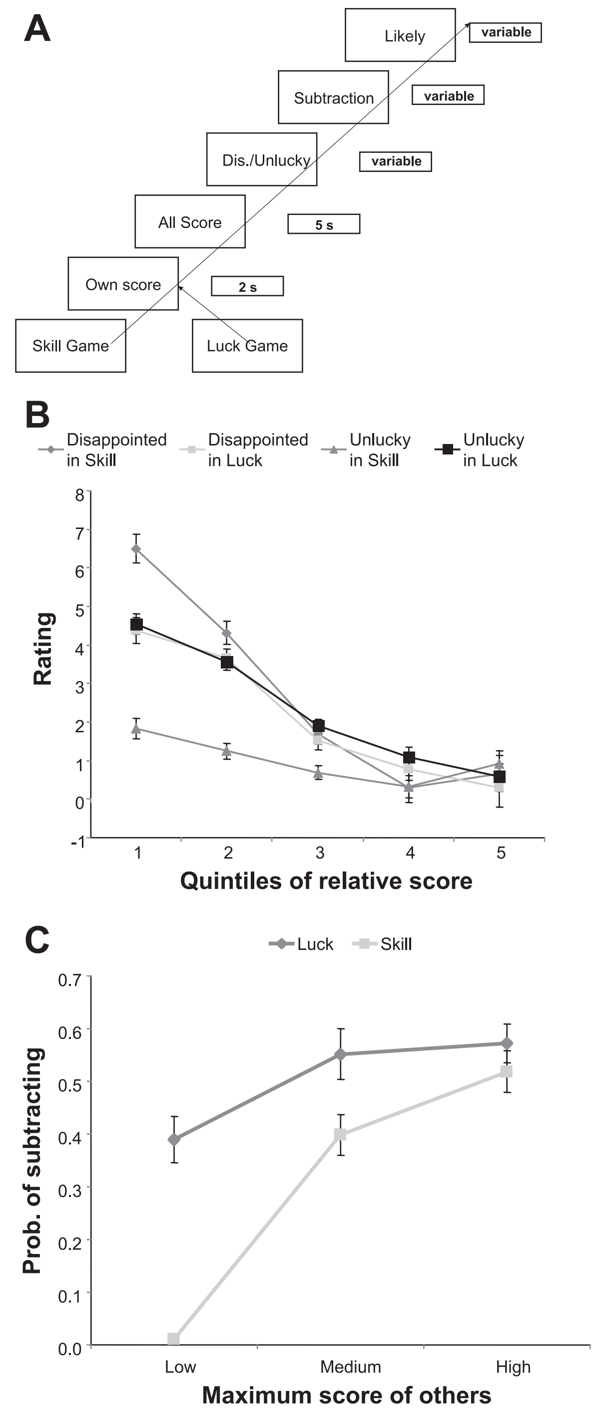

Fig. 1. Design and behavioral results. *A*: experimental design. The figure displays the sequence of events in a trial. An experimental session consisted of 24 trials, and in each trial the subject played a game with a computer. The game was either a skill game (*left*) or a luck game (*right*). The 24 trials were separated in blocks of 3 by a 20-s break in which the subject was looking at a fixation point. The 3 trials in a block were of the same type (skill or luck). The sequence of events was the same in every trial: after the game, subjects 1st were informed whether they had won or lost and given their score for 2 s (own score); then they saw the score of all participants for 5 s (all score), stated how disappointed (Dis.) and unlucky they felt, decided whether, how much, and from whom to subtract, and stated how likely it was that the others were subtracting from them. There was no time constraint on these latter 3 task components. A new trial would then begin. *B*: disappointed and unlucky ratings in skill and luck games. After they saw their own score and the score of the other players in a trial, subjects gave a numerical rating on a scale from 0 to 10 of how disappointed and unlucky they felt. The graph presents the subjects' mean (bars represent standard error of the mean) ratings on disappointed and unlucky scales in games of skill and luck. On the horizontal axis, we report the quintiles of the variable relative score, which is equal to the difference between the score of the subject and the maximum of the scores of the other 2: 1 is the lowest quintile, where subjects were relatively worst off. The size and effect of the variables changed slightly over the experimental session but did not reduce the effect of the reward of others on ratings; instead, the effect of the maximum score of others was increasing ($P = 0.0012$ for the interaction between maximum score of others and number of skill games played) as the sessions progressed. *C*: decision to subtract and maximum score of others. The graph presents the mean (bars represent standard error of the mean) frequency of a decision to subtract from others in the low, medium, and high group of the maximum score of others. The probability (Prob.) of subtracting in skill is lower than in luck, but it is more sensitive to the maximum score of others.

of each trial, subjects could see their score and the score of the others, and they had to rate on a positivity scale whether they felt disappointed or unlucky. They had then the choice of subtracting (as in Zizzo and Oswald 2001), at no cost, from the score of either of the other two players. Subjects were never informed of the decision of others to subtract. At the end of the experiment, they were only told the total net payment. Hence, they could not condition their decision, and their brain responses could not depend on the action of others during the experimental session.

Implementation. A total of 108 subjects participated in our experiment, so 36 subjects were scanned. Subjects were students recruited at the University of Minnesota (mean age = 22.4 yr, range = 20–25 yr), all male. All three subjects in a session performed exactly the same tasks in the same sequence. No deception was used at any time. All subjects participating in the experiment gave written informed consent to participate according to the procedures approved by the University of Minnesota Institutional Review Board. We chose to have 2 subjects outside of the scanner (instead of 1) to insure sufficient variability of the outcomes and to give some degree of anonymity to the subjects. With 3 participants, no subject could tell who had subtracted money from him. Anticipating this fact, a subject would not feel his behavior limited by the awareness that he would then meet the other at the end of the session. The regressions we present are limited to subjects in the scanner to insure that behavioral and imaging data come from the same pool of subjects.

Subjects were briefly introduced before the experiment, and informed that they would later "interact" in some way to be specified in the instructions. Subjects were then informed that they would play some games against a computer; they would then have to answer some questions and make additional choices. The rules of the skill game were presented to all subjects only immediately before the task was performed so that subjects would not be able to think about the solution in advance. The sequence of events in each trial, after the game was played, was identical in skill and luck trials: first, participants observed their own winnings, and, after a 2-s display, they were shown the screen reporting the scores of all three participants. This display lasted 5 s; after that, they were asked to give evaluations of their performance, and they were given the choice to subtract money from one of the other players. They were finally asked to evaluate the probability that one of the others had subtracted scores from them, and, after a 10-s break, the new trial would begin. Subjects had no time constraint when deciding their moves, providing the feedback, or deciding in the subtraction step.

Subjects received 10 points for every win in the skill game, and 1 point was subtracted for every move made. In the luck game, they were paid 6 points minus the distance between their number and the number chosen by the computer. For both games, the range of possible scores was between a minimum of 0 and a maximum of 6. The distribution was estimated in a pilot study to be such that the expected payoff from the 2 games was approximately the same, 2.5 points. Each point was worth 25¢ of $1 paid at the end of the experiment in cash, minus the amount subtracted.

Visual displays and times. A block of 3 games of the same type were followed by a 20-s break. At the end of the skill game, the message "You won" or "You lost" was displayed for 2 s. After the choice in luck game, the blue hand rotated for 3 s; when it stopped, the subject could see how much he had won. There were no time constraints on the choices in both games. Before the 1st, 7th, and 10th skill games, subjects in the scanner passively observed a screen displaying the board for the skill game for 8 s. The dial was presented as a visual display for 8 s before the 1st, 4th, and 10th luck games. These visual display trials were used to control for the effect of visual stimuli.

Payments. The subject in the MRI scanner was paid $40 for participation; the other two were paid $20. The difference in the flat payment for participation in the experiment was presented as a compensation for the discomfort of lying in the scanner. Subjects were not informed of the final payment to others. Each point earned in the session was converted into 25¢. The average variable earning in the experiment was $15.6.

Imaging parameters. During the entire experiment, the subject was lying in supine position in the bore of the scanner. The subject communicated his choices through a button box. Choices were presented on a screen located behind the subject, who could see them through a mirror in the head coil. A 3-Tesla whole body MR system (Magnetom Trio; Siemens Medical Center, Erlangen, Germany) at the Center for Magnetic Resonance Research at the University of Minnesota was used for image acquisition. Before the functional run, 144 or 160 (depending on the subject's head size) FLASH images were acquired in slices of 1-mm thickness in the sagittal plane (256 $\times$ 256 mm), giving a spatial resolution of 1 mm^3 for the anatomic volume. The repetition time (TR) was 20 ms, the echo time (TE) was 4.7 ms, and the flip angle was 22°.

After that, a whole brain functional MRI (fMRI) was performed using an echoplanar imaging sequence (EPI) measuring the blood oxygenation level-dependent (BOLD) signal. A total of 30–38 functional slices per volume were acquired for each subject. The slices had 3-mm thickness, acquired in transversal plane, in a field of view of 192 $\times$ 192 mm. No gap separated the slices. The TR was 2,000 ms, the TE was 23 ms, and the flip angle was 90°. The matrix size was 64 $\times$ 64, the resolution 3 $\times$ 3 $\times$ 3 mm. The total number of volumes was variable, depending on the length of time necessary to complete the task.

