

Adaptive neural reward processing during anticipation and receipt of monetary rewards in mindfulness meditators

Ulrich Kirk,¹ Kirk Warren Brown,² and Jonathan Downar^{3,4}

¹Institute of Psychology, University of Southern Denmark, 5230 Odense, Denmark, ²Department of Psychology, Virginia Commonwealth University, Richmond, Virginia 23284, USA, ³Neuropsychiatry and Sleep Clinic, Toronto Western Hospital, Toronto, Ontario M5T 2S8, Canada, and ⁴Centre for Addition and Mental Health, University of Toronto, Toronto, Ontario M5T 1R8, Canada

Reward seeking is ubiquitous and adaptive in humans. But excessive reward seeking behavior, such as chasing monetary rewards, may lead to diminished subjective well-being. This study examined whether individuals trained in mindfulness meditation show neural evidence of lower susceptibility to monetary rewards. Seventy-eight participants (34 meditators, 44 matched controls) completed the monetary incentive delay task while undergoing functional magnetic resonance imaging. The groups performed equally on the task, but meditators showed lower neural activations in the caudate nucleus during reward anticipation, and elevated bilateral posterior insula activation during reward anticipation. Meditators also evidenced reduced activations in the ventromedial prefrontal cortex during reward receipt compared with controls. Connectivity parameters between the right caudate and bilateral anterior insula were attenuated in meditators during incentive anticipation. In summary, brain regions involved in reward processing—both during reward anticipation and receipt of reward—responded differently in mindfulness meditators than in nonmeditators, indicating that the former are less susceptible to monetary incentives.

Keywords: mindfulness; reward processing; fMRI; connectivity analysis; dorsal striatum; insular cortex

Much of human behavior is built around obtaining desirable outcomes and avoiding undesirable ones. Neuroscience has now identified key loci in a distributed brain network supporting reward processing, including regions involved in anticipatory and outcome phases of both primary and secondary rewards (Rangel *et al.*, 2008). An accumulating body of research using monetary rewards has revealed a neural functional dissociation between anticipatory and reward outcome processes, such that the anticipation of monetary reward or no-reward preferentially activates the striatum (in a manner that scales with the amount of gain or loss at stake), as well as the anterior insula, among other regions (Knutson *et al.*, 2001). In contrast, receipt of monetary gain, *vs* no gain, has shown activations in regions of the ventromedial prefrontal cortex (VMPFC), among other regions, including the parietal cortex and posterior cingulate (Knutson *et al.*, 2003; Kringelbach *et al.*, 2003; Rangel *et al.*, 2008; Hare *et al.*, 2009; Lebreton *et al.*, 2009).

There are reasons to believe that normative reward processing is adaptive for outcomes such as behavior regulation, but there are potential drawbacks as well. A considerable body of research has shown that the anticipation and receipt of extrinsic rewards in particular, including money and social approval, can undermine intrinsic (self-guided) motivation, task performance, creativity, and subjective well-being (Deci *et al.*, 1999). This ‘undermining effect’, recently supported by neuroimaging investigations (Murayama *et al.*, 2010; Ma *et al.*, 2014), has significant implications for education, business, psychiatric treatment and other sectors where performance-based incentives are

commonly used. However, individuals differ in their susceptibility to the undermining effect of extrinsic rewards (Hagger and Chatzisarantis, 2011), and self-awareness is theorized to foster forms of adaptive behavior regulation that support an interpretation of extrinsic rewards as informational rather than as, for example, inherently desirable (Deci *et al.*, 2015).

MINDFULNESS MEDITATION AND REWARD PROCESSING

A primary way in which self-awareness is enhanced is through mindfulness and related forms of meditation. In the present study, we asked whether the practice of mindfulness meditation, which a growing corpus of research indicates has manifold benefits for behavior regulation, emotion regulation and other salutary outcomes (Brown *et al.*, 2015), is associated with reduced neural activations in brain regions associated with the anticipation and receipt of monetary reward. Mindfulness meditation involves an intentional open or receptive attention to ongoing events and experiences. Thoughts, emotions, kinesthetic experiences and sensory phenomena, whether pleasant, unpleasant or neutral, are attended to without mentally retaining them or removing them from conscious awareness (Sahdra *et al.*, 2010).

There are several reasons to expect that experienced meditators may show reduced neural activations in regions associated with both phases of reward processing discussed above. In accordance with proposals that mindfulness facilitates reduced appraisals of self-relevant stimuli (Brown *et al.*, 2007), Brown *et al.* (2013) found that those higher in dispositional mindfulness showed lower event-related potential amplitudes in response to motivationally salient visual stimuli, both pleasant and unpleasant. Central to the present research, mindfulness has also predicted reduced engagement of extrinsic rewards in daily life in favor of intrinsic self-generated rewards (Brown and Ryan, 2003; Levesque and Brown, 2007). Finally, mindfulness has been positively associated with nonattachment, expressed phenomenologically as a reduced fixation on ideas, images or sensory objects and a relative absence of internal pressure to acquire, hold, avoid or change

Received 24 February 2014; Revised 18 July 2014; Accepted 13 August 2014

Advance Access publication 5 September 2014

We thank Krystle Bartley, Carrie Howard, Christine Cortelyou and Monica Alexander for data collection, Mark Ross and Nathan Apple for implementing the NEMO experiment client (<http://labs.vtc.vt.edu/hnl/nemo/>) and Claudia Bracero for administrative assistance. The authors respectfully thank P. Read Montague for financial and intellectual support to the present work. This work was supported by grants from the Kane Family Foundation (P. Read Montague), the National Institute of Health (R01-DA11723; R01-MH085496, P. Read Montague).

