

# Decision-making in a Risk-taking Task: A PET Study

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*As decision-making is central to motivated behavior, understanding its neural substrates can help elucidate the deficits that characterize various maladaptive behaviors. Twenty healthy adults performed a risk-taking task during positron emission tomography with  $^{15}\text{O}$ -labeled water. The task, a computerized card game, tests the ability to weigh short-term rewards against long-term losses. A control task matched all components of the risk-taking task except for decision-making and the difference between responses to contingent and non-contingent reward and punishment. Decision-making (2 runs of the active task minus 2 runs of the control task) activated orbital and dorsolateral prefrontal cortex, anterior cingulate, insula, inferior*

*parietal cortex and thalamus predominantly on the right side, and cerebellum predominantly on the left side. In an exploratory analysis, guessing (run 1 minus run 2 of the active task) accompanied activation of sensory-motor associative areas, and amygdala on the left side, whereas informed decision-making (run 2 minus run 1) activated areas that subserved memory (hippocampus, posterior cingulate) and motor control (striatum, cerebellum). The findings provide a framework for future investigations of decision-making in maladaptive behaviors.*

**[Neuropsychopharmacology 26:682–691, 2002]**

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**KEY WORDS:** *Reward; Punishment; Guessing; Informed decision; Orbital frontal cortex; Cognitive task; Neuroimaging*

Decision-making is embedded in a series of cognitive steps that are difficult to isolate from one another in laboratory studies. Because of the central role of decision-making in behavior, its impairment underlies dysfunction in

many psychiatric disorders. The study of its underlying neural mechanisms, therefore, can be instructive in delineating the neural substrates of pathological behaviors. In this work, we define decision-making as the operation that takes place after coding for the features of the stimulus (input phase), and before acting on the decision (output phase). Although this view of decision-making is reductionistic, it provides a framework to design and interpret investigations of this complex cognitive operation.

For this study, we selected a task of decision-making (Bechara et al. 1994) that is clinically sensitive, and that is performed differently in individuals with various disorders, including substance abuse (Bartzokis et al. 2000; Grant et al. 2000). Patients with lesions of the orbitofrontal cortex (OFC) perform worse than healthy individuals on this task (Bechara et al. 1994). This observation is consistent with neuropsychological examinations of these patients, which indicate that integrity of the OFC

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Received June 24, 2001; revised October 1, 2001; accepted October 19, 2001.

is necessary for adaptive decision-making (Damasio 1994). Studies that have paired brain imaging with decision-making tasks have demonstrated activation of the OFC and other brain regions, including the dorsolateral prefrontal cortex and anterior cingulate gyrus (Elliott et al. 1999; Rogers et al. 1999). In these studies, positive and negative feedback was provided during performance of the decision-making task but not during performance of the control task. Therefore, differences between the active and the control tasks reflected decision-making, expectations of outcomes, and responses to outcomes; and the contributions of the activated brain regions specifically to decision-making could not be discerned. Tasks that present reward have recruited insula, amygdala/hippocampus, and ventral striatum (Buchel et al. 1998, 1999; Critchley et al. 2000; Elliott et al. 2000b; Knutson et al. 2000; Zalla et al. 2000). In the present design, the anticipation component of brain activation was removed because rewards and punishments were present in both the active and the control tasks. However, the contingency attribute of the outcomes remained after subtraction between the tasks.

The goals of this study were: (1) to examine regional brain activations associated with decision-making, after controlling for expectations of outcomes; and (2) to identify the brain regions that are activated by guessing and, conversely, by the learned aspect of decision-making which permits strategizing. We predicted that the educated decision would engage predominantly structures of executive function because of the use of coded information, whereas the guessing would engage predominantly limbic/paralimbic structures because it occurs in an emotionally guided context.

## METHODS

### Research Participants

Male and female volunteers were recruited through newspaper advertisements. All participants gave written informed consent after receiving an explanation of the study and its procedures. Inclusion criteria were age between 21 and 45 years, IQ > 80 (assessed by the Shipley Institute of Living Scale) (Zachary et al. 1985) and right-handedness. Exclusion criteria were current psychopathology (SCL-90) (Derogatis et al. 1976), history of psychiatric disorders (Diagnostic Interview Schedule (DIS)) (Robins et al. 1981), and evidence of acute or chronic medical problems (medical history, physical examination, and routine blood screen).