Preprocessing of fMRI data. BrainVoyager QX version 2.1 (Brain Innovation, Maastricht, The Netherlands) software was used for fMRI data preprocessing and analysis. The two-dimensional images of every subject were preprocessed to correct for motion artifacts, with a threshold of 3-mm movements in any direction. Also, a correction for differences in slice scan time acquisition and for temporal linear trends was used. The functional images were then used to construct a three-dimensional (3D) functional volume for every subject and every run. Spatial smoothing was performed by using a Gaussian full width at half maximum (FWHM) kernel of 7 mm. The 3D functional volume was then aligned with the corresponding 3D anatomic volume. Both were then normalized to standard Talairach space. The statistical parameters of the model were computed voxelwise for the entire brain, and activation maps were computed for various contrasts between the predictors. Data were convolved with a 2-γ-hemodynamic response function with the following parameters: onset displacement, 1 TR; response to undershoot ratio, 6 s; time to peak of the positive function, 5 s; time to peak of the negative function, 15 s.

Event-related average analysis. Event-related average analysis in all figures is executed with the file-based method. In the file-based method, the baseline for the conditions that are being compared is computed by taking the average over subjects and conditions in a given time interval before the onset of the condition. This method is different from the epoch-based method where the baseline is taken to be the specific value in the trial (Stark and Squire 2001). In our analysis, this time interval is 2 s; percentage change with respect to this baseline is then computed and averaged. Data are displayed for a window of 2 s before the event and 18 s after. The values displayed in the figures are percentage changes with respect to this baseline. Note that the values at baseline in the file-based method may be different from zero in the two treatments because the average is taken over the treatments. Of course, they may also be zero as they seem to be in the evaluation and OFC estimate; this simply indicates that there is little difference between the two treatments at baseline. So the difference in the OFC is mostly on the path, and the difference in the striatum is mostly on the baseline.

Cluster-level statistical threshold estimator. The cluster-level statistical threshold estimator is implemented as a plugin available in BrainVoyager (Goebel et al. 2006). It uses the idea (presented in Forman et al. 1995 and modified in Goebel et al. 2006) that a true signal will be more likely to stimulate several contiguous voxels. The method provides a threshold value for each individual voxel as a function of the desired level of probability of false positive and a threshold of cluster size of contiguous voxels. The method precludes the identification of true activations in clusters of size smaller than the threshold but increases the statistical power for regions of larger size. The FWHM value was set to 1.275 in units of the functional voxel ($3 \times 3 \times 3$ mm) corresponding to an isotropic Gaussian kernel of 3.825 mm. The number of iterations was 1,000.

RESULTS

Behavioral results. We first tested whether only their outcome or also the comparison with that of others mattered to subjects. To quantify the influence of others' outcomes, we computed the difference between their own score and the maximum score of the others, and we call it relative score. Both ratings of feeling disappointed and unlucky decreased in the score of the subject but also in the relative score. The effect was significant: the coefficient of regression on relative score was negative and significant in both games ($P < 0.005$ in both games; see Supplemental Tables S3–S5). Thus, irrespective of the game played, subjects value a reward not only in absolute terms, but also in relative terms through a comparison with the rewards of other players.

Subjects show in their ratings that they perceived the two games very differently: for any unfavorable relative score in the game of skill, the feeling of disappointment was largely and significantly higher than the feeling of being unlucky. Conversely, in the game of luck, the two ratings were statistically equal (Fig. 1*B*). The difference in the effect of relative score on the two ratings was confirmed by regression analysis (Wald $\chi^2 = 620.2$, $P < 0.00005$): interacted with skill, the relative score had a negative and significant effect on the disappointed score (coefficient -0.17, $P = 0.008$) and a positive and significant one on the unlucky score (coefficient 0.60, $P < 0.0005$). Thus an unfavorable relative reward difference affects disappointment more in skill than in luck games, and the unlucky evaluation more in luck games.

We finally studied whether the nature of the game influences the way in which subject respond to differences in the relative outcomes. The dependent variable we focus on is the probability that the subject decides to subtract from others. We chose this instead of, for instance, the amount subtracted because this variable is constrained to have a total value of 1, hence it cannot be rescaled. So, if an interaction between nature of the game and amount of the difference is found, this difference is invariant to rescaling, and comparisons of the sensitivity of the response with the difference in outcome in skill and luck are meaningful. The merit principle should make subjects feel more justified in subtracting in luck than in skill; hence the probability of an individual subtracting should be higher in luck when the score of others is only little higher than his. The signaling principle should make them more likely to subtract in skill in proportion to the difference in performance. The net effect would be that the difference in amount subtracted is small in the two environments, whereas the likelihood of subtracting is more sensitive in skill to the difference in performance.

In agreement with the merit principle, skill trials reduced the probability of subjects subtracting from others compared with luck trials (Supplemental Table S6). However, in agreement with the signaling principle, the probability that the subject subtracted from others decreased with the relative score more in the skill games than in the luck games. An easy way to see this is to consider the coefficients in the logit regression (Wald $\chi^2 = 102.8$, $P < 0.00005$). The direct effect of skill game was negative (coefficient -3.5, $P < 0.0005$; the total effect is a reduction of 52%). This is the merit principle: everything else being equal, subjects subtracted more in luck. On the other hand, the interaction between relative score and skill has a negative and significant effect (coefficient -0.60, $P < 0.0005$). The effect is large: the total variation induced over the range of the relative score is ~79%; one additional point in the relative score reduces the probability of deciding to subtract by 8.6 percentage points more in the skill game than in the luck game. Results were similar when relating subtraction probability to the maximum outcome of others (Fig. 1*C*, Supplemental Table S6).

Subjects behave according to the two principles but also expect others to behave this way. We confirm this by considering subjects' belief about the subtraction behavior of other players. In each trial, a subject gave a rating, on a scale from 0 to 10, of how likely he thought it was that one of the two other subjects had subtracted points from him. We analyze (Supplemental Table S8) the probability that the rating is >5. Regression analysis shows that score and the relative score of a subject increased (Wald $\chi^2 = 115$, $P < 0.0005$) the expectation that others subtract (marginal effect 9.3% for each unit of score, $P < 0.005$, and 3.2% for each unit of relative score, $P = 0.003$). However, skill, everything else being equal, reduced the expectation by 10.1% ($P = 0.008$). These data support the idea that the relative comparisons are important, that the merit principle is widely accepted, and that individuals expect others to do the same.

In summary, the nature of the game affected both the perception of the relative reward and the behavior of subjects. Disappointment was more sensitive to relative rewards than the feeling of being unlucky. Everything else being equal, subjects subtracted more in luck games, but subtraction was more responsive to the difference between own score and others' in skill games. The behavioral data support the hypothesis that evaluation of outcomes and behavior depend on the interaction of both merit and signaling principles.

Imaging results. Using fMRI, we analyzed brain activity at the time when the score of all players was revealed and when the decision to subtract was taken. When scores of all players were displayed, subjects saw the same visual stimuli and observed own and relative outcomes, both in skill and luck trials. The only difference was the background information that those scores were obtained in a skill or luck game. The hypothesis we tested is that OFC has a different response to relative score depending on whether the outcomes arise from skill or luck.

A general linear model (GLM) including parametric and categorical regressors was constructed to explain brain activity at the moment in which the score of all subjects was displayed. *Time 0* was the moment of display of the score of all subjects. The duration of regressors was 5 s. The GLM included the subject's score in the game and the relative score as a parametric modulator of that time point separately for skill and luck conditions. The regressor relative score was multiplied by the indicator function of the time point in which subjects observed the score of all participants. This value was convolved with a

2-γ-hemodynamic response function (onset displacement, 1 TR; response to undershoot ratio, 6 s; times to peak, 5 and 6 s, respectively).

Figure 2*A* displays results of the contrast between two estimated coefficients of the relative score variable: the one in skill and the one in luck. The only cluster showing a significant difference (at $P < 0.0001$, uncorrected) is the OFC cluster. It occupies a medial and anterior region of OFC with x-coordinates in the interval 9, 20, y-coordinates in the interval 36, 49, and z-coordinates in −21, −12. The peak (lowest) P value, 0.0008, was at Talairach coordinates 12, 38, −17. The results are robust to the introduction of different parametric model specifications: for example, the length of the time interval after onset was varied between 2 s and the full length of the interval (5 s) with no significant difference in results.