Correspondence should be addressed to Ulrich Kirk, Institute of Psychology, University of Southern Denmark, Denmark. E-mail: ukirk@health.sdu.dk

(Sahdra *et al.*, 2010). Importantly, mindfulness meditation concerns a participatory observation that involves an awareness of experience while being immersed in it, rather than aloof or disinterested spectatorship (Brown *et al.*, 2007). Thus, we did not expect that meditators would perform less well than matched control participants in incentive task performance in this study.

THE PRESENT RESEARCH

Using event-related functional magnetic resonance imaging (fMRI), the present study was designed to examine whether, relative to matched controls, experienced meditators would show altered neural activations during reward processing. Specifically, we hypothesized that meditators would show reduced neural reward-related activations during reward anticipation—specifically the striatum and anterior insula—and in reward-related regions associated with receipt or outcome of monetary gains or losses—particularly the VMPFC. To accomplish these experimental aims we used the monetary incentive delay (MID) task (Knutson *et al.*, 2000). In this widely used task, participants are presented with potential monetary gain and loss trials, which, depending on response latency, result in monetary gain, loss or neither.

RESULTS

Behavioral results

Meditators and controls performed similarly on the MID task. The average hit rate across all trials for meditators was 55.35% (s.d. = 1.4) and for controls 55.82% (s.d. = 2.0) (Figure S2), a non-significant difference ($P = 0.85$). Mean reaction time (RT) for meditators was 257 ms (s.d. = 25 ms) and for controls 226 ms (s.d. = 48 ms), also a non-significant difference ($P = 0.63$).

Hit rates on each trial type were averaged for each individual and subjected to repeated-measures within-subjects 2 (valence) \times 3 (magnitude) analyses of variance (ANOVA). The results showed significant main effects of monetary magnitude on hit rate in both trial types. Meditators displayed a main effect of magnitude in gain trials [$F(2,101) = 13.65$; $P < 0.0001$] and in loss trials [$F(2,101) = 22.46$; $P < 0.0001$]. Similarly, controls showed a main effect of monetary magnitude on hit rate in gain trials [$F(2,131) = 15.08$; $P < 0.0001$] and in loss trials [$F(2,131) = 24.58$; $P < 0.0001$]. Post hoc *t*-tests revealed that both groups hit on a larger percentage of \$1 and \$5 trials than on \$0 trials in the gain domain (both P values < 0.001), as well as on a greater percentage of \$1 and \$5 trials than on \$0 trials in the loss domain (both P values < 0.001).

There was no main effect of trial type (gain and loss trials) within each group or between groups, as assessed in a mixed model ANOVA. Thus, although both groups displayed elevated hit rates on incentive trials (\$1 and \$5), this effect was not different between gain and loss trials. Finally, there was no interaction effect within group or between groups of trial type and monetary magnitude. These behavioral analyses, demonstrating no significant between-group differences in performance on the MID task, suggest that group differences in the fMRI data are not confounded by behavioral task performance.

fMRI results

Reward anticipation differences across meditators and controls

The neural data showed that meditators and controls exhibited differential neural activations in dorsal striatum and posterior insula at corrected threshold during both reward and no-reward anticipation ($P < 0.01$, FDR-corrected). In the within-group contrast during gain anticipation (A) [$\text{Gain}_A > \text{Nongain}_A$], we observed that controls showed elevated activity in the striatum, anterior insula, posterior

Table 1 Areas of neural activation in the control group during anticipation

Region	Laterality	Cluster size	x	y	z	t
[Gain > Nongain _{CTR}]						
Caudate	R	46	4	8	4	6.25
	L	55	-4	6	5	8.01
Putamen	R	22	20	12	-4	4.53
	L	30	-16	12	-3	4.78
IFG/anterior insula	R	19	36	24	-4	3.87
Posterior cingulate	R	84	5	-60	6	6.12
Precuneus	L/R	111	-4	-64	60	7.23
Thalamus	R	65	8	-2	6	7.01
	L	45	-5	-8	8	6.88
Middle frontal gyrus	R	17	40	60	8	4.12
Superior frontal/SMA	R	128	4	4	56	8.52
Lingual gyrus	R	62	4	-80	-4	5.95
	L	52	-5	-78	-5	6.71
Cerebellum	R	74	33	-72	-24	5.81
	L	65	-32	-58	-28	6.13
[Loss > Nonloss _{CTR}]						
Caudate	R	36	6	7	5	7.29
	L	54	-8	5	3	9.31
Putamen	R	29	16	12	-4	4.85
	L	33	36	28	0	4.23
IFG/anterior insula	R	20	-32	24	0	4.44
	L	94	4	-56	8	6.32
Posterior cingulate	R	70	-16	-80	44	6.21
	L	65	11	-75	43	6.77
Thalamus	R	42	8	-4	14	7.24
	L	43	-8	-8	14	5.63
Middle frontal gyrus	R	25	40	56	10	4.17
Superior frontal/SMA	R/L	123	0	2	63	8.22
	R	48	8	-88	-4	5.07
Lingual gyrus	L	69	-16	-83	-15	5.15
	R	107	24	-76	-20	5.88
Cerebellum	R	101	-16	-76	-24	5.56