### Study Design

The research participants were admitted to an NIH-funded General Clinical Research Center for 48 h prior to the PET study to ensure common environment around

the time of brain imaging, and to allow extensive neuropsychological testing (not reported here). Smokers could smoke ad libitum up to 3 h prior to the study. Participants could also drink coffee but were instructed to avoid caffeine for 3 h prior to the study.

PET sessions comprised six 1-min scans at 12-min intervals, each following the intravenous injection of 10 mCi of  $^{15}\text{O}$ -labeled water to measure regional cerebral blood flow (rCBF). During each scan, participants performed the risk-taking task (active task), a control task, or a visual fixation task. The fixation task, i.e., fixation on a central cross on the screen, was used only for quality control purposes, and data collected using this procedure were not included in the analysis presented here. Each task was performed twice in a test session. The order of tasks was counterbalanced across subjects and was either (1) fixation, active, control, active, control, fixation, or (2) fixation, control, active, control, active, fixation.

### Risk Taking Task (Active Task)

The risk-taking task is a computerized gambling card game that tests the ability to choose between high gains with a risk for even higher losses, and low gain with a risk for smaller losses. It was developed to assess neurological patients, who have ventromedial prefrontal lesions and exhibit poor decision-making in everyday life (Bechara et al. 1994). Research participants were instructed to accumulate as much (play) money as possible by picking one card at a time from each of four decks (A, B, C, and D) until they were told to stop (after selection of the 100<sup>th</sup> card). Subjects were also told that they would receive one cent for each dollar amount accumulated (maximum possible \$20.00). Cards could be selected from any deck in any order, with no time limit for each choice. Once the participant selected a card, a first response, "you win \$50.00" (or \$100.00), immediately appeared on the screen, and remained for 1.5 s until the subject was prompted to play again by the message "Pick a card". If a loss was also attached to that choice, a 1.5 s loss message was added on the screen (e.g., "you lose \$75.00"). At the end of the 1.5 s, subjects were ready to make their next choice, such that the self-pacing of the task was not determined by variable time to think about the next choice. The number of cards picked during the 1 min period of collection of rCBF data did not differ significantly between run 1 (mean (SD) = 20.4 (3.7) cards) and run 2 (mean (SD) = 21.9 (3.2) cards), and the coefficient of variation (SD/mean) was 17.6% for run 1 and 14.6% for run 2. The amount of money left to the participant was updated on the screen after each card pick. On average, subjects chose 20 cards per minute. Each PET scan started 1 min after initiation of the task (after selection of 20 cards) and lasted for 1 min (during selection of the next 20 cards). Subjects

continued to play until the game was over (100 cards selected). The active task took an average of 5 min.

The decks differed along two dimensions: immediate gain and risk of penalties. Every card from Decks A and B yielded a gain of \$100, and every card from Decks C and D yielded a gain of \$50. A certain number of cards in each of the four decks *also* carried a penalty, in such a way that the accumulated penalties were larger than the accumulated gains in Decks A and B (disadvantageous decks), and the accumulated penalties were smaller than the accumulated gains in Decks C and D (advantageous decks). Thus, continued choice from either Deck C or D led to a net gain (\$250/10 cards), whereas choice from either Deck A or B led to a net loss (−\$250/10 cards). The optimal strategy was to minimize the overall loss by avoiding the short-term appeal of Decks A and B in favor of the slower, but ultimately positive, gain of Decks C and D.

Performance on the risk-taking task was measured by a global outcome score (net score), consisting of the total number of cards chosen from the advantageous decks (C+D) minus the number of cards chosen from the disadvantageous decks (A+B) (Bechara et al. 1994).

### Control Task

The control task was designed to replicate the risk-taking task in all aspects except for decision-making. Compared with the active task, the four decks used for the control task were equal in gains and losses. Therefore, the tasks were similar in sensory motor demands and in exposure to gains and losses. For the control task, however, the participants were instructed to pick cards from the decks sequentially in the fixed order of A-B-C-D-A-B-C-D-etc. Thus, the participants did not decide from which deck they would select the cards.