A categorical GLM corroborates the results obtained with the parametric specifications. In this GLM, a categorical regressor was defined with onset at the moment at which the outcome is communicated and with duration of 5 s. Relevant events were "top skill" and "no top skill." Top skill is equal to 1 in all the skill trials in which the score of the subject was strictly larger than the maximum score of the other two players. No top skill corresponds to the remaining skill events in which the subject's score was equal or less compared with that of the

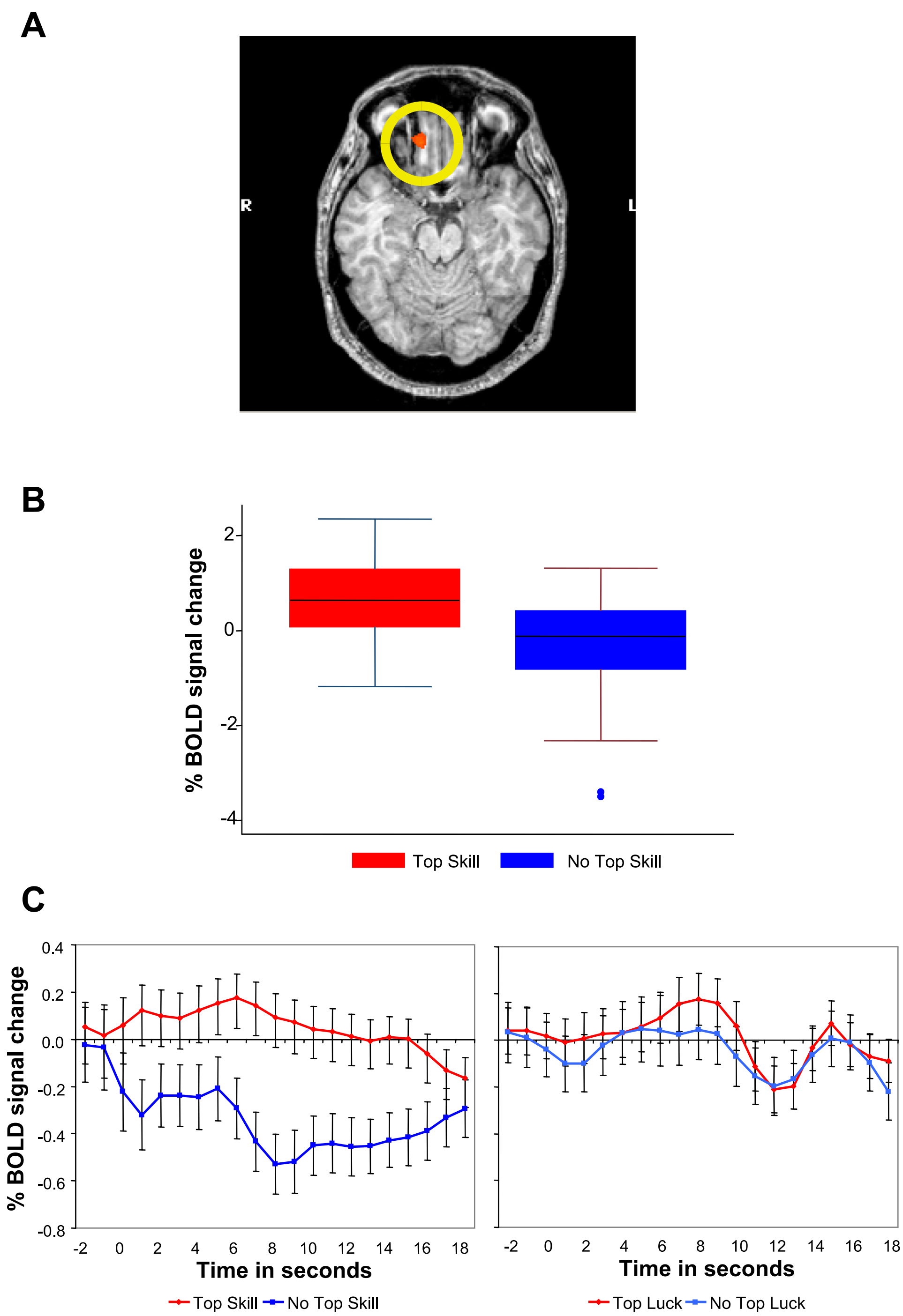

Fig. 2. Orbitofrontal cortex (OFC) activation. *A*: OFC activation for relative score in skill compared with luck. Mean Talairach coordinates: 14, 39, −16; uncorrected P value threshold: 0.0005 ($z = 3.87$). Contrast: relative score in skill > relative score in luck. The cluster is significant at the 5% level after cluster threshold estimator correction (see MATERIALS AND METHODS and supplemental material). In the categorical model, with contrast (top skill − no top skill) > (top luck − no top luck), 2 clusters show similar significance. The mean coordinates of the 2 clusters are 15, 39, −16 and −3, 35, −20; the categorical cluster in the right hemisphere has large overlap with the parametric cluster displayed here (see supplemental material). R, right; L, left. *B*: brain activation in skill trials. The figure displays median (horizontal line in the box) and range from 25th to 75th percentile (box) of percentage blood oxygenation level-dependent (BOLD) change (PBC) in top skill and no top skill in the right OFC cluster identified by the parametric model. Mean value at top skill is 0.68, and at no top is −0.28. Wilcoxon matched-pairs signed-ranks test that the PBCs in the 2 events have the same distribution for skill yields $z = 4.46$, $P < 0.0005$. The same test for luck: $z = 0.50$, $P = 0.615$. See supplemental material for the figure in luck trials. *C*: brain activation to distinct relative rewards in skill and luck trials. Event-related average (ERA) analysis in top and no-top events, in the categorical model, for skill (*top*) and for luck (*bottom*). Mean and standard error of the mean are reported at each second.

others. We proceeded similarly for luck trials and classified them into "top luck" and "no top luck" events. The relative effect of skill and luck was expressed in this case by the difference between top skill and no top skill and top luck and no top luck. Note that the information on the outcome of others is new and independent from the subject's own score, thereby dissociating own vs. relative reward effects on hemodynamic response. With this model and contrast, we found a region in OFC largely overlapping with the one determined in the parametric model: peak P value = 0.0008 at 12, 41, −17. (Supplemental Fig. S5 reports both clusters, overlapped.) The peak voxels for the parametric and categorical models were in the OFC, right Broadman Area (BA) 11.

Thus the difference in OFC activity between top and no top was significantly higher for skill than for luck (Fig. 2*B*). Hence OFC activity appears to correlate with the social relevance of the signal that a success in skill reports to individuals. Average event-related time course analysis (with *time 0* equal to the moment of display of the score of all subjects) revealed a clear activation pattern difference for skill trials where the subject's score was strictly larger than the maximum score, and those trials where the score was less than or equal to the maximum score. There was no such difference for luck trials (Fig. 2*C*).

The results we have reviewed suggest that OFC activity may distinguish relative rewards depending on whether they are caused by skill or luck. OFC activation to obtaining an outcome larger than others in skill can be taken as a neural measure of the subject's sensitivity to interpersonal comparisons when the outcome is a signal of skill. A related measure of sensitivity to comparative rewards is the difference between sensitivity to having the largest outcome and not having it. The correlation with subtracting behavior in skill is similar (r = 0.417, P = 0.011). It is natural to conjecture that these measures will predict subsequent subtraction behavior when the reward is deserved and carries signaling information. To test this conjecture, we considered their relation with behavior at a later moment, when subjects decided whether and how much to subtract from others. Figure 3 shows that the mean amount subtracted by a subject increased with activation in the right OFC cluster at the moment when outcomes of all subjects were revealed and the subject had the highest score in skill games rather than not (Fig. 3*A*). Conversely, the mean amount subtracted in luck did not increase with activation in the same cluster for the corresponding event in luck games (Fig. 3*B*).

A subset of 12 out of 36 subjects never subtracted points from others. Whether a subject belonged to this group was partly predicted by the intensity of the top skill activation in the OFC cluster. We call "subtractors" the 24 subjects who subtracted from others at some point during the experiment. Activation for being on top in skill was significantly higher for subtractors than for the 12 "nonsubtractors" (0.94 and 0.11%, respectively; $P < 0.005$, Mann-Whitney nonparametric test). We also directly estimated how the OFC activation predicted whether a subject belonged to the group that never subtracted by looking at either the activation difference between *top* and *no top* in skill or the activation of *top skill* alone. In both cases, the correlation was negative and significant (P = 0.048 and $P < 0.005$, respectively). Thus the larger the activation, the smaller is the probability of belonging to the nonsubtracting group. There was no correlation between the average score in skill and these two activation values ($P > 0.05$): this shows that the relative score, but not the personal score, matters.

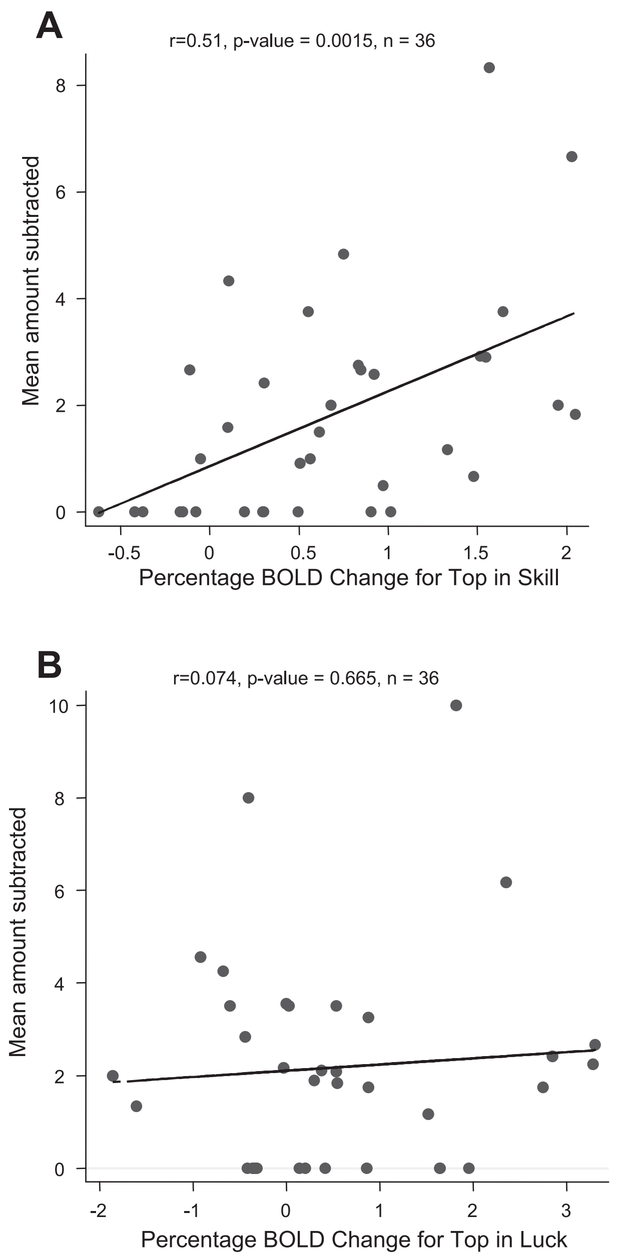

Fig. 3. OFC and subtraction behavior. *A*: relation of OFC activation to best relative reward and subsequent subtraction from others in skill rounds. On the horizontal axis: percentage BOLD change in skill when the subject's outcome was the highest. On the vertical axis: mean amount subtracted in skill. The independent variable in the regression was the estimated coefficient in the region of interest analysis, so it was subject to measurement error; hence the displayed effect was subject to an attenuation error, that is, the estimated effect was smaller than the true effect. We could, however, estimate the true coefficient (see Fuller 1987; Leamer 1987) to be larger than the estimated coefficient (which is equal to 1.03) and smaller than the inverse of the coefficient in the reverse regression (which is equal to 5.46); so the effect was significant and positive. *B*: subtraction and brain activation in OFC in luck rounds, as in *A* but for luck rounds.

