Human Medial Orbitofrontal Cortex Is Recruited During Experience of Imagined and Real Rewards

Signe Bray, Shinsuke Shimojo and John P. O'Doherty

You might find this additional info useful...

Supplemental material for this article can be found at:
http://jn.physiology.org/content/suppl/2010/03/12/01030.2009.DC1.html

This article cites 40 articles, 24 of which can be accessed free at:
http://jn.physiology.org/content/103/5/2506.full.html#ref-list-1

Updated information and services including high resolution figures, can be found at:
http://jn.physiology.org/content/103/5/2506.full.html

Additional material and information about *Journal of Neurophysiology* can be found at:
http://www.the-aps.org/publications/jn

This infomation is current as of May 7, 2011.

Human Medial Orbitofrontal Cortex Is Recruited During Experience of Imagined and Real Rewards

Signe Bray,[1,2] Shinsuke Shimojo,[1,3] and John P. O'Doherty[1,4,5,6]

[1]*Computation and Neural Systems,* [3]*Humanities and Social Sciences, and* [4]*Biology Division, California Institute of Technology, Pasadena, California;* [2]*Center for Interdisciplinary Brain Science Research, Stanford University, Palo Alto, California; and* [5]*Institute of Neuroscience and* [6] *School of Psychology, Trinity College Dublin, Dublin, Ireland*

Bray S, Shimojo S, O'Doherty JP. Human medial orbitofrontal cortex is recruited during experience of imagined and real rewards. *J Neurophysiol* 103: 2506–2512, 2010. First published March 3, 2010; doi:10.1152/jn.01030.2009. Human decision-making frequently relies on mental simulation of future rewards to guide action choice. In this study, we sought to uncover brain regions engaged during reward imagery and to address whether these regions functionally overlap with regions activated by tangible rewards. We found that medial orbitofrontal cortex (mOFC) is engaged both for real and imagined rewards and is preferentially engaged for imagery with rewarding content compared with other nonrewarding imagery. These findings support a critical role for mOFC in the representation of rewarding goal states, even if hypothetical.

INTRODUCTION

The human capacity to mentally simulate rewards that are unobtainable, at least in the foreseeable future, may serve more than frivolous ends and play an important role in our ability to form long-term goals and plan behaviors accordingly. Despite the centrality of such a mechanism to human behavior, efforts to study the brain's reward responsive regions have focused mainly on stimuli that possess endogenous, or learned, reward value (Aharon et al. 2001; Blood and Zatorre 2001; Cox et al. 2005; Elliott et al. 2003; Knutson et al. 2001; O'Doherty et al. 2001). The goal of this study was to measure the brain's response to imagined reward and establish whether similar brain regions are engaged to represent imagined rewards, as have been shown to respond to tangible rewards.

A growing literature has been devoted to studying the neural substrates of content-specific imagery. Of particular interest is whether similar neural circuitry is engaged during real and imagined events. A common, although not always supported, finding is that imagery evokes neural activity in similar regions as actual motor (Porro et al. 1996), perceptual (O'Craven and Kanwisher 2000), and emotional (D'Argembeau et al. 2008) events. However, the neural substrates of imagined reward remain heretofore relatively unexplored. Studies of emotional imagery, in which subjects are asked to either remember, or imagine future, emotional events, have shown engagement in a network of brain regions known to be involved in emotional processing: ventromedial prefrontal cortex (vmPFC) (D'Argembeau et al. 2008; Sharot et al. 2007), amygdala (Sharot et al. 2007) and posterior cingulate cortex (PCC) (D'Argembeau et al. 2008; Sharot et al. 2007). Sharot et al. (2007) found that the rostral anterior cingulate showed significantly elevated activity for cued imagery of positive events compared with negative. Although many events that people label as positive are also rewarding, positive events can be much more complex than, and sometimes distinct from, rewarding events. For example, imagining participating in a wedding ceremony, eating at a fancy restaurant, or cooking an elaborate meal will likely involve a complex mix of affective states (social anxiety, pride, joy, etc.) other than merely eliciting a rewarded state. It is also likely that in the context of a cued imagery task, events will vary in reward value to individual subjects and thereby evoke a range of rewarding and nonrewarding emotional states, making it difficult to infer that neural activity is related to reward value per se.

In this study, we specifically tested neural responses to reward-related imagery by asking subjects to imagine situations that they found personally rewarding. Our design included a monetary reward condition that allowed us to perform a direct comparison with responses to actual monetary rewards and therefore specifically assess whether regions involved in reward imagery functionally overlap with regions known to be engaged by experience of tangible rewards, such as medial orbitofrontal cortex (mOFC)(Cox et al. 2005; Hare et al. 2008; O'Doherty et al. 2001). Additionally, we scanned subjects in a second session involving real and imagined visual and motor stimuli, allowing us to compare reward-related imagery to other forms of imagery.

METHODS

Subjects

A total of 44 healthy right-handed subjects from the Caltech population participated in this experiment (10 females), with a mean age of 21.7 ± 3.7. All subjects gave informed consent, which was approved by the local research ethics committee.

Stimuli

Visual stimuli were presented via a projector positioned at the back of the room. Subjects viewed a reflection of the projected image (800 × 600 pixels) in a mirror attached to the scanner head coil. Stimulus presentation and response recording were controlled with the Cogent 2000 toolbox in Matlab (Mathworks, Natick, MA).