Notes. Activations thresholded at $P < 0.01$, FDR. Extent threshold > 10 voxels. IFG = inferior frontal gyrus; SMA = supplementary motor area.

cingulate, thalamus, precuneus, lingual gyrus and cerebellum (Table 1). During no-reward anticipation [$\text{Loss}_A > \text{Nonloss}_A$], the control group showed significant activations in the striatum, anterior insula, posterior cingulate, precuneus, middle frontal gyrus, thalamus, lingual gyrus, and cerebellum (Table 1). In the gain anticipation contrast [$\text{Gain}_A > \text{Nongain}_A$] the meditator group showed elevated activity in the striatum, thalamus, precentral gyrus, postcentral gyrus and cerebellum (Table 2). In the no-reward anticipation contrast condition [$\text{Loss}_A > \text{Nonloss}_A$] meditators had activity in striatum, inferior frontal gyrus/anterior insula, precuneus and cerebellum (Table 2).

A significant interaction during gain anticipation between the two groups [$\text{Gain}_A > \text{Nongain}_A$ Controls] $>$ [$\text{Gain}_A > \text{Nongain}_A$ Meditators] showed that activation in bilateral dorsal striatum was greater for gain anticipation in controls relative to meditators (Figure 1A). A similar pattern was observed during no-reward anticipation [$\text{Loss}_A > \text{Nonloss}_A$ Controls] $>$ [$\text{Loss}_A > \text{Nonloss}_A$ Meditators] (Figure 1A). The inverse interaction in the gain domain [$\text{Gain}_A > \text{Nongain}_A$ Meditators] $>$ [$\text{Gain}_A > \text{Nongain}_A$ Controls] as well as in the loss domain [$\text{Loss}_A > \text{Nonloss}_A$ Meditators] $>$ [$\text{Loss}_A > \text{Nonloss}_A$ Controls] showed elevated activity in bilateral posterior insula in meditators during gain anticipation relative to controls (Figure 1B). Table 3 displays the between-group differences in neural activations during the anticipation phase.

Reward outcome differences across meditators and controls

The neural data showed that during the outcome phase, controls and meditators displayed different neural patterns of activation. Both

groups displayed activity in the VMPFC when successfully hitting the target on gain trials. Specifically controls had elevated VMPFC activity in the outcome (O) phase in the main effect [Gain_O (hit) > Nongain_O (miss)], whereas meditators showed a comparable neural signature in the VMPFC for the main effect [Gain_O > Nongain_O] (Table 4). However, the strength of VMPFC activity during gain trials was significantly greater in controls compared with meditators (Figure 2). This neural difference was further validated when extracting the beta estimates in the VMPFC (Figure 2, right panel).

Table 2 Areas of neural activation in the meditator group during anticipation

Region	Laterality	Cluster size	x	y	z	t
[Gain > Nongain_{MEDI}]						
Caudate	R	16	12	8	7	4.53
	L	12	-6	4	1	4.53
Putamen	R	15	16	12	-8	4.74
	L	15	-16	8	-8	4.63
Thalamus	R	21	11	-10	13	4.84
	L	31	-12	-8	12	4.39
SMA	R	62	4	0	64	5.58
	L	75	-3	4	61	4.85
Precentral gyrus	R	52	56	4	40	4.32
	L	76	-56	4	36	4.26
Postcentral gyrus	L	12	-52	-24	16	4.23
Cerebellum	R	52	36	-56	-24	4.56
	L	35	-28	-56	-24	4.44
[Loss > Nonloss_{MEDI}]						
Caudate	R	15	12	8	8	4.18
	L	23	-7	8	5	4.01
Putamen	R	28	18	12	-5	4.65
	L	20	-16	12	-4	4.23
IFG/anterior insula	R	13	40	20	0	4.20
SMA	R	54	6	0	56	3.91
	L	42	-2	0	58	4.02
Precuneus	R	17	4	-72	52	4.42
	L	84	-24	-64	52	4.95
Cerebellum	R	73	16	-52	-20	4.75
	L	56	-24	-60	-20	5.01

Notes. Activations thresholded at $P < 0.01$, FDR. Extent threshold > 10 voxels. IFG = inferior frontal gyrus; SMA = supplementary motor area.

Functional connectivity analyses during reward anticipation

To assess the modulation of the dorsal striatum during reward anticipation between meditators and controls in more detail, we assessed functional connectivity parameters implemented as psychophysiological interactions (PPI; Friston *et al.*, 1997). Thus, we chose the seed region in the right caudate across the entire time series. This

Table 3 Areas of neural activation displaying between group differences during anticipation