Since striatum is involved in reward processing, it is natural to expect activity in the striatum area at the moment in which the score of the subject is revealed, in proportion to the amount won, both in skill and luck games. In the GLM model, a categorical regressor was defined taking values high win (defined as winning 3 points or more in both games) and low win (in the other case) with onset at the moment in which the win is communicated and with a duration of 3 s. The contrast between high and low win in both games reveals a large cluster in the caudate body (peak P value = 0.0002 at −13, 5, 3). The activity is driven in large part by the high wins in skill games; the contrast between skill and luck of the difference high win and low win is marginally significant (peak P value 0.006 at −12, 20, 10). In a GLM model where prediction error was estimated, the striatum was found also coding the prediction error difference between what is expected and what actually occurs in relative score (peak P value = 0.0002 at −12, 5, −2). These data are in agreement with a bulk of evidence implicating the striatum in reward processing (in our case, both private and social) and in prediction error coding.

Striatal activation was different between skill and luck trials at the moment of the decision whether to subtract. This suggests that the striatum is part of a network performing a different role, involving the decision to subtract. The contrast between the activation at subtraction in skill and that in luck revealed a significant cluster of activation in the ventral and medial striatum, including parts of the caudate (Fig. 4; peak value at −15, 4, 4). These data suggest that the striatum might contribute to the distinction between the two situations only later in time, when subjects decide how much to subtract.

A natural interpretation of a larger striatal activity when deciding to subtract in skill may be based on the signaling principle. Subtracting points is more rewarding in skill than in luck because skill signals permanent differences, and luck only transitory ones. Thus a larger distance from the outcome of the others has a stronger negative affect, and more rewarding is the response to subtract to compensate for the difference. To test further this possibility, we related individual rating and subtraction behavior to striatal activations. The mean rating of disappointment was significantly and positively related to the difference between the percentage BOLD change (PBC) at subtraction in skill and in luck in the left striatum cluster (P = 0.047). Mean disappointment rating was 1 point larger in the group of subtractors than in the group of nonsubtractors. The striatal activation at subtraction in skill games also predicted whether the subject belonged to the group of those who subtracted points. Subtraction-related activation in the left striatum cluster was larger in skill games for subtractors than nonsubtractors (the mean PBCs are 0.37 for subtractors and 0.22 for the others; Mann-Whitney nonparametric 2-pair test yields z = 2.28, P = 0.003). The marginal effect of this activation on the probability of belonging to the group of subtractors was large (standardized coefficient = −0.37) and significant (P = 0.026). Also, the mean amount that each subject subtracted in the skill trials was significantly increasing with the activation in the left striatum (P = 0.047; Fig. 4*D*). Controlling for the average score in skill games did not affect size or significance of this relation. Finally, there were no comparable effects in luck trials.

DISCUSSION

Our results show that the cause (be it skill or luck) of rewards and of reward inequality matters both for behavior and brain activation of individuals evaluating the reward. Thus causes of rewards are critically involved in judgment of justice

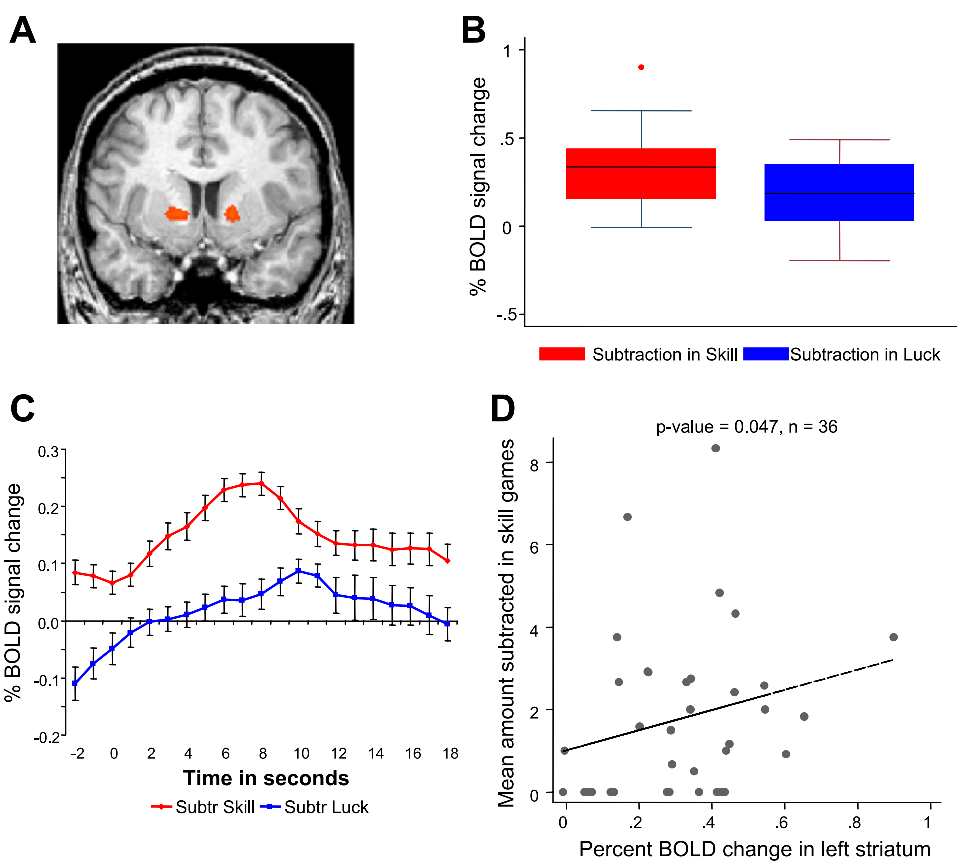

Fig. 4. Striatum activation. *A*: striatum activation in subtraction in skill trials compared with luck trials. The mean Talairach coordinates of the 2 clusters in the striatum were in a roughly symmetrical position: mean coordinates at −15, 4, 4 and 12, 3, 4; uncorrected P value threshold: 0.0005 (z = 3.87); the cluster is significant at the 5% level after cluster threshold estimator (CTE) correction (see supplemental material for details on CTE). *B*: brain activation at subtraction. The figure displays PBC at the time of subtraction in skill and in luck in the left striatum cluster (see Fig. 2*B* for details). Mean value for skill is 0.32, for luck 0.18. Wilcoxon matched-pairs signed-ranks testing whether the PBCs in the 2 events have the same distribution yielded z = 3.61, P = 0.0003. Thus the striatum showed larger activity during subtraction in skill than in luck trials. *C*: brain activation at subtraction (Subtr) in striatum. The figure displays ERA analysis at the time of subtraction in skill and luck trials in the left striatum cluster. Method as described in Fig. 2*C*. *D*: amount subtracted predicted by striatum activation. The figure displays the mean amount subtracted in skill games and PBC in left striatum at subtraction in skill games. Controlling for the effect of the average score at skill does not alter either significance or effect size (see MATERIALS AND METHODS for details).

and merit of those rewards. By explicitly comparing skill and luck and revealing the interplay of merit and signaling principles, these results go beyond previous findings of humans following the merit principle, which had been the focus of earlier related investigations. Our subjects, just as those in principle (Hoffman et al. 2008; Hoffman and Spitzer 1982, 1985), too behaved as Lockeans in that they followed the merit principle and were less likely to subtract, everything else being equal, from others in skill than luck trials. However, they also paid great attention to the signal that outcomes give on relative ability: by increasing their probability of subtracting more in skill than luck games, subjects followed the signaling principle.

Particularly relevant here is the study of inequality-averse social preferences in Tricomi et al. (2010). They report results of an experiment where subjects were matched in pairs, and the subject in the scanner received a transfer, randomly determined, which could be $0 (low-pay subject) or $50 (high-pay subject). The subject then observed further positive potential monetary transfers from the experimenter to themselves and to the other player and rated his subjective response to such transfers. Activity in the ventral striatum and ventromedial prefrontal cortex (vmPFC) was stronger in response to transfers to others than to self for high-pay subjects, whereas the activity of the low-pay subjects exhibited the opposite pattern. The vmPFC activation was bilateral, right at 9, 45, −13, close to our 12, 41, −17 activation.