Prescan training

All functional MRI (fMRI) tasks described below were first practiced outside the scanner to ensure that subjects understood the rules and so that they could practice the required imagery.

fMRI scanning

In this study, we were interested in regions of functional overlap for real and imagined stimuli. As such, all tasks involved both exogenous stimuli and endogenously generated imagery. All subjects participated in two scan sessions. One session consisted of an instrumental reward task during which subjects made choices and received monetary reward or punishment on each trial, followed by blocks of reward imagery. A second session included real and imagined hand-tapping and real and imagined visual motion stimuli. The order of the two sessions was counterbalanced across subjects. After these two scans, subjects participated in additional functional scans (results not reported here).

Instrumental reward learning and reward imagery tasks

In this study, we aimed to assess brain regions activated both by experience, and imagination, of reward. A range of tasks have been used to study neural responses to experienced reward including passive receipt (O'Doherty et al. 2003b; Small et al. 2001), passive conditioned associations (Bray and O'Doherty 2007), and instrumental learning tasks, including reversal learning (Knutson et al. 2001, 2005; O'Doherty et al. 2001, 2003a, 2004). These tasks have shown that mOFC/vmPFC consistently responds to experienced reward value. In this study we implemented a probabilistic reversal learning task (Fig. 1A), similar to Hampton and O'Doherty (2007), with a monetary reinforcer. On each trial, subjects were presented with the same two abstract fractal images, randomly assigned to the left or right side of a central fixation cross. These stimuli were presented for 2.9 s, during which time the subject was asked to choose between the two images and press the left or right button on a button box held in their right hand (Current Designs, Philadelphia, PA) to choose the image on the left or right side of the screen. The chosen image became brighter for 2.9 s, followed by feedback for 2.9 s, indicating whether the subject had won a quarter or lost a quarter. The next trial immediately followed. Rewarding feedback was indicated with a picture of a U.S. quarter in the center of the screen, while punishing feedback was indicated by a picture of a quarter with a red X across the image. A running total of subjects' earnings during this task was presented above the quarter. Missed trials were indicated with a red X in the center of the screen and no change in the running total.
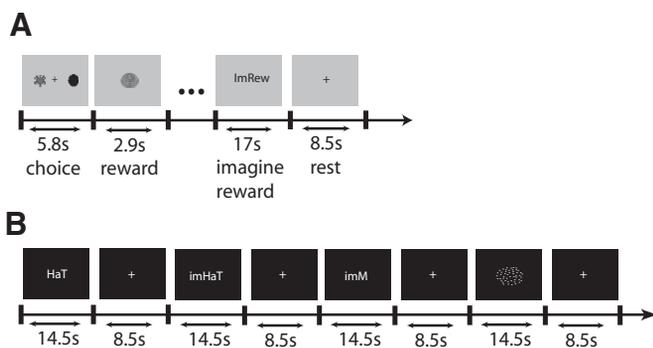

FIG. 1. Illustration of task design. Subjects performed the tasks in A and B in counterbalanced order. A: instrumental reward task. On each trial, subjects were given 2.9 s to choose between 2 stimuli and press the corresponding button. Their response was highlighted for 2.9 s and then the reward or punishment feedback was displayed for 2.9 s. There were 40 trials interspersed with 20 null events. After the instrumental trials, within the same scan, subjects were asked to imagine situations they found personally rewarding for 17.5 s and rest for 8.5 s while looking at a fixation cross. The imagine reward blocks repeated 6 times. B: real and imagined motor and visual stimuli. Subjects followed the onscreen cues, which indicated that they should tap fingers (HaT), imagine tapping fingers (imHaT), watch moving, or static dot stimuli, imagine visual motion (imM) or rest (+).

The images were randomly assigned to be the correct or incorrect choice. Choosing the correct option was associated with the subsequent delivery of a monetary reward (gaining 0.25 USD) on 80% of trials and a monetary punishment (losing 0.25 USD) on 20% of trials. Contingencies for the incorrect choice were the opposite: 80% probability of punishment and 20% probability of reward. Subjects were instructed to sample both choices to ascertain which was more rewarding (they were not told the exact probabilities but merely that one-image delivered rewards more often). The subjects were also instructed that sometimes the contingencies associated with the images would reverse, that is the image that delivered reward more often would begin to deliver less often and vice versa. Subjects were not informed of the specific details of the reversal probabilities, but contingency reversals only occurred after they showed that they had learned which was the correct image, by choosing this image on three consecutive trials. Once this association had been acquired, the contingencies had a one in four probability of reversing on each subsequent trial. Subjects practiced this task for several minutes outside the scanner during the pretraining session. In the scanner, subjects performed a session that included 40 task trials with 20 null events (during which the fixation cross was presented for the duration of a normal trial) randomly interspersed for a duration of ~8.5 min.

Within the same scan, subjects performed several blocks of reward imagery. The order of the two tasks was fixed: reversal learning always preceded reward imagery. Subjects saw a fixation cross at the center of the screen for 8.5 s, followed by the letters "ImR" presented in the middle of the screen for 17 s. This was a cue for subjects to begin a period of reward imagery. Subjects were not given specific instructions about what to imagine but were simply asked to imagine things that they found personally rewarding. We asked subjects to imagine whatever they found most rewarding, because the reward value of specific scenarios differs across individuals, and by allowing subjects to imagine scenarios most rewarding for them, we aimed to elicit the strongest possible neural response. The imagery condition, alternating with the fixation cross, was presented six times.