### PET

Rates and patterns of rCBF can be determined with PET after the administration of the freely diffusible, positron-emitting radiotracer,  $H_2^{15}O$ . Because of the short half-life of  $^{15}O$  (2.05 min), repeated PET measurements can be performed every 10–12 min. The tracer  $H_2^{15}O$  is administered by i.v. bolus, and a 60-s scan is obtained after the radiotracer reaches the brain (Herscovitch et al. 1983; Raichle et al. 1983). The relationship between counts of radioactivity in brain and rCBF is almost linear, and the PET image closely reflects differences in perfusion between brain regions, providing a measure of relative rCBF. PET scans were performed on a Siemens ECAT EXACT HR+. This instrument produces images of 63 contiguous transaxial slices, with 15.5-cm field of view, and 4.6-mm transaxial resolution. A thermoplastic mask, custom-made for each subject, was used to minimize head movement. Counts of radioac-

tivity were recorded for 1 min. Scan data were reconstructed with corrections for attenuation (calculated using transmission scans). As arterial blood was not sampled, absolute rates of rCBF were not determined.

### Data Analysis

**Demographic, Cognitive, and Subjective Variables** Demographic and cognitive (net score) data are described using means  $\pm$  sd. The performance score, or net score, used for data analysis was the result of the total number of cards (100 cards) taken from the advantageous decks (C + D) minus the total number of cards taken from the disadvantageous decks (A + B). The performance score was based on all 100 cards rather than the 20 cards selected during each 1-min scan acquisition, because selection of only 20 cards does not reflect overall performance and is too variable for interpretation.

### Brain Imaging Analysis

To correct for head motion between scans, all PET data for each subject were co-registered using the Automated Image Registration Program (Woods et al. 1992). Data were analyzed using Statistical Parametric Mapping (SPM99; Wellcome Department of Cognitive Neurology, London, UK) (Friston et al. 1991, 1995). The mean of the counts of all voxels common to all registered scans of an individual (i.e., global counts) was used to normalize regional data (proportional scaling). The registered data were resized and reshaped to a standard space corresponding to the stereotactic atlas of Talairach and Tournoux (1988). Data were then smoothed with a 3-dimensional Gaussian filter (10 mm each in the x, y and z planes, respectively) to reduce high-frequency noise and the effects of individual differences in gyral anatomy. The adjusted mean image of two replicate acquisitions for each given condition was used for random effect analysis. Finally, a voxel-by-voxel analysis was performed for all planes common to all subjects (from 28 mm below to 54 mm above the intercommisural line). Activations were analyzed by testing the rCBF differences between the active and the control tasks, providing values for each unit of volume (voxel). The resultant *t* values were transformed to a normal standard distribution (*z* statistics). In the results, we present maps of the *z* statistics that showed clusters of at least 50 contiguous voxels (= 1 cc volume) all activated at a level of  $p < .001$ , and a table of the stereotactic coordinates of the epicenters (i.e., maxima at  $p < .001$ ) of activated clusters. Correlation analyses were also performed between activation and net scores, using the same statistical thresholds.

In a secondary analysis, we contrasted the active task condition at first administration (run 1) to that at second administration (run 2), approximately 24 min apart, to explore the effect of learning. A less stringent statisti-

cal criterion was applied for this analysis because having only a single rCBF measure (scan) per subject and condition significantly increases variability. Maxima at  $p < .001$  in clusters of 50 contiguous voxels all activated at  $p < .005$  were considered statistically significant.

Anatomical localization of regional activations was performed using rendering on a structural T1 MRI. Two investigators (JM, ME) independently examined the locations of activation sites, and agreed in each case. The activations were determined on the co-registered structural MR image, and are reported using the stereotactic coordinates of Talairach and Tournoux (1988).

## RESULTS

### Sample

Twenty healthy controls (8 women, 12 men; mean  $\pm$  sd: age  $30.4 \pm 6.3$  years; Hollingshead socioeconomic status  $4.3 \pm 1.1$ ; IQ  $99.5 \pm 9.3$ ) completed the study.