The observed brain activations involving OFC and striatum in evaluations of social outcomes are also in line with neuroeconomic investigations on social norms in economic games (Behrens et al. 2009; de Quervain et al. 2004; Fliessbach et al. 2007; Izuma et al. 2008; King-Casas et al. 2005) and charitable giving (Hsu et al. 2008). An experimental environment is strategic if payoffs are jointly determined by the actions of players. Thus, for a player in a game, it is important to predict what the other will do because, depending on what the other does, the best response of the player changes. In the trust game, for example (King-Casas et al. 2005), the first player has to predict how the second player will behave when deciding how much money to transfer. In contrast, outcomes in the present experiment arose in nonstrategic environments, and subjects compared their outcome with the outcome of peers performing independently a similar activity. A theoretical investigation of behavior of individuals in this situation is developed in Maccheroni et al. (2011).

In contrast with this literature, in our study, behavior and brain activations arose from monetary outcomes that were independent of the actions and mental models of others. Our main innovation, in method and research question, is the explicit role assigned to skill and luck.

Disappointment was higher, the feeling of being unlucky lower, and the propensity to subtract from others more sensitive to others' rewards in skill than luck trials. These behavioral differences were reflected by OFC activations discriminating outcome inequality due to skill in a more pronounced fashion than inequality due to luck. One would expect such differences if the reward or the reward inequality is regarded as a product of personal characteristics and effort rather than chance. An inequality that is due to pure chance is perceived as less consequential for the future of the individual because it is likely to be balanced by later positive events and its affective impact should be small. On the contrary, an inequality that is due to skill is perceived as relevant because it affects one's relative position in the future. This difference has two implications: on how subjects perceive the inequality in reward and what they are willing to do when they are given an opportunity to correct it.

The distinction between two different bases for the inequality of rewards has significant consequences for the willingness of individuals to modify reward distributions. In both environments, the reward subtracted increases with the difference: the higher the reward of others compared with one's own, the more subjects are willing to subtract to compensate for the difference. Our results show that if a reward can be attributed to chance rather than personal characteristic or merit then subjects are more willing to reduce the differences, but the sensitivity to the size of the difference is higher when the reward signals skill. In other words, if we think of a simple linear relationship between the amount subtracted and the difference between the reward of others and the one of the individual, then the intercept is larger in luck, but the slope is larger in skill.

The OFC has a fundamental role in processing rewards (Kringelbach 2005; Kringelbach and Rolls 2004; O'Doherty 2007), not only in an absolute, but also in a relative fashion (Padoa-Schioppa and Assad 2006; Tremblay and Schultz 1999). Moreover, regret for not having made the right decision is coded in OFC (Bault et al. 2008; Camille et al. 2004; Coricelli et al. 2005). In these studies, outcomes usually arose from the experimenter or luck. In an imaging study, Bault et al. (2011) compare activity of subjects in a private condition (where they observe the outcome of an unchosen lottery) with that in a social condition (where they observe the outcome of a lottery chosen by another person). Both striatum and medial prefrontal were more activated by social gains than any other event. Our data extend the role of the OFC into a novel dimension by indicating that it is involved also in processing the causes of rewards where the merit and signaling principles operate. The data suggest that the OFC is particularly sensitive to the cause of relative social reward differences when that cause has merit and signaling implications as is the case in skill. Indeed, OFC activation may contribute to reducing inequality that has such signaling implications. In accordance with the merit and signaling principles, medial OFC activation preferentially reflected deserved rewards and reward differences and predicted the reduction of undeserved outcome differences.

The OFC is a heterogeneous structure, both anatomically and functionally (Kringelbach 2005; Kringelbach and Rolls 2004; Ongür and Price 2000). The location of the presently found cluster in the OFC is closer to the medial regions, the general area identified in metaanalysis as processing rewards (for example monetary gains, see Fig. 12 of Kringelbach and Rolls 2004). In the posterior-anterior direction, the cluster is in an anterior position, consistent with the abstract and complex nature of the reinforcers (relative comparison of outcomes) that we are considering and in contrast to the coding of primary reinforcers in more posterior regions. Thus the present findings are in good agreement with the previously proposed functional parcellation schemes of the OFC.

We observe activation of striatum at two distinct moments. The first is the time in which subjects observe their reward: in this case, the striatum shows activation increasing in the size of the reward. This finding is coherent with previous reports of striatal involvement in reward processing (Schultz 2000; Schultz et al. 1998). Delgado (2007) surveys studies (in particular, imaging studies) that identify the role of the striatum in mediating goal-directed behavior, extending from primary to social and economic rewards. This activity, as we noticed, is driven mostly by outcomes in skill rather than luck, a finding consistent with the additional value given to an outcome in skill by the signaling principle.

At the time of subtraction, striatal activity reflected the amount subtracted in skill more than in luck trials. These data suggest that it is more rewarding to subtract in skill than luck because of the signaling and merit implications of skill. This is consistent with social reward and reward difference coding in the striatum (Behrens et al. 2009; Fliessbach et al. 2007; Izuma et al. 2008). A related set of data has implicated striatal activity in processing the misfortunes of envied people (Takahashi et al. 2009), punishing defectors in an altruistic fashion (de Quervain et al. 2004), and males observing unfair players receiving pain (Singer et al. 2006). Thus the striatum (and perhaps particularly the caudate) may mediate the rewarding effects of setting the record straight in the social domain. Together with the present behavioral data, the evidence might suggest that particularly the signaling implications of reward inequality are important for striatal reward activity, not just the processing or reduction of inequality as such.

In summary, the present study has indicated some of the components of the mechanism by which social perception of the causes of the rewards affects reward processing and the behavior induced by this evaluation. OFC activation correlated with difference in outcome at the earlier time of reward occurrence (evaluation and action planning); striatal activation correlated with monetary subtractions from other players at time of subtractions (decision). Both regions have been found in the process of evaluating relative outcomes due to chance (Tricomi et al. 2010); the OFC cluster in this study is very close to the one found here. These results suggest that this region in OFC codes evaluation of relative outcomes, hence the distinction to be operated according to the cause (skill, luck, or effort) of the difference might be executed elsewhere. Striatum and OFC are strongly interconnected (Haber et al. 2006); their functional roles are the processing of reward expectation and occurrence, object-based value representation, and target selection (e.g., Samejima et al. 2007), so it is reasonable to find that they act together in evaluation of and response to relative outcomes. However, some findings also point to functional differences, with striatum being more involved in the processing of errors in reward prediction and OFC in coding of reward value (Hare et al. 2008). Our results add a novel distinction between the two regions in the social domain: the OFC seems to incorporate the value of social reward differences with the selection of future actions that reduce these differences, whereas the striatum is associated with the execution of such actions (in the absence of prediction errors).

The relation between justice and merit is the focal point in theories of social justice, which analyze how benefits and burdens should be distributed among individuals of a society. Ethical and political theories have different views of the relation between justice and merit. For Aristotle, Locke, and Mill, an allocation is just if it gives every individual according to what they deserve; for Adam Smith, justice depends on what an impartial observer would perceive an individual to deserve; for Rawls, generally accepted rules and past behavior legitimate an allocation as deserved, but merit is irrelevant to the fairness of an allocation.

GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

A.V. and A.R. conception and design of research; A.V. and A.R. performed experiments; A.V. and P.N.T. analyzed data; A.V., P.N.T., and A.R. interpreted results of experiments; P.N.T. and A.R. prepared figures; P.N.T. and A.R. drafted manuscript; A.R. edited and revised manuscript; A.R. approved final version of manuscript.

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Supplemental Material for "Causes of social reward differences encoded in human brain"

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Contents

1 Experimental Design

1.1 The Two Games

Skill Game

The skill game was played on a 5x5-cells board (presented in Figure 1) against a computer. Subject and computer had to move the black ball in turns. A player could move the ball horizontally left or vertically down by any number of cells. The player who moved the ball to the lower left corner of the board won; in this case the number of points he received was equal to 10 points, minus the number of moves made in the game. A player who lost received no points.

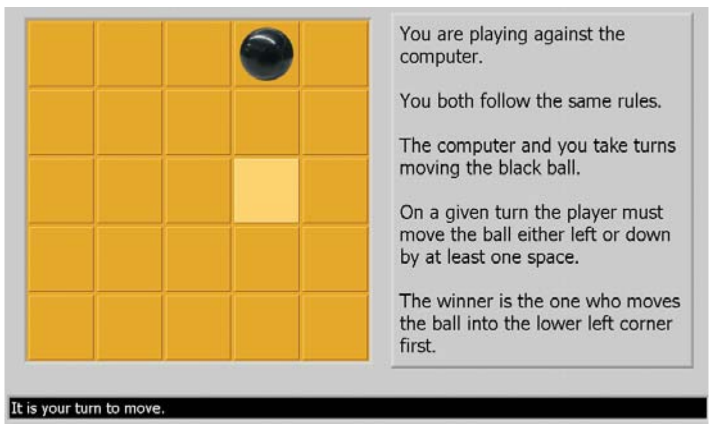

Figure 1: The skill game

The game is a graphical representation of the two piles Nim game [1], with an initial number of items in the two piles between 1 and 5. Positions on the main diagonal are losing positions (the player who has to move will lose against a player using the optimal strategy), all others are winning positions. The optimal strategy is to move the ball to a cell on the main diagonal, if possible.