Hand-motor and visual motion tasks and imagery tasks

In a separate scan session (Fig. 1B), the stimuli presented to the subject consisted of a central fixation cross for 8.5 s, which alternated with blocks of task specific stimuli, each presented for 14.5 s. All stimuli were low-contrast and light gray, presented on a darker gray background. The first three task-specific stimuli consisted of an array of 10,000 dots arranged in a circle at the center of the screen with a 100-pixel radius. In the first two blocks, the dots moved outward from or inward to the center of the circle at a rate of 66 pixels/s. The third stimulus was a similar array of dots, but not moving. The fourth stimulus was the letters "ImM," which indicated to the subjects to imagine visual motion. That is, any kind of visual imagery of motion in the visual field, similar to the moving dot patterns. The fifth stimulus was the letters "HaT," for hand tap; here, subjects were instructed to bend fingers II–V at the metacarpophalangeal joint at a rate of ~1 Hz. The sixth and final stimulus was the letters "ImHaT", in response to which subjects were instructed to imagine the sensation of tapping their fingers as in the previous task, without actually moving. This series of stimuli cycled through five times.

Motion recordings

To control for subject motion during periods of imagined movement, we recorded EMG from the forearm (flexor digitorum superficialis muscle) to measure muscle activity related to finger flexion and extension, using an MRI-compatible recording device (BIOPAC, Goleta, CA).

Postexperimental questionnaire

After leaving the scanner, the last 28 of 44 subjects were asked to complete a short questionnaire. In this questionnaire, they were requested to report the content of their imagery during the imagine blocks of the tasks.

fMRI scanning procedure

fMRI data were acquired on a Siemens (Erlangen, Germany) 3-T TRIO MRI scanner; blood oxygenation level–dependent (BOLD) contrast was measured with gradient echo T2*-weighted echo-planar images (EPI). Imaging parameters were optimized to minimize signal dropout in medial ventral prefrontal and anterior ventral striatum: we used a tilted acquisition sequence at 30° to the AC-PC line (Deichmann et al. 2003), and an eight-channel phased array coil that yields an ~40% signal increase in this area over a standard coil. The first three volumes of each session were discarded to permit T1 equilibration. Other parameters were as follows: 49 slices, in-plane resolution, 3×3 mm; slice thickness, 3 mm; repetition time, 2.88 s; echo time, 30 ms; field of view, 192×192 mm. T1- and T2-weighted structural images were also acquired for each subject.

fMRI analysis

Data were preprocessed using the SPM5 software package (http://www.fil.ion.ucl.ac.uk/spm/software/spm5/). Images were corrected for slice timing and spatially realigned to the first image from the first scan. The EPI images were coregistered to the T1-weighted anatomical scan. The T1 image was segmented into white and gray matter, and the gray matter was coregistered and normalized to the template gray matter image distributed with SPM5 (in Montreal Neurological Institute space). These parameters were subsequently applied to the T1 image itself, as well as the set of EPI images. Spatial smoothing was applied to the EPI images using a Gaussian kernel with full width at half-maximum of 8 mm.

For each subject, we constructed general linear models in SPM for each session. The reversal learning/reward imagery session model consisted of impulse regressors at the time of reward or punishment feedback, as well as 17 s events for the reward imagery blocks. The hand-tapping/visual motion session was modeled using 14.5 s events during the hand tapping, imagine hand tapping, moving dots, static dots, and imagined visual motion. All regressors were convolved with the canonical hemodynamic response function, and a high-pass filter with a cut-off of 128 s was used to correct for signal drift. For each session, the six ongoing motion parameters estimated during realignment were included as regressors of no interest. Linear contrast images from the single subject analyses were taken to the random effects level by applying a *t*-test between them to produce group statistical parametric maps. For whole brain analyses, we report only voxels surviving a threshold of $P < 0.05$ false discovery rate (FDR) (Genovese et al. 2002) corrected over the whole brain; however, we show activation maps at $P < 0.001$. In the tangible reward condition (i.e., the contrast of reward − punishment), we found significant mOFC activity at our whole brain FDR-corrected threshold. We used the marsbar toolbox (http://marsbar.sourceforge.net/) (Brett et al. 2002) to define a region of interest (ROI) in the mOFC, consisting of the 106 voxels around [3 39 −18] that survived at a threshold of $P < 0.01$ whole brain FDR corrected. Using the same threshold, we calculated a similar ROI in the PCC, which consisted of the 26 voxels around [6 −51 15]. We used these ROIs to perform small-volume corrections (SVCs) in the imagery conditions.

In addition to modeling each session separately, we constructed a model including both sessions for the purpose of comparing responses to reward imagery (in one session) and nonreward motor and visual imagery (in a separate, consecutive scan session). Parameters were similar to the single session models. Finally, we used marsbar to extract and average the percent signal change in these ROIs, and we compared activation in the reward imagery condition with the nonreward imagery conditions.