Region	Laterality	Cluster size	x	y	z	t
[Gain > Nongain_{CTR}] > [Gain > Nongain_{MEDI}]						
Caudate head	R	16	8	4	4	4.36
	L	15	-8	4	0	4.36
Lingual gyrus	R	22	8	-80	-12	4.32
	L	17	-17	-80	-16	4.73
Posterior cingulate	R	86	4	-46	7	6.18
Precuneus	R	14	16	-72	52	4.50
	L	23	-23	-72	50	5.05
Premotor cortex/SMA	R	25	32	0	60	4.53
	L	32	-40	-4	60	6.05
[Gain > Nongain_{MEDI}] > [Gain > Nongain_{CTR}]						
Posterior insula	R	27	40	-24	20	4.96
	L	33	-40	-20	16	4.13
Postcentral gyrus	R	22	64	-12	24	4.15
Superior frontal gyrus	L	14	-12	40	52	4.42
Angular gyrus	L	26	-40	-56	24	5.14
[Loss > Nonloss_{CTR}] > [Loss > Nonloss_{MEDI}]						
Caudate	R	27	7	0	11	4.13
Posterior cingulate	R	12	2	-44	4	5.22
Precuneus	R	13	4	-76	44	4.31
	L	17	-4	-80	40	4.82
Premotor cortex/SMA	R	23	44	-4	56	4.35
	L	40	-28	-4	68	6.12
[Loss > Nonloss_{MEDI}] > [Loss > Nonloss_{CTR}]						
Posterior insula	R	31	44	-12	8	4.15
	L	23	-36	-12	12	4.71
Parahippocampal gyrus	L	31	-28	-32	-11	5.44

Notes. Activations thresholded at $P < 0.01$, FDR. Extent threshold > 10 voxels. SMA = supplementary motor area.

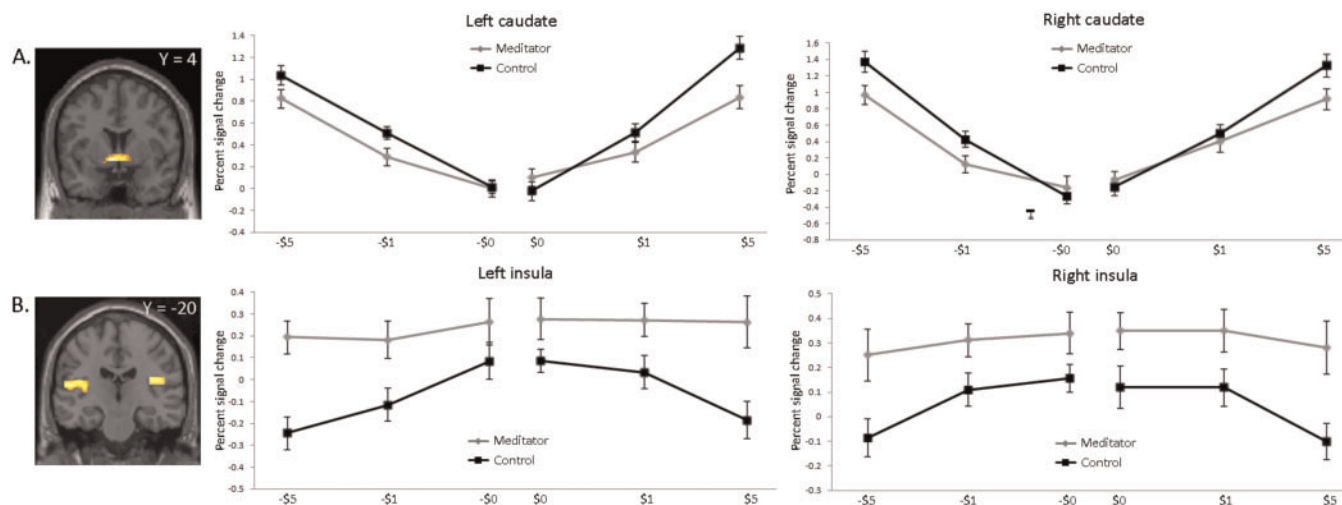


Fig. 1 Group differences in incentive processing during anticipation phase. (A) Controls showed elevated bilateral caudate activity during incentive anticipation. Plots displayed in top row display significant group differences between controls and meditators in high-incentive gain trials (\$1 and \$5) and loss trials (\$1 and \$5). (B) Meditators displayed elevated bilateral posterior insula activity in the anticipation phase of the task. Plots displayed in the bottom panel show the extracted beta estimates for left and right posterior insula, respectively. SEM is given in the plots.

region was selected based on the contrast $[\text{Gain}_A > \text{Nongain}_A \text{ Controls}] > [\text{Gain}_A > \text{Nongain}_A \text{ Meditators}]$.

This analysis yielded increased connectivity with bilateral anterior insula (Right: 40 16 0; $z = 4.40$. Left: -40 13 -1 ; $z = 4.11$; $P < 0.05$,

Table 4 Areas of neural activation by subject group during outcome

Region	Laterality	Cluster size	x	y	z	t
[Gain ('hit') > Nongain ('miss')_{CTR}]						
VMPFC	L/R	64	0	48	-12	6.94
Ventral striatum	R	52	16	8	-8	6.81
Posterior cingulate	R	113	4	-52	12	8.24
Parahippocampal gyrus	R	11	24	-16	-16	5.27
Middle occipital gyrus	R	19	24	-92	0	4.07
[Gain ('hit') > Nongain ('miss')_{MEDI}]						
VMPFC	L/R	18	0	60	0	4.53
Ventral striatum	R	21	16	8	-4	5.22
Posterior cingulate	L	32	-4	-48	16	5.53
Superior parietal lobule	L	19	-24	-76	44	3.89
Middle occipital gyrus	R	17	48	-64	-8	3.87
[Nonloss ('hit') > Loss ('miss')_{CTR}]						
Ventral striatum	R	60	28	-4	8	4.33
Inferior frontal gyrus	L	12	-40	36	-8	4.12
Superior frontal gyrus	L	16	-20	36	48	3.43
Angular gyrus	L	13	-48	-68	36	3.51
[Nonloss ('hit') > Loss ('miss')_{MEDI}]						
Ventral striatum	R	25	20	4	-8	6.05
Thalamus	L	24	-16	4	-8	4.12
Posterior cingulate	L	22	-4	-44	8	4.33
Cerebellum	L	30	-4	-8	-32	4.91

Notes. Activations thresholded at $P < 0.01$, FDR. Extent threshold > 10 voxels.