The computer used the following strategy. In a winning position, move to the lower left corner (i.e. the final win position) whenever possible. In all other situations move to a diagonal cell with probability 85 per cent. With the complementary 15 per cent probability the computer chose with equal probability a move different from the winning move among moving left or down by one cell. The positive expected reward for the subject was given by the fact that half of the initial positions were winning positions for him and in addition by the 15 per cent error of the computer when the position was a winning position for the computer. In a losing position the computer would move randomly to any feasible position with uniform probability. In a losing position the computer would move randomly to any feasible position with uniform probability.

A 3-button box was used to make decisions. The first two buttons moved left or down (respectively) to a cell that would then be highlighted. The choice was confirmed with the third button. Moves to illegal positions were impossible. Figure 1 shows the screen observed by a subject during the skill game. The current position is indicated by the black ball. The highlighted cell indicates the position where the ball would move if the subject pushed the third button. The rules of the game were written on the right of the screen at all times. Messages relevant to the game were shown in the black box on the bottom of the screen; the messages were: “It is your turn to move”; “You won” and “You lost”.

Luck Game

In the luck game (see figure 2) a subject had to guess a number to be drawn with equal probability between 1 and 12. First, he would choose a number from 1 to 12 on a dial (red hand). Then the computer chose (blue hand) one of the numbers randomly with equal probability. A subject earned 6 points minus the shortest distance between the two hands.

Figure 2: The luck game

This game is clearly a pure luck game: the probability of winnings is the same for any choice of the of the subject.

Questions

After each game (skill or luck), subjects were shown the number of points won by all three (Figure 3.a). Then they were asked to answer questions. First, they were asked to evaluate how disappointed and unlucky they felt (Figure 3.b). After that, they had a choice of subtracting points money from another player (Figure 3.c). If someone chose to subtract money, he selected the winnings of one other player and then decided by how much he wanted the score to be reduced. The reduction occurred with probability

25 per cent at no cost to him. The last question (Figure 3.d) asked how likely it was that other players subtracted money from him.

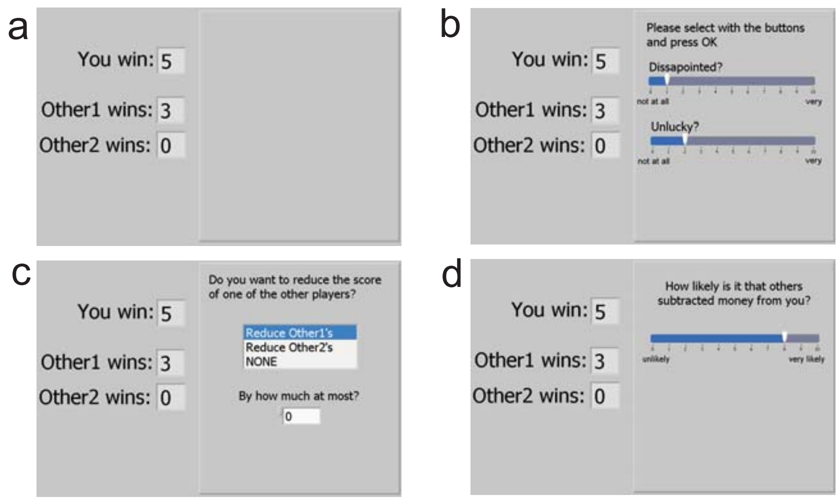

Figure 3: Evaluation and subtraction screens.

1.2 Time-line and Payment

Timing

The subject in the scanner observed a screen displaying the board for the skill game for 8 seconds without doing anything. This happens before first, seventh and tenth skill games. The image of the dial is presented for 8 seconds before first, fourth and tenth luck games. A block of three games of the same type were followed by a 20 seconds break. At the end of the skill game the message "You won" or "You lost" was displayed for 2 seconds. After the choice in luck game the blue hand rotated for 3 seconds; when it stopped the subject could see how much he had won. There were no time constraints on the choices in both games.

Payments

The subject in the MRI scanner was paid $40 for participation; the other two were paid $20. Each point earned in the session was converted into 25 cents. These variable earnings in the experiment were on average $15.6.

2 Analysis of Behavior

The statistical analysis of behavioral data is done with the statistical software *Stata/SE*, Release 11, Stata Corp LP, College Station, TX.

2.1 Subjective Ratings: Disappointed and Unlucky

Subjects provided a subjective rating on their feeling of being disappointed and unlucky after every game. Table 1 reports the descriptive statistics of these two variables.

Table 1: Descriptive Statistics of Disappointed and Unlucky.

Variable	Observations	Mean	Std. Error	[95% Conf. Interval]
disappointed	837	2.592	.117	[2.36, 2.82]
unlucky	837	1.757	.097	[1.56, 1.94]

The variable *maxother* is the maximum of the score of the two other subjects, while the variable *minother* is the minimum of the two scores. The variable *relscore*, relative score, is equal to the difference between the score of the subject and *maxother*. *skill* is equal to 1 when the round is a skill round.

Table 2 reports the median values of the evaluation scores for each quintile of relative score. It corresponds to Figure 1b of the main text that reports instead the *mean* values of the same variables.

Table 2: Median value of evaluation scores (Disappointed and Unlucky) per quintile of relative score in games of Skill and Luck.

Quintile of relative score	1	2	3	4	5
Disappointed in Skill games	8	4	0	0	0
Disappointed in Luck games	4	3	0	0	0
Unlucky in Skill games	0	0	0	0	0
Unlucky in Luck games	5	3	1	0	0

The next two tables, Table 3 and 4 report panel data analysis of the ratings, fitting the random-effect model using a *GLS* estimator.

The size and effect of the variables changes over the experimental session. The models presented in Table 3 when estimated separately for the first half and the second half of the experimental session show an effect of experience. An estimate of the effect of the number of skill games that the subject has played at the moment in which he gives the

Table 3: Rating as Disappointed.

Disappointed	M1 b/se	M2 b/se	M3 b/se
score	–0.776***	–0.924***	–0.928***
	(0.065)	(0.065)	(0.065)
score × skill	–0.073	–0.248***	–0.245***
	(0.053)	(0.080)	(0.080)
rscore	–0.148**		
	(0.060)		
rscore × skill	–0.175***		
	(0.066)		
maxother		0.148**	0.092
		(0.060)	(0.074)
maxother × skill		0.175***	0.199**
		(0.066)	(0.085)
minother			0.113
			(0.091)
minother × skill			–0.044
			(0.117)
constant	4.499***	4.499***	4.512***
	(0.286)	(0.286)	(0.289)
Wald χ^2	620.2	616.4	621.2
p-value	< 0.00005	< 0.00005	< 0.00005
N	837	837	837

Table 4: Rating as Unlucky

Unlucky	M1	M2	M3
	b/se	b/se	b/se
score	–0.282***	–0.732***	–0.733***
	(0.060)	(0.060)	(0.060)
score × skill	–0.313***	0.292***	0.297***
	(0.049)	(0.074)	(0.075)
rscore	–0.449***		
	(0.056)		
rscore × skill	0.605***		
	(0.061)		
maxother		0.449***	0.398***
		(0.056)	(0.069)
maxother × skill		–0.605***	–0.533***
		(0.061)	(0.079)
minother			0.112
			(0.085)
minother × skill			–0.158
			(0.108)
constant	2.669***	2.669***	2.654***
	(0.260)	(0.260)	(0.262)
Wald χ^2	293.2	293.2	295.6
p-value	< 0.00005	< 0.00005	< 0.00005
N	837	837	837

Table 5: Rating as Unlucky

	unlucky1	unlucky2	unlucky3
	b/p	b/p	b/p
score	–0.282***	–0.732***	–0.733***
	(0.000)	(0.000)	(0.000)
scoreskill	–0.313***	0.292***	0.297***
	(0.000)	(0.000)	(0.000)
rscore	–0.449***		
	(0.000)		
rscoreskill	0.605***		
	(0.000)		
maxother		0.449***	0.398***
		(0.000)	(0.000)
maxotherskill		–0.605***	–0.533***
		(0.000)	(0.000)
minother			0.112
			(0.186)
minotherskill			–0.158
			(0.146)
_cons	2.669***	2.669***	2.654***
	(0.000)	(0.000)	(0.000)
r2			
N	837	837	837

ratings is presented in table 6. The effect of the maximum score of others in skill games increases as the sessions progresses.

Table 6: Rating as Disappointed: effect of experience. The variable $Numberofskillgames$ is the sum up to the current round of the number of skill games played.

Disappointed	M1	M2
	b/se	b/se
score	–1.074***	–0.986***
	(0.044)	(0.059)
Number of skill games × Skill	–0.152***	–0.114***
	(0.035)	(0.038)
Number of skill games × Skill × maxother	0.036***	0.037***
	(0.009)	(0.009)
score × skill		–0.157**
		(0.070)
constant	5.520***	5.336***
	(0.259)	(0.270)
Wald χ^2	594.1	601.5
p-value	< 0.00005	< 0.00005
N	837	837

2.2 Decision to Subtract and Amount Subtracted

In this section we analyze the behavior at the subtraction stage, considering first the decision to subtract from others. The next table reports the logit random effects effects panel data analysis of the probability to decide a positive subtraction from others.

The likelihood ratio test of Model 2 with the same model without the variable maxother×skill confirms that this effect is significant: $LR\chi^2 = 14.26, Prob > \chi^2 = 0.0002$. A similar estimate for Model 3 gives $LR\chi^2 = 9.13, Prob > \chi^2 = 0.0025$.