RESULTS

Regions activated by reversal learning and reward imagery tasks

We first tested for regions activated by reward compared with punishment in the reversal learning task. Figure 2*A* shows the reward versus punishment contrast (thresholded at $P < 0.001$ for display purposes). In Table 1, we report all regions surviving a threshold of $P < 0.05$ FDR-corrected over the whole brain, with an extent of ≥ 10 voxels. These include regions of parietal cortex, superior temporal cortex, PCC, and mOFC.
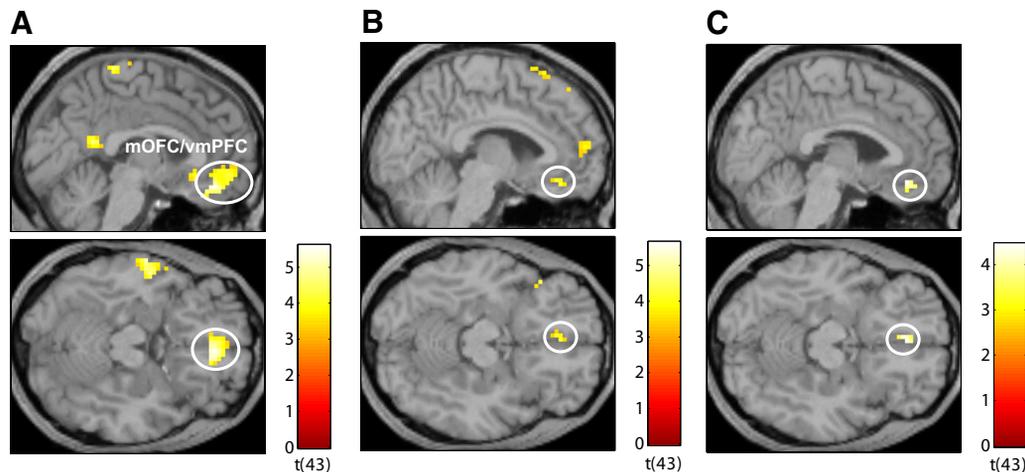

FIG. 2.   Neural activity correlating with real and imagined rewards (shown at $P < 0.001$ uncorrected) *A*: reversal learning, reward vs. punishment contrast. We found an activation peak in mOFC/vmPFC at [3 39 −18] ($Z = 4.7$, $P < 0.05$, whole brain FDR-corrected, cluster size = 526). *B*: imagine reward vs. baseline contrast. No regions are activated at $P < 0.05$ whole brain corrected. We performed SVC in the mOFC region of interest (ROI) derived from the reward punishment contrast and found a peak at [0 33 −21] [$Z = 3.6$; $P < 0.05$ small-volume FDR-corrected, cluster size = 38]. *C*: conjunction of the reward versus punishment and imagine reward contrasts. SVC in the mOFC ROI showed a peak at [−3 36 −15] ($Z = 4.21$; $P < 0.05$ small-volume FDR-corrected, cluster size = 43), indicating that mOFC was coactivated by both tangible and imagined rewards.

TABLE 1. *Regions activated in reversal learning reward versus punishment contrast P < 0.05 FDR-corrected over the whole brain*

Region (BA)	No. Voxels	Laterality	MNI Coordinates			EquivZ
			x	y	z	
mOFC, anterior cingulate (32/11)	526	R	9	24	−9	4.82
		R	3	39	−18	4.7
		L	−3	45	−3	4.68
Parietal (2)	488	R	30	−39	66	4.61
Angular gyrus, posterior temporal (39)	281	L	−45	−69	30	4.6
Posterior cingulate (30)	449	R	6	−51	15	4.48
Inferior temporal (21)	82	L	−63	−12	−18	4.41
Superior frontal gyrus (8)	64	L	−27	24	54	3.87
Superior frontal gyrus (10)	11	L	−15	60	9	3.65
Cingulate gyrus (31)	11	R	18	−33	45	3.71
Inferior parietal lobule (40)	36	L	−54	−33	27	3.33
Inferior frontal gyrus (45)	11	L	−45	30	3	3.27
Superior temporal gyrus (42)	17	R	60	−27	15	3.11

FDR, false discovery rate; mOFC, media orbitofrontal cortex.

Next, we tested whether similar regions were activated by imagined reward; Fig. 2*B* shows the contrast of imagine reward versus baseline. No regions survived whole brain correction at $P < 0.05$ FDR. We performed SVC in the mOFC ROI defined from the reward-punishment contrast and found a cluster with a peak at [0 33 −21] ($Z = 3.6$; $P < 0.05$ small-volume FDR-corrected, cluster size = 38). The PCC has been reported in several studies on reward and valuation (Lebreton et al. 2009; O'Doherty et al. 2003a,b); because this region was activated in the reward versus punishment contrast, we also performed SVC on the imagined-reward contrast in this region, using the ROI derived from the reward-punishment contrast, but did not find any significant activation.

We also performed an exploratory analysis at a more lenient threshold of $P < 0.001$ uncorrected, to see if the NAcc, a region frequently implicated in reward learning, was activated. We did not find any activity in this region in either the reversal learning reward-punishment contrast or the imagine-reward contrast, even at this reduced threshold.

We computed the conjunction of the reward versus punishment and imagine-reward contrasts (Fig. 2*C*). No voxels survived whole brain correction at FDR $P < 0.05$. SVC in the mOFC ROI showed a peak at [−3 36 −15] ($Z = 4.21$; $P < 0.05$ small-volume FDR-corrected, cluster size = 43), indicating that mOFC was coactivated by both tangible and imagined rewards. SVC did not identify any significant activity near the PCC.

Comparing reward imagery to nonreward imagery

Having established that mOFC was engaged for both real monetary reward and imagined reward, we tested whether mOFC activity was generally engaged by imagery tasks or whether this activity was specific to instances of reward-related imagery. We first examined hand-motor imagery versus baseline and visual-motion imagery versus baseline contrasts; no activity in mOFC survived either whole brain correction or correction in the mOFC or PCC ROIs.