### Performance Measures

Performance on the risk-taking task (mean  $\pm$  sd net score =  $9.4 \pm 27.4$ ) was lower than previous scores for normal healthy adults reported in our laboratory (Grant et al. 2000, net score =  $26 \pm 5.3$ ). This difference may reflect the context in which the task was adminis-

tered as well as the use of a computerized version in the present study compared with a real card game used in earlier studies. Consistent with previous reports, the scores between the first (mean net score  $\pm$  SD  $1.0 \pm 23.7$ ) and the second task administration (mean net score  $\pm$  SD  $17.8 \pm 37.9$ ) significantly improved ( $df = 19$ ;  $p = .028$ ).

### Brain Activation

Brain regions activated during the risk taking task (mean of both runs of active task minus mean of both runs of control task) included the OFC bilaterally (Brodmann areas (BA) 11, 47), dorsolateral prefrontal cortex (DLPFC BA 6,8,9,10), predominantly on the right side, right anterior cingulate gyrus (BA 24,32), right inferior parietal cortex (BA 40), thalamus (bilaterally, but predominantly on the right), anterior insula bilaterally, and lateral cerebellum (bilaterally, but predominantly on the left side) (see Table 1 and Figure 1).

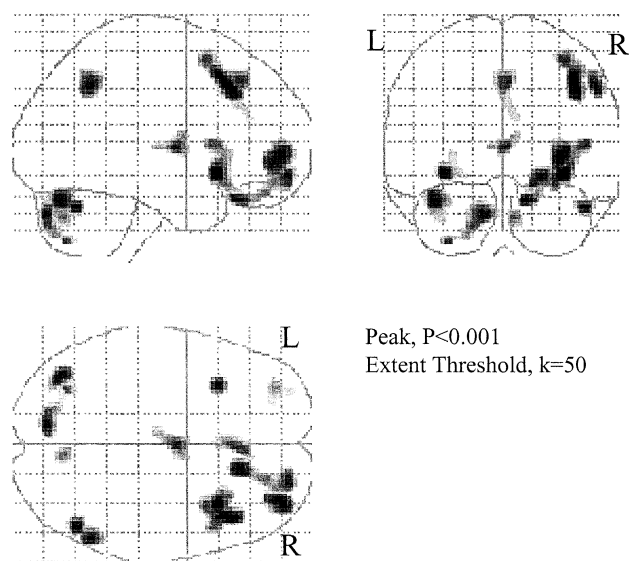
### Correlations between rCBF Activation Maps and Performance Scores (Better Performance, Greater Activation)

Regions whose relative rCBF were significantly correlated with performance scores included the right ventrolateral prefrontal cortex (BA 44,45), right anterior in-

**Table 1.** Statistical Parametric Mapping Activation (Active Task Minus Control Task) (n = 20). Statistical Thresholds: Cluster = 50, Peak = 0.001 Uncorrected

Cluster size k	Peak T	Coordinates (mm)		Region, BA	Side
		x,y,z			
630	4.97	32,54,0	GFM, 10	Right	
	4.79	14,30,-24	OFC, 11	Right	
	4.53	22,58,-10	GFS, 11	Right	
328	5.15	42,26,40	GFM, 9	Right	
	4.19	36,12,56	GFM, 6	Right	
70	3.85	-32,52,-8	OFC, 47	Left	
	3.51	-30,60,0	GFM, 10	Left	
195	4.33	2,30,44	GFD, 8	Right	
	3.58	4,30,30	Cingulate, 32	Right	
	3.41	8,38,22	Cingulate, 24/32	Right	
278	5.21	36,18,-8	Insula	Right	
	4.11	48,16,8	Insula	Right	
69	4.81	-34,18,-8	Insula	Left	
149	4.58	54,-54,42	LPI, 40	Right	
95	4.26	0,-6,6	Thalamus	Medial (R>L)	
	3.75	6,-2,12	Thalamus	Right	
	3.72	-6,-16,6	Thalamus	Left	
61	4.74	48,-64,-28	Cerebellum	Right	
215	4.64	-40,-72,-24	Cerebellum	Left	
204	4.55	-10,-80,-32	Cerebellum	Left	
	4.11	-32,-70,-48	Cerebellum	Left	
51	3.93	6,-70,-34	Cerebellum	Right	