The anticipation that others may subtract from him also increases the probability that the subject himself subtracts; and the effect is higher if the score of the subject is higher. This is confirmed if we consider the effect on the probability of subtracting of the probability given by the subject to the event that others are subtracting from them (see table 8). Note that this effect is even stronger when we consider the interaction between own score and this probability.

The amount subtracted follows a pattern which is similar to the decision to subtract. It decreases with the relative score. The difference between the amounts subtracted in

Table 7: Decision to Subtract: logit analysis, random effects

Decision to Subtract	M 1	M 2	M 3
	b/se	b/se	b/se
score	0.979***	–0.060	–0.057
	(0.109)	(0.094)	(0.094)
score × skill	–0.141**	0.175	0.169
	(0.069)	(0.122)	(0.123)
rscore	–0.863***		
	(0.096)		
rscore × skill	0.033		
	(0.089)		
skill		–3.547***	–3.495***
		(0.766)	(0.767)
maxother		0.508***	0.525***
		(0.116)	(0.132)
maxother × skill		0.608***	0.543***
		(0.166)	(0.182)
minother			–0.031
			(0.121)
minother × skill			0.128
			(0.156)
Wald χ^2	106.8	102.8	103.03
p-value	< 0.00005	< 0.00005	< 0.00005
N	837	837	837

Table 8: Decision to Subtract: the effect of the expectation that others are subtracting too.

Decision to Subtract	M 4	M 5
	b/se	b/se
score	–0.414***	–0.627***
	(0.118)	(0.148)
skill	–3.534***	–3.767***
	(0.804)	(0.819)
score × skill	0.189	0.230*
	(0.126)	(0.130)
maxother	0.625***	0.632***
	(0.140)	(0.142)
maxother × skill	0.544***	0.546***
	(0.190)	(0.192)
minother	0.031	0.035
	(0.125)	(0.127)
minother × skill	0.136	0.137
	(0.160)	(0.162)
Prob.Others Subtr.	3.063***	1.386
	(0.587)	(0.867)
score × Prob.		0.552**
		(0.219)
Wald χ^2	112.7	115.8
p-value	< 0.00005	< 0.00005
N	837	837

skill and luck is not large, and the amount subtracted in luck is larger than the one in skill (see Figure 4 in this Supplementary Material).

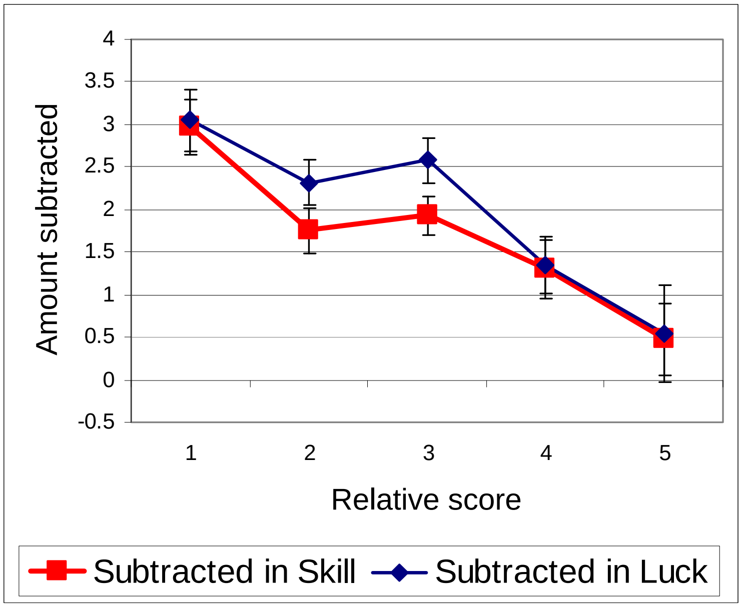

Figure 4: Amount subtracted in games of skill and luck, and quintiles of relative score.

2.3 Subjective Ratings: Likely

In each round, the last answer a subject had to give was a rating, on a scale from 0 10, of how likely he thought that one of the two other subjects had subtracted points from him. A natural and conservative hypothesis is that subjects are approximately correct in the method of their expectation, that is they expect the others to behave as we find them to behave. Table 9 confirms that this is the case. The score and the relative score of a subject increases the expectation that others subtract; skill, everything else being equal, reduces it (desert principle). We derive similar conclusions if we use *top* as the independent variable instead of relative score.

3 fMRI Analysis

3.1 Methods

Models

Several models were considered in this study. All models share common time structure. The independent variables were always defined at the same time intervals (see Table 10).

The categorical model has categorical variables corresponding to all events except `sk_rscore` and `lk_rscore`. These two events were split into two separate sub-events, one called *topskill* (all the events in which the score of the subject was strictly larger than the maximum of the other two subjects' score) and *notopskill* (subject's score was less or equal to the maximum of the other two subjects' score). Corresponding sub-events *topluck* and *notopluck* were constructed analogously for the luck rounds. This is referred to as the Categorical model. The parametric model also has categorical variables for all the events except $sk_r score$ and $lk_r score$. These two events were replaces by a parametric variable equal to *relative score* in skill and in luck respectively, convolved with the HRF function described in the text. This is referred to as the Parametric model.

A different model was also used where together with the indicator function of the event *top skill*, for example, was introduced as regressor the value of *relative score* times

Table 9: Panel data logit analysis of Likely (a variable equal to 1 if the subjects thinks there is some probability that the others are subtracting score from him, in answer to the question *How likely it is that the others have subtracted from you?*.

Likely	M1 b/se	M2 b/se
score	0.755***	0.872***
	(0.093)	(0.084)
skill	–0.820***	–0.812***
	(0.247)	(0.254)
relative score	0.261***	
	(0.071)	
top		0.765***
		(0.282)
constant	0.461	–0.489
	(0.451)	(0.355)
Wald χ^2	167.8	168.1
$Prob > \chi^2$	< 0.0005	< 0.0005
N	837	837

Table 10: Time intervals of the events in each round.

Name of the time interval	Game	Description	Length
`sk_visual`	Skill	The time of visual stimulus	8 sec
`sk_plays`	Skill	The time when the game is played	variable
`sk_score`	Skill	Own score after the game	4 sec
`sk_rscore`	Skill	Winnings of all three subjects	5 sec
`sk_disunl`	Skill	Disappointed and unlucky evaluations	variable
`sk_subtract`	Skill	Subtraction decision	variable
`sk_likely`	Skill	Likely/unlikely evaluation	variable
`lk_visual`	Luck	The time of visual stimulus	8 sec
`lk_plays`	Luck	The time when the game is played	variable
`lk_score`	Luck	Own score after the game	variable
`lk_rscore`	Luck	Winnings of all three subjects	5 sec
`lk_disunl`	Luck	Disappointed and unlucky evaluations	variable
`lk_subtract`	Luck	Subtraction decision	variable
`lk_likely`	Luck	Likely/unlikely evaluation	variable

the HRF (as described in [2]). This model gives results substantially similar to the Parametric model described above.

3.2 Activation at relative comparison of scores

Table 11 below reports the Talairach coordinates for active clusters at the evaluation of relative score, in skill compared to luck.

Table 11: Active clusters at evaluation of relative score, in skill *versus luck*. The table reports the clusters for the parametric and categorical model.

Region	mean x	mean y	mean z	N. of Voxels	Model
Right OFC	14	39	-16	61	Parametric
	(1.7)	(1.3)	(1.3)		
Right OFC	15	39	-16	266	Categorical
	(2.2)	(3.1)	(1.5)		
Medial OFC	-3	35	-20	69	Categorical
	(1.3)	(2.2)	(0.6)		

The Right OFC cluster for the parametric model is displayed in Figure 3:a of the main text. The two clusters in the categorical model are displayed in Figure 5 below.

The two clusters in the right OFC in Parametric and categorical models are largely overlapping. Figure 6 below displays the overlap between the two clusters: in both cases

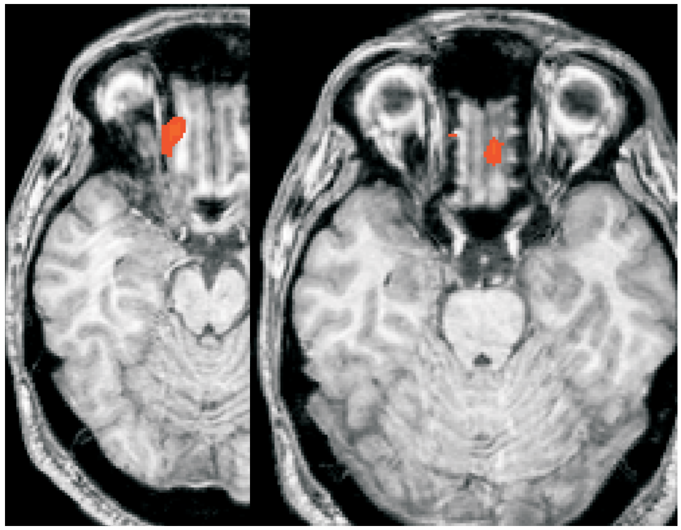

Figure 5: Two OFC Clusters active at evaluation of the relative score, in skill *versus* luck, in Categorical model. The contrast is *(top skill - no top skill) -(top luck - no top luck)*. The z coordinates are -17 for the left, and -20 for the right panel.

the significance level was set at $t = 3.29$.