Next, we compared activity during reward imagery to visual motion imagery (Fig. 3*A*). We found that, at a threshold of $P < 0.05$, whole brain FDR-corrected, there was significant activation in mOFC/vmPFC at [−9 12 −12] ($Z = 4.56$; $P < 0.05$ whole brain FDR-corrected, cluster size = 75), PCC at [−9 −57 30] ($Z = 4.77$; $P < 0.05$ whole brain FDR-corrected, cluster
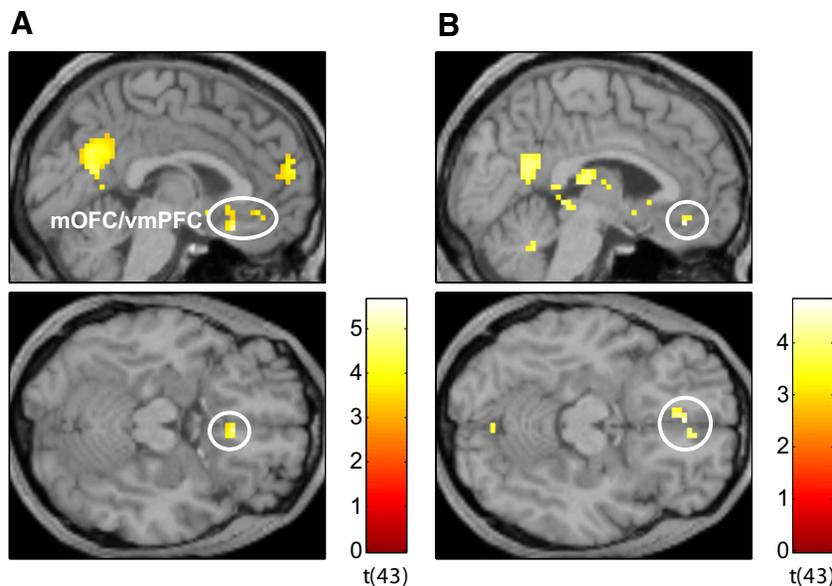
A **B**

FIG. 3. Neural activity correlating with reward imagery compared with nonreward imagery (shown at $P < 0.001$ uncorrected). *A*: reward-imagery vs. visual motion imagery contrast. We found significant activity in the mOFC at [−9 12 −12] ($Z = 4.56$; $P < 0.05$ whole brain FDR-corrected, cluster size = 75), and posterior cingulate cortex (PCC) at [−9 −57 30] ($Z = 4.77$; $P < 0.05$ whole brain FDR-corrected, cluster size = 522). *B*: reward imagery vs. hand motor imagery contrast. We tested for significant voxels in both the mOFC and PCC ROIs and found significant clusters at [−3 36 −15] ($Z = 4.08$; $P < 0.01$ small-volume FDR-corrected; cluster size = 70) and [9 −54 15] ($Z = 4.16$; $P < 0.05$ small-volume FDR-corrected; cluster size = 26), respectively.

size = 522), and several other regions, including bilateral posterior superior temporal gyrus, frontal pole, and along the left parieto-occipital sulcus (Supplemental Table S1).[1] We similarly compared activity during reward imagery to hand-motor imagery (Fig. 3*B*). No regions survived at a threshold of $P < 0.05$ FDR-corrected over the whole brain. We tested for significant voxels in the mOFC ROI and found a significant cluster at [−3 36 −15] ($Z = 4.08$; $P < 0.01$ small-volume FDR-corrected; cluster size = 70). In this contrast, we also found significant activity near the PCC [9 −54 15] ($Z = 4.16$; $P < 0.05$ small-volume FDR-corrected; cluster size = 26).

Finally, we extracted and averaged the percent signal change over the reward and nonreward imagery blocks in both the mOFC (Fig. S1*A*) and PCC (Fig. S1*B*) ROIs. We used a paired *t*-test to compare activation in these conditions and found that, in mOFC, percent signal change was significantly higher in the reward imagery condition compared with visual motion imagery ($T(43) = 3.215$, $P < 0.05$) and hand motion imagery ($T(43) = 3.62$, $P < 0.05$). Similarly, in the PCC, we found that activity in the reward imagery condition was significantly higher than in the imagine visual motion condition ($T(43) = 2.93$, $P < 0.05$) and the motor imagery condition ($T(43) = 3.4$).

Regions coactivated in hand movement and motor imagery tasks

The contrast of hand motion versus baseline showed activation in sensory and motor cortices with peaks at [−36 −27 60], [−33 −24 48], and [−48 −27 57] ($T = 14.68$, 14.51, and 13.52, respectively, $P < 0.001$ FDR-corrected). The hand motor imagery contrast showed activation peaks in the precentral gyrus at [−48 −3 48] ($Z = 5.28$, $P < 0.05$ whole brain FDR-corrected). The conjunction of hand motion and imagined hand motion showed a region of overlap in precentral gyrus at [−48 −9 51] ($Z = 3.72$, $P < 0.05$ whole brain FDR-corrected), although this was not at the "hand knob" of motor cortex where hand motion–related activity has been previously found (Yousry et al. 1997).