(FDR) in controls relative to meditators (Figure 3). The inverse contrast $[\text{Meditators} > \text{Controls}]$ did not yield significant voxels at the corrected level. To further examine whether dorsal striatal responding during monetary reward processing was related to degree of mindfulness practice skills within the meditator group, we performed a linear regression to explore whether individual differences in mindfulness skills, as measured by the Kentucky Inventory of Mindfulness Skills (KIMS; Baer *et al.*, 2004) were related to neural measures of task impact on the caudate and posterior insula activity during the reward anticipation phase. Specifically, the neural measures were given by the estimated beta value at peak voxels from the left caudate derived from the interaction $[\text{Gain}_A > \text{Nongain}_A \text{ Controls}] > [\text{Gain}_A > \text{Nongain}_A \text{ Meditators}]$, and the left posterior insula beta coefficients was derived from $[\text{Gain}_A > \text{Nongain}_A \text{ Meditators}] > [\text{Gain}_A > \text{Nongain}_A \text{ Controls}]$. The analysis showed that left caudate correlated negatively with total KIMS score ($R = -0.40$, $P = 0.009$) (Figure 4A). We further estimated a linear regression to assess the relation between posterior insula and KIMS scores. This correlation was positive in meditators ($R = 0.54$, $P = 0.001$) (Figure 4B). Age was not a plausible confound of these relations, as it was uncorrelated with KIMS score ($R = -0.14$).

DISCUSSION

This study found that meditator and control participants showed no differences in MID task performance; the two groups had similar hit rates on reward and no-reward trials. However, as predicted, meditators showed lower neural activations in the dorsal striatum during reward and no-reward anticipation, and higher bilateral posterior insula activation during reward anticipation. Also, as predicted,

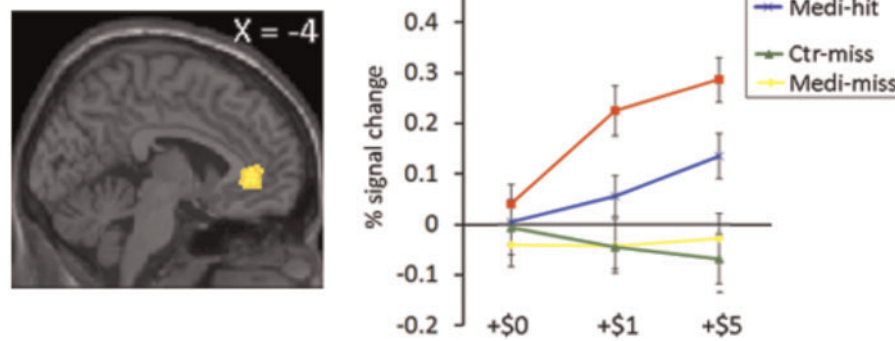


Fig. 2 Group differences in incentive processing during outcome phase. Direct comparison between controls and meditators showed elevated activity in VMPFC in controls. The strength of VMPFC activity during gain trials was significantly greater in controls compared with meditators. SEM is given in the plots. See Table 4 for full activation table during outcome phase.

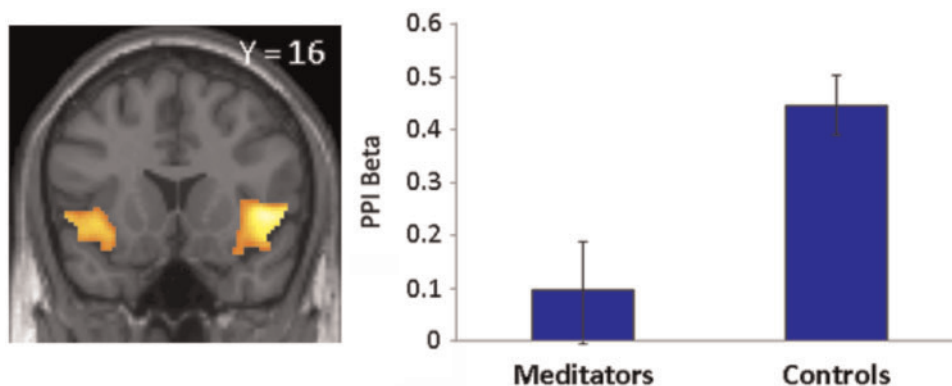


Fig. 3 Group-specific changes in effective connectivity. Controls exhibited an increased connectivity between the caudate seed and bilateral anterior insula. The average beta estimates from the right anterior insula are displayed. All error bars denote SEM.