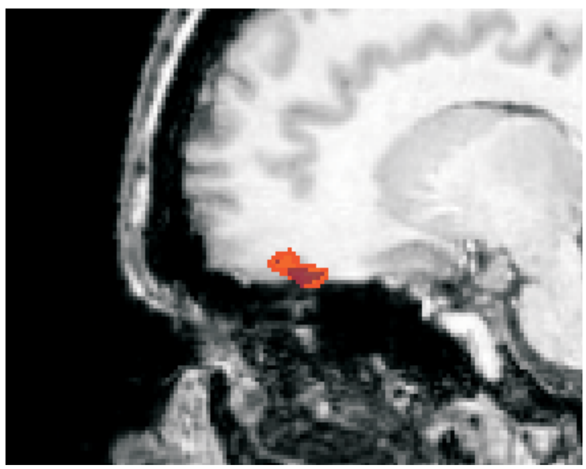

Figure 6: Overlay of the OFC Clusters in Categorical model (darker) and Parametric model (lighter). The Parametric model cluster occupies a region with x coordinates in the interval $[9, 20]$, y coordinates in the interval $[36, 49]$, and z coordinates in $[-21, -12]$.

3.3 Activation at subtraction

Figure 7 displays the relative location of the cluster in the striatum. The cross is center at coordinates $(-13, 5, 3)$. In the figure, the lighter green is the Putamen, the darker green is the Caudate Head.

The next table reports the list of all clusters active at $t = 3.59, uncorrected p = 0.001$:

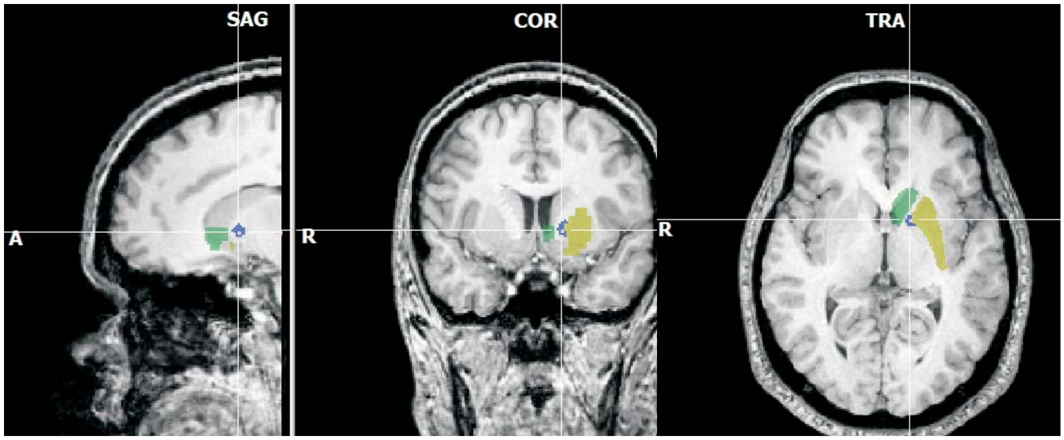

Figure 7: Relative location of the striatum cluster.

Table 12: Active clusters at subtraction in skill *versus luck*.

Region		mean x	mean y	mean z	N. of Voxels
Temporal Lobe	Superior Temporal Gyrus	59	-21	-4	207
Temporal Lobe	Superior Temporal Gyrus	57	13	-9	246
Parietal Lobe	Inferior Parietal Lobule	50	-50	35	530
Sub-lobar	Lentiform Nucleus Putamen	12	3	4	639
Limbic Lobe	Posterior Cingulate	15	-54	6	165
Occipital Lobe	Cuneus (BA 23)	10	-75	10	2535
Anterior Lobe	Culmen	6	-40	3	1914
Limbic Lobe	Cingulate Gyrus (BA 23)	2	-28	27	588
Limbic Lobe	Cingulate Gyrus (BA 31)	1	-43	36	247
Posterior Lobe	Uvula	-12	-84	-26	726
Sub-lobar	Lentiform Nucleus Putamen	-15	4	4	227

4 Brain Activation and Behavior

4.1 Evaluation of relative score

Table 13 presents the regression of the mean disappointed and unlucky rating on the PBC at *top skill*. The relation is non linear, so the independent variable is taken as the exponential of PBC.

We now examine the effect of the PBC on the decision to subtract, and how much.

Table 14 reports the marginal effect of the PBC in skill at subtraction on the probability that the subject belongs to the effect of the

Table 13: Affective ratings (Disappointed and Unlucky) and PBC in the OFC cluster.

	Disappointed	Unlucky
	b/se	b/se
PBC at Top Skill	0.248*	0.015
	(0.138)	(0.101)
Constant	2.159***	0.941***
	(0.442)	(0.323)
N	36	36

Table 14: Marginal effect of PBC of subtraction at skill on the probability that the subject belongs to the group of those who never subtract. Mean effect: 0.30

	Marginal Effect
	b/se
Subtraction Skill	-1.058**
	(0.475)
pseudo R^2	0.12
N	36

Tables 15 and 16 report the regression of the mean amount subtracted by the subject at skill and luck (respectively) on the PBC at top skill (and top luck respectively) as well as the average score in the two games.

Table 15: Mean amount subtracted in Luck regressed on PBC in Top Skill and on the average score in skill.

Mean Amount Subtracted Skill	M 1	M 2	M3	M 4
	b/se	b/se	b/se	b/se
Top Skill	1.405***	1.405***	1.454***	1.454***
	(0.445)	(0.406)	(0.446)	(0.406)
Avg. Score Skill			0.285	0.285
			(0.206)	(0.241)
Constant	0.857***	0.857**	0.169	0.169
	(0.290)	(0.398)	(0.475)	(0.704)
Robust Regression	Yes	No	Yes	No
R^2	0.260	0.260	0.291	0.291
N	36	36	36	36

Table 16: Mean amount subtracted in Luck regressed on PBC in Top Luck and on the average score in luck.

Mean Amount Subtracted Luck	M 1	M 2	M 3	M 4
	b/se	b/se	b/se	b/se
Top Luck	0.134	0.134	0.214	0.214
	(0.277)	(0.308)	(0.283)	(0.309)
Avg. Score Luck			1.076	1.076
			(0.820)	(0.774)
Constant	2.105***	2.105***	–1.130	–1.130
	(0.394)	(0.430)	(2.284)	(2.365)
Robust Regression	Yes	No	Yes	No
R^2	0.006	0.006	0.061	0.061
N	36	36	36	36

The difference in PBC at top skill and no top skill is a measure of how responsive the brain activation is to these two events. The next two tables show how this difference can help to predict whether the subject belongs to the group of those who never subtracted points from others.

Table 17 reports descriptive statistics on the PBC at Top Skill for the two groups of subjects who never subtracted and the others. The two-sample Wilcoxon rank-sum (Mann-Whitney) for the H_0 that the two values are the same gives $z = 3.289, p-value = 0.001$.

Table 17: PBC at top skill, in the two groups that did and never did subtract, respectively.

	Observations	Mean	Std. Error	[95% Conf. Interval]
Top Skill, subtracted	24	0.946	0.135	[0.66, 1.22]
Top Skill, never subtracted	12	0.116	0.148	[-0.20, 0.44]

Table 18 reports the marginal effect (change in the probability due to a unit change in the independent variable) of the difference between the PBC at Top Skill and No Top Skill (Model 1) and of the PBC at Top Skill (Model 2).

Table 18: PBC at evaluation of relative score affects the probability of belonging to the group that never subtracts.

Marginal effect	Model 1 b/se	Model 2 b/se
difference Top NoTop Skill	–0.929*	
	(0.499)	
Top Skill		–2.462***
		(0.894)
Constant	–0.014	0.504
	(0.483)	(0.538)
N	36	36

4.2 Subtraction

Table 19 reports the regression of the mean disappointed rating for each subject on the difference between the PBC in subtraction at skill and subtraction at luck. The regression on the left reports the result for the entire sample, the one on the right reports the same estimate for the sub sample of subjects who subtracted points sometimes during the experiment.

The *PBC* at subtraction in the striatum affects the average amount subtracted by subjects in the skill rounds. In the next two tables, 20 and 21, *PBC* indicates the PBC at subtraction in skill in the left striatum cluster. *Amount Subtracted* indicates the average amount subtracted by the subject in the skill rounds. *Average Score* denotes the average score of the subject in skill rounds.

Table 20 reports the regression of the average amount subtracted at skill on the other two variables.

For an appropriate evaluation of the coefficient size, table 21 below reports the average value of the three variables *PBC*, *Amount Subtracted*, *Average Score*.

Table 19: Disappointed ratings and PBC in left striatum cluster.

Disappointed rating	M 1	M 2
	b/se	b/se
Difference PBC Skill and Luck	4.839***	3.856**
	(1.492)	(1.837)
Constant	2.119***	2.240***
	(0.239)	(0.366)
Sample	All Subjects	Subjects who subtracted
R^2	0.291	0.208
N	36	24

Table 20: Mean amount subtracted in skill and PBC in left striatum cluster.

	Model 1	Model 2
	b/se	b/se
PBC	2.446**	2.537**
	(1.184)	(1.219)
Average Score		0.225
		(0.210)
Constant	1.012*	0.467
	(0.506)	(0.833)
R^2	0.059	0.077
N	36	36

Table 21: Descriptive Statistics for *PBC*, *Amount Subtracted*, *Average Score*.

Variable	Observations	Mean	Std.Error	[95% Conf. Interval]
PBC	36	0.321	0.032	[0.25, 0.38]
Amount Subtracted	36	1.798	0.333	[1.12, 2.47]
Average Score	36	2.298	0.203	[1.88, 2.71]

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