Regions activated in visual motion and motion imagery tasks

The contrast of moving compared with static dots elicited activity with peaks in V5/MT bilaterally at [−48 −75 3] ($Z = 6.83$, $P < 0.001$ whole brain FDR-corrected) and [48 −72 0] ($Z = 6.65$, $P < 0.001$ whole brain FDR-corrected), which correspond well with peaks identified by Dumoulin et al. (2000) at [−47 −76 2] and [44 −67 0], respectively. The imagine visual motion contrast did not elicit any activity near V5/MT, nor did the conjunction.

Postexperiment questionnaire

After the experiment, we asked subjects to complete a short questionnaire about their experience during the experiment. Specifically, we asked subjects what they were thinking about during imagery blocks: *1*) imagine visual motion, *2*) imagine hand tapping, and *3*) imagine reward. These results are summarized in Table 2. During the imagine visual motion task, subjects reported imagining the moving dots or other moving

TABLE 2. *Self-reported contents of imagery*

Imagery Instructed	Reported Imagery Contents	No. Subjects
Reward imagery	Money	21
	Travel	2
	Acquiring new things	5
	Food	3
	Winning	8
	Praise	5
	Work/success	5
	Sex	3
	Rest/relaxation	3
Finger-tapping imagery	Clenching fist	7
	Holding/pressing	3
	Tapping	18
	Playing guitar	1
	Exercise	1
Visual motion	Objects moving across field of view	20
	View while running/driving/cycling	7

patterns, moving in a vehicle, or other things moving around them like baseballs and joggers. During the imagine hand tapping task, subjects reported using motor imagery including thinking about tapping, contracting muscles, and squeezing motions. During the imagine reward task, subjects reported imagining monetary rewards, praise, compliments, and erotic imagery.

DISCUSSION

In this study, we showed that an overlapping region of mOFC is activated both during experience of real monetary rewards and when subjects merely imagined situations they found personally rewarding. Furthermore, we found that activation in this region is specific to imagery that is rewarding, because it was not seen in instances of motor or visual imagery.

Recent studies have found a common network of regions involved in mental construction of past real, imagined, or future events (Hassabis and Maguire 2009), including hippocampus, parahippocampal gyrus, retrosplenial and posterior parietal cortices, middle temporal cortices, medial PFC, and posterior cingulate cortex. In addition to this more general network, studies of motor (Porro et al. 1996) and object (O'Craven and Kanwisher 2000) imagery, for example, have also shown activation in regions of cortex specifically involved in motion or object processing. Here we show that imagery with content specific to reward similarly activates reward processing circuitry. This finding adds to a growing body of literature suggesting that imagery shares overlapping neural circuitry with endogenous events.

Experiencing a reward is clearly the best way to learn its value, and in our study, subjects were free to imagine remembered, or purely fictional, rewarding situations. Hassabis and colleagues (Hassabis and Maguire 2007, 2009; Hassabis et al. 2007) argued that both episodic memory and imagery depend on mental "scene construction," which engages a common network of regions—including hippocampus, parahippocampal gyrus, and retrosplenial cortex (Hassabis et al. 2007). In this study, they found that a network, including the anterior medial prefrontal cortex, precuneus, and PCC, was more engaged during memory relative to imagery. Interestingly, in this study, we found the PCC to respond to tangible rewards and to be preferentially engaged by imagery with emotional content

---

[1] The online version of this article contains supplemental data.

compared with motor or visual imagery. Indeed, PCC has frequently been found to be active in studies of reward and valuation (Lebreton et al. 2009; O'Doherty et al. 2003a,b) and therefore likely has a general role in experience of emotion, whether through imagery, memory (Sharot et al. 2007), or tangible reward.

To elicit maximal brain activity in the reward imagery task, we asked subjects to imagine situations that they found to be personally rewarding. In addition, we used nonemotional imagery to control for neural activity broadly engaged by imagery processes. However, there may be components of the scenarios imagined in the reward condition other than reward per se that are responsible for the activation difference. For example, according to subjects' reports, reward imagery sometimes contained social interactions. An interesting follow-up to this study would be a parametric design, in which subjects are asked to imagine specific scenarios and provide ratings of each scenario's reward value. This design would allow the possibility of evaluating how brain activity is modulated by the reward value of imagery, similar to previous studies using tangible stimuli (Elliott et al. 2003; Small et al. 2001). This design could also include nonrewarding emotional, or aversive, imagery, similar to studies that have used positive and negative emotional memories (Sharot et al. 2007).

We chose to use monetary reinforcers in our tangible reward condition. Monetary reinforcers have become the standard reinforcer in fMRI studies of reward learning, both because money has a high motivational value for human subjects and because it elicits reliable activations in reward-sensitive brain structures (Elliott et al. 2003; Knutson et al. 2005; O'Doherty et al. 2001; Valentin and O'Doherty 2009). Money is not a primary, or innate, reinforcer, but rather takes on a learned value through experience. Therefore it is possible that reward activation in the tangible reward condition is actually related to thoughts about how the money will be spent. Although we cannot completely rule out this possibility, it is probable that "imagination" is not the primary mechanism by which monetary reinforcement is encoded as valuable. Given the extent to which monetary reinforcement has become ubiquitous in our society, it is more parsimonious to presume that money has acquired value through well-learned conditioned associations rather than requiring a cognitive strategy of imagining future attainment for each monetary amount evaluated. An interesting topic for future study will be to compare neural responses to tangible and imagined primary and secondary reinforcers.