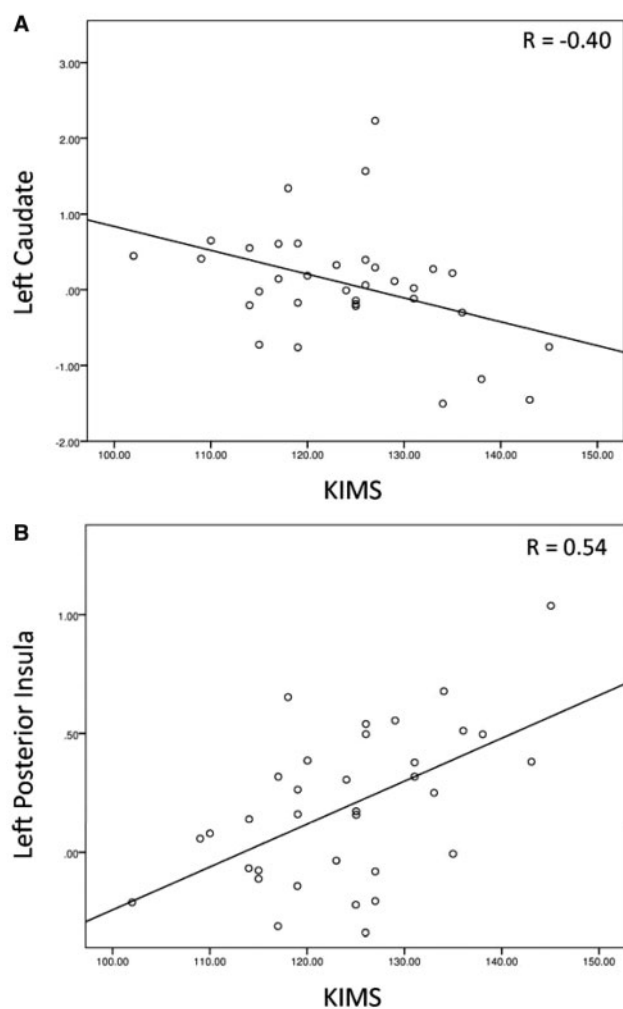


Fig. 4 Individual differences in trait mindfulness levels as measured by the KIMS in the meditator group ($n=34$). (A) Left caudate exhibit a negative correlation with KIMS and (B) left posterior insula exhibit a positive correlation with KIMS. The Pearson correlation coefficient (R) is given in the plot. Each data point represents a subject.

meditators showed reduced activations in the VMPFC during reward receipt relative to controls. Finally, we found support for the hypothesis that the meditation group showed altered incentive anticipation, specifically lower connectivity between the right caudate and bilateral anterior insula was found in meditators than in controls.

Our results demonstrate that the VMPFC computes value signals during reward receipt for both groups, which is in accordance with the theory that the VMPFC is part of a general valuation mechanism (Rangel et al., 2008). However, the results showed a significant difference between meditators and controls in the VMPFC, in that this region was significantly elevated in the control group. This finding is consistent with recent neuroimaging studies, demonstrating a modulation in the VMPFC by the degree of value assigned to external cues (McClure et al., 2004; de Araujo et al., 2005; Plassmann et al., 2008; Harvey et al., 2010). This supports the theory that the VMPFC computes relative value signals. Further, the VMPFC has recently been shown to modulate value signals in several expertise groups (Kirk et al., 2009, 2011a). Level of expertise may interact with task engagement to determine the relative computation of value enforced by the VMPFC.

Little is known about reward processing in meditators in the context of incentive processing, and this study affords a first glimpse at how

activation in this region may be affected by level of meditation experience. We also observed that in the meditator group, higher scores on a measure of mindfulness practice skills were related to diminished left (but not right) caudate activation during reward anticipation. This suggests that degree of reduced striatal responding during reward anticipation was conditional on meditation practice skills. In contrast to the diminished caudate activity in the meditators, elevated activity was found in an entirely separate network comprising primarily the mid and posterior insula. These areas are more typically associated with interoception, the representation of the body's internal state (Craig, 2002, 2009). A model proposed by Craig (2009) argues that the anterior insula processes social motivational and cognitive conditions, whereas the posterior part processes visceral interoceptive representations. This model is in line with recent findings involving mindfulness, whereby posterior insula is involved in focused attention to internal experiences (Holzel et al., 2008) and momentary self-reference (Farb et al., 2007). Our previous results (Kirk et al., 2011b) showed activation in the posterior insula, suggesting that expert meditators particularly during presentation of unfair offers in the context of the Ultimatum Game were better able than controls to maintain interoceptive awareness presumably by attending to internal bodily states. In this study (Kirk et al., 2011b), it was also found that the anterior insula activation was reduced when expert meditators were presented with unfair economic offers. By contrast, in normal healthy controls an unfair economic offer is associated with negative emotions processed in the anterior insula (Sanfey et al., 2003). This bifurcation of the posterior and anterior insula in our previous study (Kirk et al., 2011b) is consistent with the present findings. As such, it is likely in the present study that during high incentive processing, meditators were better able than controls to maintain interoceptive awareness. This interpretation is further supported by the finding that posterior insula was positively correlated with mindfulness practice skills in meditators.

In the connectivity analysis, we found an increased coupling between the caudate and anterior insula in controls during high-incentive gain trials. The anterior insula is consistently activated during high-incentive trials in the MID task (Knutson et al., 2000, 2001, 2003, Samanez-Larkin et al., 2007) and has been interpreted as increased arousal during anticipation of high-stakes outcomes. However, relative to controls, meditators in this study showed reduced connectivity between caudate and anterior insula. Although decreased negative arousal (anterior insula) may enhance well-being in meditators (Creswell et al., 2007), it may also engender bias in certain decision-making scenarios. However, we did not find any behavioral differences in performance between the two groups. Further research is required to establish the implications of decreased negative arousal on decision-making in the domain of mindfulness meditation.