BA: Brodmann Area; GFM: middle frontal gyrus; OFC: orbitofrontal cortex; GFS: superior frontal gyrus; GFD: dorsal frontal gyrus; LPI: lateral inferior parietal cortex; R: right; L: left



**Figure 1.** Statistical parametric maps showing brain activation during performance of a task of decision-making (active task minus control task). Maps of the T statistics showing all voxels significantly activated at  $p < .001$  (peak) within a cluster of an extent threshold of  $k > 50$ . Regional activation includes the orbitofrontal cortex (OFC) bilaterally (Brodmann areas (BA) 11, 47), predominantly right dorsolateral prefrontal cortex (DLPFC BA 6,8,9,10), right anterior cingulate gyrus (BA 24,32), right inferior parietal cortex (BA 40), thalamus (bilaterally, but predominantly on the right), anterior insula bilaterally, and lateral cerebellum (bilaterally, but predominantly on the left side).

sula, and right head of the caudate nucleus. No regions showed significant negative correlations with performance (see Table 2 and Figure 2).

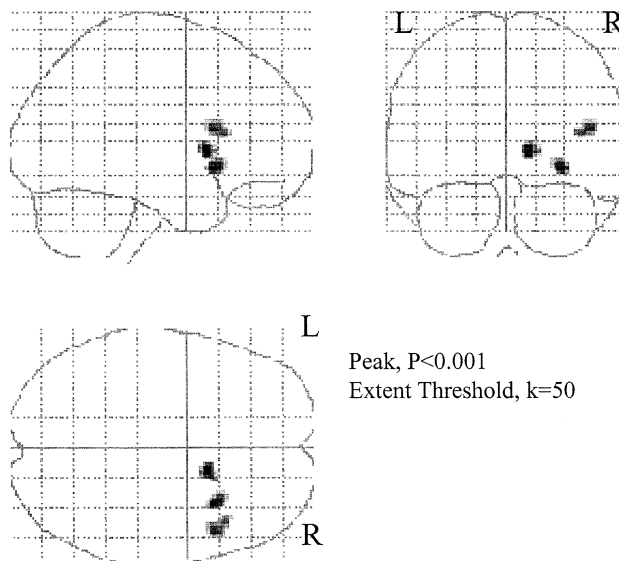
### Learning Effect on the Risk-taking Task

Compared with the learned task (second administration), the unlearned task (first administration) activated the left amygdala, the left middle prefrontal cortex (BA 6, Supplementary Motor Area) and the left posterior parietal cortex (BA 7) (Table 3 and Figure 3). In contrast,

**Table 2.** Statistical Parametric Mapping Correlation between Activation (Active Task Minus Control Task) and Performance Score (Netscore) ( $n = 20$ ). Statistical Thresholds: Cluster = 50, Peak  $p = .001$  Uncorrected

Cluster size k	Peak T	Coordinates (mm)		Region, BA	Side
		(x,y,z)			
66	4.66	48,16,16	GFI 44	Right	
	4.33	42,22,14	GFI 45	Right	
52	5.09	32,16,-6	Insula	Right	
55	5.69	12,12,4	Caudate	Right	
	3.85	-10,-16,6	Caudate	Left	

BA: Brodmann Area; GFI: inferior frontal gyrus



**Figure 2.** Statistical parametric maps showing correlations between performance on the risk-taking task (net score) and brain activation. Maps of the T statistics showing all voxels significantly activated at  $p < .001$  (peak) within a cluster of an extent threshold of  $k > 50$ . Significant correlations are found in the right ventrolateral prefrontal cortex (BA 44,45), right anterior insula, and right head of the caudate nucleus.

compared with the unlearned task, the learned task activated the right cerebellar peduncle, left and right cerebellum, left and right caudate nucleus/anterior globus pallidus, left hippocampus (BA 28), and right posterior cingulate (BA 23) (Table 4 and Figure 4).