It is notable that, in contrast to mOFC/vmPFC, we did not find significant activity in the ventral striatum in this study. These findings could be consistent with a possible dissociation in the functions of the mOFC from that of the ventral striatum (Hare et al. 2008). Previous findings have implicated the mOFC/vmPFC in representing the value of experienced rewards and the value of goal states (Chib et al. 2009; Elliott et al. 2008; Gottfried et al. 2003; Hare et al. 2008; Knutson et al. 2003; Kringelbach et al. 2003; Small et al. 2001; Ursu and Carter 2005). On the other hand, the ventral striatum has been especially implicated in encoding prediction errors rather than experienced reward or goal values per se (Bray and O'Doherty 2007; Delgado et al. 2000; Hare et al. 2008; McClure et al. 2003; Pagnoni et al. 2002; Tobler et al. 2006). The absence of ventral striatum activity could be consistent with the putatively distinct contributions of these neural structures.

Previous studies implicating mOFC in goal valuation have depicted goals by an explicit stimulus representation, e.g., a picture depicting the goal item, or by a cue previously associated with a particular food or money outcome (Hare et al. 2008; Plassmann et al. 2007; Valentin et al. 2007). However, in everyday life, behavior is often planned without an explicit representation of the goal state being present and initiated to obtain hypothetical outcomes. Thus it is often necessary to rely on mental simulation of prospective future reward states to initiate such plans of action. This study represents an important advance toward understanding this process, and specifically, the role of mOFC in representing goal states generated through mental construction. However, there are a number of outstanding issues in understanding the role of simulated rewards in motivating behavior. One highly relevant question is whether we can show conditioned behaviors to imagined rewards. Furthermore, reward responses in mOFC have been shown to be modulated by context (Plassmann et al. 2008) and therefore be strongly influenced by factors other than the sensory properties of stimuli. We show here that mOFC is specifically engaged by the overt mental generation of emotional context; an interesting question for future study is whether overt reward imagery influences valuation, similar to covert processes such as marketing.

Humans are capable of forming goals that guide behavior over days, months, and years. Our ability to imagine future possible rewards is likely to be critical for this capacity: without this, it is unlikely we would be willing to durably undertake effortful tasks such as studying for an examination or going to the gym. Previous studies have found that mOFC activity is modulated by goal values (Plassmann et al. 2007) and that this region plays an important role in goal-directed learning (Valentin et al. 2007). Our finding that this region is also active during simulated reward lends strong support to the notion that mOFC is engaged to represent rewarding goal states very generally and suggests a mechanism by which mental simulation of future reward can influence behavior.

DISCLOSURES

No conflicts of interest are declared by the authors.

REFERENCES

Aharon I, Etcoff N, Ariely D, Chabris CF, O'Connor E, Breiter HC. Beautiful faces have variable reward value: fMRI and behavioral evidence. *Neuron* 32: 537–551, 2001.

Blood AJ, Zatorre RJ. Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Proc Natl Acad Sci USA* 98: 11818–11823, 2001.

Bray S, O'Doherty J. Neural coding of reward-prediction error signals during classical conditioning with attractive faces. *J Neurophysiol* 97: 3036–3045, 2007.

Brett M, Anton J-L, Valabregue R, Poline J-B. Region of interest analysis using an SPM toolbox. 8th International Conference on Functional Mapping of the Human Brain, Sendai, Japan, June 2–6, 2002.

Chib VS, Rangel A, Shimojo S, O'Doherty JP. Evidence for a common representation of decision values for dissimilar goods in human ventromedial prefrontal cortex. *J Neurosci* 29: 12315–12320, 2009.

Cox SM, Andrade A, Johnsrude IS. Learning to like: a role for human orbitofrontal cortex in conditioned reward. *J Neurosci* 25: 2733–2740, 2005.

D'Argembeau A, Xue G, Lu ZL, Van der Linden M, Bechara A. Neural correlates of envisioning emotional events in the near and far future. *Neuroimage* 40: 398–407, 2008.

Deichmann R, Gottfried JA, Hutton C, Turner R. Optimized EPI for fMRI studies of the orbitofrontal cortex. *Neuroimage* 19: 430–441, 2003.

Delgado MR, Nystrom LE, Fissell C, Noll DC, Fiez JA. Tracking the hemodynamic responses to reward and punishment in the striatum. *J Neurophysiol* 84: 3072–3077, 2000.

Dumoulin SO, Bittar RG, Kabani NJ, Baker CL, Le Goualher G, Pike GB, Evans AC. A new anatomical landmark for reliable identification of human area V5/MT: a quantitative analysis of sulcal patterning. *Cereb Cortex* 10: 454–463, 2000.

Elliott R, Agnew Z, Deakin JFW. Medial orbitofrontal cortex codes relative rather than absolute value of financial rewards in humans. *Eur J Neurosci* 27: 2213–2218, 2008.

Elliott R, Newman JL, Longe OA, Deakin JFW. Differential response patterns in the striatum and orbitofrontal cortex to financial reward in humans: a parametric functional magnetic resonance imaging study. *J Neurosci* 23: 303–307, 2003.

Genovese CR, Lazar NA, Nichols T. Thresholding of statistical maps in functional neuroimaging using the false discovery rate. *Neuroimage* 15: 870–878, 2002.

Gottfried JA, O'Doherty J, Dolan RJ. Encoding predictive reward value in human amygdala and orbitofrontal cortex. *Science* 301: 1104–1107, 2003.