Collectively these findings indicate that meditators are less susceptible to extrinsic, and specifically monetary, incentives. The results are consistent with previous research on mindfulness, which has indicated that this mode of processing is associated with diminished evaluative processing of motivationally salient stimuli (Brown et al., 2013) and a reduced engagement of extrinsic rewards in daily life (Brown and Ryan, 2003). Research has indicated that mindful attention promotes adaptive psychological functioning and behavior regulation (Baer, 2003; Brown et al., 2007; Hofmann et al., 2010). Yet, the diminished local activations observed during reward anticipation and receipt in this study resemble those observed among individuals suffering from depression (Gotlib et al., 2010) and other psychiatric conditions. An important distinction, however, is that performance on the MID task in subjects with depression seem to involve increased RT compared with healthy controls (Pizzagalli et al., 2009), which could suggest a deficit in global reward responding consistent with anhedonic

traits (Downar *et al.*, 2013). By contrast, we find that the meditation group and control group perform identical on the MID task in terms of performance in the MID including RT, suggesting that behavioral output is not impaired in the meditation group.

Limitations and future research

Meditation practice can take a variety of forms that differ both between and within practice traditions (Lutz *et al.*, 2007). While all the meditators in the present study came from a single practice tradition, information on the specific practice forms of each individual was not gathered—for example, whether their mindfulness-related meditation practice took a focused attention or open awareness form. Thus, the present results do not specifically indicate what form of meditation was responsible for the diminished brain activations observed. Future research should attend to differences in practice forms to better characterize the role of specific forms of meditation in altered reward processing.

Also, this study cannot determine that meditative practice was responsible for the group differences in incentive processing. We sought to control potential demand and other experimenter effects on the outcomes through experimenter blinding to participants' group membership. Additionally, the fact that scores on a measure of mindfulness practice skills were related to the diminished reward anticipation neural activations seen for the entire meditator group suggests that meditation practice was key to the group differences found. However, experimental research comparing the effects of mindfulness meditation training to well-matched active control training, such as relaxation (Kirk *et al.*, 2014) or listening comprehension (Allen *et al.*, 2012), will provide more conclusive causal evidence on the role of mindfulness training in altering neural responses to reward. Future research using longitudinal designs are in a better position to address the exact nature of emerging blood oxygenation level-dependent (BOLD) differences than the present study, where fluctuations in the BOLD signal cannot be compared with a natural baseline condition and thus disclose reasons for meditators' nonnormative neural responses. Another limitation of the study concerns the MID task itself; because monetary outcome is tied to performance (RT), it is impossible to determine whether the meditators' lower reward activations reflected comparative disengagement from monetary rewards, from performance feedback or both. Lutz *et al.* (2012) showed that striatal activity differentiates the two outcomes. Research is needed to disentangle them, as it potentially concerns the effect of mindfulness training on extrinsic *vs* intrinsic reward processing.

CONCLUSIONS

The present findings are to our knowledge the first to show that brain regions involved in reward processing—both anticipation and receipt—respond differently in mindfulness meditators than in nonmeditators. Follow-up analyses suggested that meditators' reduced engagement of reward anticipation was moderated by decreased anterior insula activity, previously associated with negative arousal in the context of the MID. Research on meditation and altered reward processing may in future studies be directed to better understanding the specific adaptive value of this form of mental training on reward-relevant behavior in daily life contexts.

MATERIALS AND METHODS

Participants

Seventy-eight subjects participated in the study, including 34 meditators (11 females) and 44 controls (24 females). The meditator group was selected primarily from a southwestern Zen center in the USA and were recruited based on the criterion of maintaining a regular

mindfulness-integrated meditation practice (minimum three sessions of 20 min per week). Practitioners' meditation experience ranged from 6 months to 24 years ($M=9.6$ years of practice; $s.d.=7.9$ years). In addition, all participants in the meditation group had completed at least one meditation retreat of min 3 days duration. Both groups maintained a normal secular lifestyle. We did not collect data on the specific form of meditation (e.g. open awareness or focused attention). The groups were matched on age, gender, socioeconomic status (education and income levels), depressive symptoms (Beck Depression Inventory; Beckham and Leber, 1985) and anxiety symptoms (Beck Anxiety Inventory; Beck and Steer, 1993) (Table S1); group differences on these variables were nonsignificant (P values >0.05). All subjects had normal or corrected-to-normal vision, and none had a history of neurological or psychiatric disorders or currently used psychoactive medications. All procedures were conducted in accordance with the institutional review board at Baylor College of Medicine.

Experimental procedures

We used a canonical version of the MID task as described by Knutson *et al.* (2001) and administered by experimenters naive to participants' group membership. During each trial, participants saw one of six trial types presented centrally on a screen ('Win \$5'; 'Win \$1'; 'Win \$0'; 'Lose \$5'; 'Lose \$1'; 'Lose \$0') for 2.5 s, fixated on a cross-hair for a jittered anticipatory period (2–2.5 s). Subsequently, a target appeared and subjects were instructed to press a button when a white star appeared on the screen for a variable length of time. A cross-hair followed the target offset (500 ms), and a feedback screen notified the participants whether they had won or lost money during that trial and displayed their cumulative total at that point. Finally, a jittered fixation period was presented (1–1.5 s). On \$1 and \$5 trials, participants could win or avoid losing money by pressing the button during target presentation. Task difficulty was adjusted dynamically by the participant's own RT. When participants hit the target, the length of the target presentation was decreased by 10 ms on the next trial, consequently increasing the task difficulty on the next trial. When participants missed the target, the length of the target presentation was increased by 10 ms on the next trial, thus decreasing the task difficulty on the next trial. Each of the six trial types was repeated 16 times, yielding 96 trials for each participant. The order of trial types was pseudo-randomized for each participant. Data were acquired in a single session.