## DISCUSSION

The findings further clarify a neural network that participates in decision-making in the contexts of guessing and risk-taking. We emphasize, however, that the combination of decision-making and the contingency aspect of the outcomes engaged this neural network. Indeed, the emotional response to a given outcome (reward or punishment) may differ as a function of whether the re-

**Table 3.** Statistical Parametric Mapping Activation of Guessing (Active Task: Run 1 Minus Run 2) ( $n = 20$ ). Statistical Thresholds: Cluster = 50, Peak  $p = 0.005$  Uncorrected

Cluster size k	Peak T	Coordinates (mm)		Region, BA	Side
		(x,y,z)			
204	3.81	-28,2,-26	Amygdala	Left	
113	3.51	-26,6,58	GFM 6	Left	
65	3.37	-32,-66,44	PPI 7	Left	

BA: Brodmann Area; GFM: middle frontal gyrus; PPI: posterior inferior parietal cortex

**Table 4.** Statistical Parametric Mapping Activation of Informed Decision-making (Active Task: Run 2 Minus Run 1) (n = 20). Statistical Thresholds: Cluster = 50, Peak p = 0.005 Uncorrected

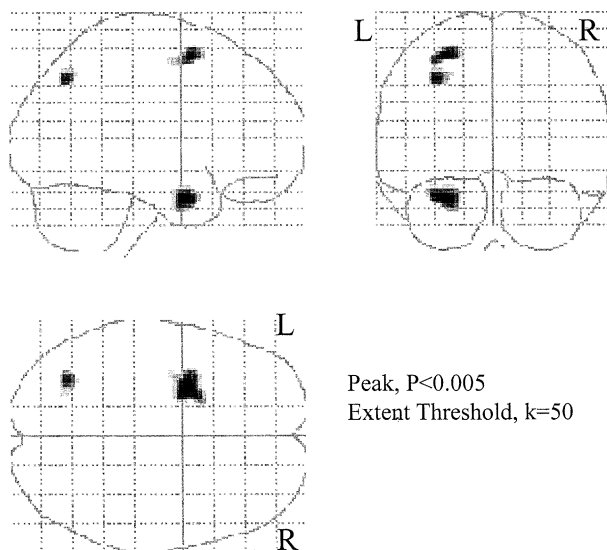
Cluster size k	Peak T	Coordinates (mm)		Region, BA	Side
		(x,y,z)			
70	3.13	6,-58,16		Cingulate 23	Right
	2.94	-4,-52,6		Cingulate 30	Left
94	3.96	-14,10,0		Caudate Nucleus	Left
	2.91	-12,-2,-6		Globus Pallidus	Left
85	3.26	22,20,8		Caudate Nucleus	Right
	2.9	28,12,10		Caudate Nucleus	Right
84	3.64	-20,-18,-8		Hippocampus	Left
78	4.48	14,-22,-26		Cerebellar Peduncle	Right
144	3.52	-18,-62,-32		Cerebellum	Left
	3.1	-24,-58,-46		Cerebellum	Left
92	3.52	20,-42,-40		Cerebellum	Right
95	3.14	10,-46,-24		Cerebellum	Right
63	3.5	50,-56,-28		Cerebellum	Right

BA: Brodmann Area

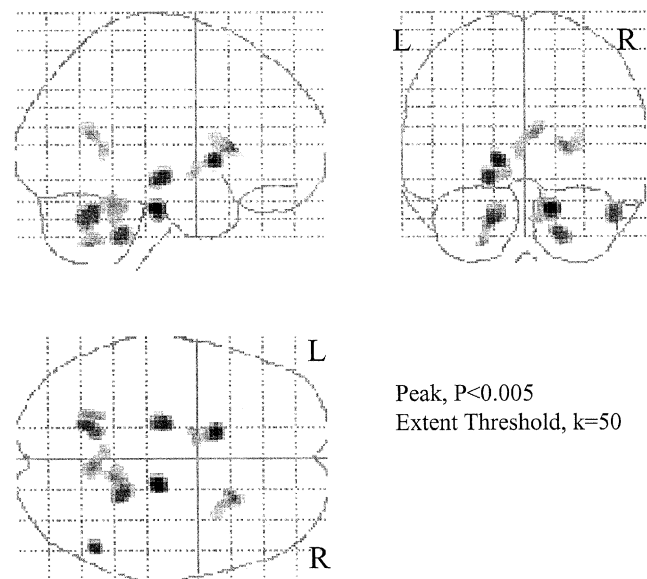
search subjects have control over the outcome (i.e., making a choice that affects the outcome directly vs. no decision over the outcome). For ease of readability, we will use “decision-making” to refer to the combination of decision-making and the contingency aspect of responses to outcomes.