Hampton AN, O'Doherty JP. Decoding the neural substrates of reward-related decision making with functional MRI. *Proc Natl Acad Sci USA* 104: 1377–1382, 2007.

Hare TA, O'Doherty J, Camerer CF, Schultz W, Rangel A. Dissociating the role of the orbitofrontal cortex and the striatum in the computation of goal values and prediction errors. *J Neurosci* 28: 5623–5630, 2008.

Hassabis D, Kumaran D, Maguire EA. Using imagination to understand the neural basis of episodic memory. *J Neurosci* 27: 14365–14374, 2007.

Hassabis D, Maguire EA. Deconstructing episodic memory with construction. *Trends Cogn Sci* 11: 299–306, 2007.

Hassabis D, Maguire EA. The construction system of the brain. *Philos Trans R Soc B Biol Sci* 364: 1263–1271, 2009.

Knutson B, Fong GW, Adams CM, Varner JL, Hommer D. Dissociation of reward anticipation and outcome with event-related fMRI. *Neuroreport* 12: 3683–3687, 2001.

Knutson B, Fong GW, Bennett SM, Adams CM, Homme D. A region of mesial prefrontal cortex tracks monetarily rewarding outcomes: characterization with rapid event-related fMRI. *Neuroimage* 18: 263–272, 2003.

Knutson B, Taylor J, Kaufman M, Peterson R, Glover G. Distributed neural representation of expected value. *J Neurosci* 25: 4806–4812, 2005.

Kringelbach ML, O'Doherty J, Rolls ET, Andrews C. Activation of the human orbitofrontal cortex to a liquid food stimulus is correlated with its subjective pleasantness. *Cereb Cortex* 13: 1064–1071, 2003.

Lebreton M, Jorge S, Michel V, Thirion B, Pessiglione M. An automatic valuation system in the human brain: evidence from functional neuroimaging. *Neuron* 64: 431–439, 2009.

McClure SM, Berns GS, Montague PR. Temporal prediction errors in a passive learning task activate human striatum. *Neuron* 38: 339–346, 2003.

O'Craven KM, Kanwisher N. Mental imagery of faces and places activates corresponding stimulus-specific brain regions. *J Cogn Neurosci* 12: 1013–1023, 2000.

O'Doherty J, Critchley H, Deichmann R, Dolan RJ. Dissociating valence of outcome from behavioral control in human orbital and ventral prefrontal cortices. *J Neurosci* 23: 7931–7939, 2003a.

O'Doherty J, Dayan P, Schultz J, Deichmann R, Friston K, Dolan RJ. Dissociable roles of ventral and dorsal striatum in instrumental conditioning. *Science* 304: 452–454, 2004.

O'Doherty J, Kringelbach ML, Rolls ET, Hornak J, Andrews C. Abstract reward and punishment representations in the human orbitofrontal cortex. *Nat Neurosci* 4: 95–102, 2001.

O'Doherty J, Winston J, Critchley H, Perrett D, Burt DM, Dolan RJ. Beauty in a smile: the role of medial orbitofrontal cortex in facial attractiveness. *Neuropsychologia* 41: 147–155, 2003b.

Pagnoni G, Zink CF, Montague PR, Berns GS. Activity in human ventral striatum locked to errors of reward prediction. *Nat Neurosci* 5: 97–98, 2002.

Plassmann H, O'Doherty J, Rangel A. Orbitofrontal cortex encodes willingness to pay in everyday economic transactions. *J Neurosci* 27: 9984–9988, 2007.

Plassmann H, O'Doherty J, Shiv B, Rangel A. Marketing actions can modulate neural representations of experienced pleasantness. *Proc Natl Acad Sci USA* 105: 1050–1054, 2008.

Porro CA, Francescato MP, Cettolo V, Diamond ME, Baraldi P, Zuiani C, Bazzocchi M, diPrampero PE. Primary motor and sensory cortex activation during motor performance and motor imagery: a functional magnetic resonance imaging study. *J Neurosci* 16: 7688–7698, 1996.

Sharot T, Riccardi AM, Raio CM, Phelps EA. Neural mechanisms mediating optimism bias. *Nature* 450: 102–106, 2007.

Small DM, Zatorre RJ, Dagher A, Evans AC, Jones-Gotman M. Changes in brain activity related to eating chocolate - from pleasure to aversion. *Brain* 124: 1720–1733, 2001.

Tobler PN, O'Doherty JP, Dolan RJ, Schultz W. Human neural learning depends on reward prediction errors in the blocking paradigm. *J Neurophysiol* 95: 301–310, 2006.

Ursu S, Carter CS. Outcome representations, counterfactual comparisons and the human orbitofrontal cortex: implications for neuroirnaging studies of decision-making. *Cogn Brain Res* 23: 51–60, 2005.

Valentin VV, Dickinson A, O'Doherty JP. Determining the neural substrates of goal-directed learning in the human brain. *J Neurosci* 27: 4019–4026, 2007.

Valentin VV, O'Doherty JP. Overlapping prediction errors in dorsal striatum during instrumental learning with juice and money reward in the human brain. *J Neurophysiol* 102: 3384–3391, 2009.

Yousry TA, Schmid UD, Alkadhi H, Schmidt D, Peraud A, Buettner A, Winkler P. Localization of the motor hand area to a knob on the precentral gyrus: a new landmark. *Brain* 120: 141–157, 1997.