Overall, the regions involved in decision-making included OFC, dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex, anterior cingulate cor-

tex, insula, parietal cortex, thalamus and cerebellum. Table 5 lists the regions activated by the task, those whose activity was related to the quality of performance, and those that were differentially activated by strategy (i.e., uneducated decision-making vs. educated decision-making). The findings in this study show that decision-making engages a predominantly right-lateralized neural network, including structures previously



**Figure 3.** Statistical parametric maps showing brain activation of guessing over informed decision-making (run 1 minus run 2 of the decision-making task). Maps of the T statistics showing all voxels significantly activated at  $p < .005$  (peak) within a cluster of an extent threshold of  $k > 50$ . Regional activations include the left amygdala, the left middle prefrontal cortex (BA 6, Supplementary Motor Area) and the left posterior parietal cortex (BA 7).



**Figure 4.** Statistical parametric maps showing brain activation of informed decision-making over guessing (run 2 minus run 1 of the decision-making task). Maps of the T statistics showing all voxels significantly activated at  $p < .005$  (peak) within a cluster of an extent threshold of  $k > 50$ . Regional activations include the right cerebellar peduncle, left and right cerebellum, left and right caudate nucleus/ anterior globus pallidus, left hippocampus (BA 28), and right posterior cingulate (BA 23).

associated with emotional and motivational coding, working memory, conflict monitoring, and response inhibition. The fact that this network is largely distributed suggests that decision-making is embedded in the processes that precede it (evaluation of stimuli) and follow it (response to outcomes). Further, beneficial (adaptive) decision-making depends on the degree of activation of right-sided structures involved in planning/working memory, behavioral inhibition and somatic coding. In contrast, uninformed decision-making (guessing) activates preferentially left-sided structures engaged in emotional, sensory and motor processes, whereas informed decision-making recruits structures that code for memory and motor control, bilaterally.

The right lateralization is consistent with findings of other studies of decision-making (Elliott et al. 1999; Rogers et al. 1999). The emotional attribute of decision-making in tasks that involve rewards or risk-taking may have favored neural processing in the right hemisphere, which is implicated preferentially in affective mental activity compared with non-affective cognition (Heilman 1997). The contingency attribute of outcomes may influence emotional responses, which may be reflected in the recruitment of brain regions associated with emotional processing. It will be important in future behav-

ioral cognitive studies to carefully analyze how contingency affects emotional responses to outcomes, before addressing the question of the neural substrates of this effect. Alternatively, the volitional aspect of decision-making may have contributed to the right lateralization, as self-initiated responses compared with externally triggered movements have also been associated with right-sided activations (DLPFC and anterior cingulate) (Deiber et al. 1991; Frith et al. 1991; Jahanshahi et al. 1995). Another possibility is that right-sided function specializes in response inhibition (de Zubizaray et al. 2000), which operates in the choosing between alternatives.

The specific functional significance of the activations of individual brain regions during the task is suggested by findings in previous work. The proposed interpretations can serve as a basis for future studies with a priori hypotheses that can further our understanding of the processes of decision-making. Testing OFC function was an objective for the development of the decision-making task used here (Bechara et al. 1994, 1999), and OFC is the cortical structure most consistently involved in motivated behavior (for review, see Damasio 1994), particularly in the processing of representations of reward and punishment (Elliott et al. 1997, 2000a; London

**Table 5.** Summary of Differential Regional Involvement in Processes of Decision-making

	Activation	Correlation	Practice Effect	
	Active task minus control task	Positive correlation between activation and performance	Guessing (run 1 minus run 2)	Informed decision-making (run 2 minus run 1)
OFC (BA 11,47)	R>L	R		
DLPFC middle inferior (BA 10,9,44,45)	R>L			
DLPFC superior (BA 8,9)	R			
Gyrus precentralis (BA 6)	R		L	
Anterior cingulate Cortex (BA 24,32)	R			
Posterior cingulate Cortex (BA 23)				R
Inferior parietal cortex (BA 40)	R			
Inferior posterior Parietal cortex (BA 7)			L	
Amygdala			L	
Hippocampus				L
Insula	R>L	R		
Thalamus	R>L			
Caudate Nucleus		R		R=L
Cerebellar Peduncles				R
Cerebellum	L>R			R=L

et al. 2000; Rolls 1996). Although we observed OFC activation by the active task, OFC activation was not correlated with the quality of performance. To some extent, this lack of correlation may reflect dissociation between decision-making and processing of the motivational attributes of the stimuli, which precedes and determines the direction of decision-making and may be mediated by a different circuitry.

Activation of the anterior cingulate cortex is consistent with its role in monitoring response conflicts (MacDonald III et al. 2000). Making a decision necessitates a choice between alternatives that may all be compelling, thus creating conflict. Of note, activation of the anterior cingulate was not correlated with performance, suggesting that the monitoring of conflicts was not directly implicated in successful performance. Whereas the anterior cingulate seems to be involved preferentially in evaluative processes, the DLPFC has been proposed to facilitate the maintenance of attentional demands of a task (MacDonald III et al. 2000), which are likely to be greater when decision-making is required. Additionally, the role of DLPFC in response inhibition (de Zubicaray et al. 2000) may also account for its activation during the task, where possible alternatives need to be inhibited in favor of the chosen one. Finally, working memory may be used more systematically when decisions are required to be made, contributing to DLPFC activation during the task (Owen et al. 1996; Smith and Jonides 1998).

The recruitment of the cerebellum in both decision-making and the use of a learned strategy is consistent with its proposed role in error-based learning (Doya 2000). Cerebellar activity would process error signals that could be used for improving performance. Although assignment of cerebellar function referred to movement control, a similar control could be exerted on cognitive performance.

Lastly, this work provides information on the structures preferentially involved in guessing vs. informed decision-making. The comparison of performance between a condition when decision-making reflects guessing (i.e., in run 1) and when decisions are made deliberately based on learned information (i.e., informed decision-making in run 2) shows that guessing activated left-sided structures involved in sensory, motor and emotional coding, and did not recruit structures subserving executive functions. Of note, guessing activated the amygdala, which was not implicated in decision-making (i.e., not activated in the subtraction of the control task from the active task). A possible explanation is that the amygdala ceases to be actively engaged once a strategy is implemented. Indeed, the amygdala plays a critical role in processing the affective significance of a stimulus (Everitt et al. 1991; Gaffan and Harrison 1987; Nishijo et al. 1988; Rolls 1992; Schoenbaum et al. 1998; Weiskrantz 1956; Zalla et al. 2000), which is considered in formulating a strategic approach (Be-

chara et al. 1999). Once the strategic approach is devised, the amygdala may be less involved. Another explanation may be that the amygdala is more active when aversive stimuli predominate (Morris et al. 1996; Paradiso et al. 1999; Zald and Pardo 1997). However, the absence of correlation of performance with amygdala activation does not support this hypothesis. In contrast to guessing, informed decision-making involved areas important for the maintenance of the cognitive strategy, i.e., hippocampus and posterior cingulate for memory requirement (Dolan and Fletcher 1997), cerebellum for error learning (see above), and striatum for motor control and action selection (Graybiel 1995; Kawagoe et al. 1998).

In conclusion, the elementary cognitive components of the task used here are entwined in a complex process. For example, the extent to which decision-making is separate from the integration of the features of the stimuli (input) and from the motor responses to the conceived choice (output) remains to be defined. In addition, the role of contingency in the coding for stimulus features, and response to outcomes needs to be better understood (e.g., reward under subject's control vs. reward independent of subject's behavior). In this regard, the examination of discrete cognitive processes may be best served by functional magnetic resonance imaging (fMRI) studies using event-related designs, which promise the temporal resolution required to dissect fine processes.

## ACKNOWLEDGMENTS

Supported by the NIDA Intramural Research Program, NIH grants DA 11426 (KB) and the JHBMC-GCRC (MO1 RR02719). The Brain Imaging Center of the National Institute on Drug Abuse was developed with funds from the Counterdrug Technology Assessment Center, Office of National Drug Control Policy.

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