The stimuli were presented at a screen resolution of 1024 × 768 pixels. Stimuli were presented and responses collected using NEMO (Human Neuroimaging Lab, Baylor College of Medicine). The stimuli were back-projected via an LCD projector onto a transparent screen positioned over the subjects' head and viewed through a tilted mirror fixed to the head coil. Before the experiment, participants were informed that at the end of the experiment they would receive the money they had won during the task.

fMRI data acquisition

The anatomical and functional imaging was performed using three Tesla Siemens Trio scanners located at Baylor College of Medicine. High-resolution T1 weighted scans were acquired using an MPRAGE sequence (Siemens). Functional imaging used an EPI sequence with a repetition time of 2000 ms, echo time = 25 ms, flip angle = 90°, 220 mm field of view, 64 × 64 matrix. Functional slices were oriented 30° superior-caudal to the plane through the anterior and posterior commissures to reduce signal dropout due to magnetic field inhomogeneities (Deichmann *et al.*, 2003). Each functional image was acquired in an interleaved way, comprising 37 of 4 mm axial slices for measurement of the BOLD effect (Ogawa *et al.*, 1990), yielding 3.4 mm × 3.4 mm × 4.0 mm voxels.

fMRI and data analysis

Image preprocessing and data analysis was performed using SPM8 (Wellcome Department of Imaging Neuroscience, London, UK). Motion correction to the first functional scan was performed using a six parameter rigid-body transformation (Friston *et al.*, 1996). The average of the motion-corrected images was co-registered to each individual's structural magnetic resonance imaging using a 12 parameter affine transformation. Slice timing artifacts were corrected, after which images were spatially normalized to the Montreal Neurological Institute (MNI) template provided in SPM8. Images were then spatially filtered with an 8 mm isotropic Gaussian kernel and for the analysis a high pass filter with a cutoff frequency at 1/128 Hz was applied.

Following preprocessing, a general linear model was applied to the fMRI time series where cue onset was modeled as single impulse response functions including the cue (2.5 s) and anticipatory fixation period (2–2.5 s) before target onset. The model included 12 regressors of interest. Six regressors modeled the anticipatory period for reward and no-reward trials (\$0, \$1 and \$5) separately and six regressors modeled the outcome period for reward and no-reward trials (\$0, \$1 and \$5) separately. Residual effects of head motion were corrected by including the six estimated motion parameters for each subject as regressors of no interest. The model was convolved with the canonical hemodynamic response function (Friston *et al.*, 1998). The mean images from the first-level analysis were entered into a second-level random effects analysis accounting for the between-subject variance. An ANOVA model using the beta estimates of the regressors of interest was used. Equal variance was not assumed, and thus SPM8's options for nonsphericity correction were applied (Glaser and Friston, 2004). T-contrasts were used to test for correlations of the fMRI BOLD signal and the parameters of interest. The resulting t maps were subsequently transformed to the unit normal z-distribution to create a statistical parametric map for each contrast. The statistical results given were based on a single-voxel t-statistic or cluster-level corrected corresponding to $P < 0.05$ corrected for multiple comparisons with an extent threshold of > 10 voxels (unless otherwise stated). The coordinates of all activations are reported in MNI space.

For the effective connectivity analysis implemented as PPI analysis (Friston *et al.*, 1997), we assessed changes in effective connectivity between the seed region in the caudate and other brain regions in which activity correlated with these voxels. The PPI engaged a regressor representing the deconvolved time series of neural activity within a 5 mm sphere centered on coordinates in the right caudate (8 4 0), which constituted the physiological variable, a second regressor representing the psychological variable [specifically gain anticipation (\$5) $>$ nongain anticipation (\$0)], and a third regressor representing the cross product of the previous two (the PPI term). The model also included motion parameters as regressors of no interest. This PPI enabled us to identify areas in which the correlation in BOLD activity with the caudate seed region increased during gain anticipation trials relative to nongain trials. The PPI was carried out for each subject and entered into random-effects analysis separately for each participant group.

SUPPLEMENTARY DATA

Supplementary data are available at SCAN online.

Conflict of Interest

None declared.

REFERENCES

- Allen, M., Dietz, M., Blair, K.S., et al. (2012). Cognitive-affective neural plasticity following active-controlled mindfulness intervention. *J Neuroscience*, 32(44), 15601–10.
- Baer, R.A. (2003). Mindfulness training as a clinical intervention: a conceptual and empirical review. *Clinical Psychology: Science and Practice*, 10, 125–43.
- Baer, R.A., Smith, G.T., Allen, K.B. (2004). Assessment of mindfulness by self-report: the Kentucky Inventory of Mindfulness Skills. *Assessment*, 11(3), 191–206.
- Beck, A.T., Steer, R.A. (1993). *Beck Anxiety Inventory Manual*. San Antonio: Harcourt Brace.
- Beckham, E.E., Leber, W., editors. (1985). *Handbook of Depression: Treatment, Assessment, and Research*. (Appendix 3). Homewood, IL: Dorsey.
- Brown, K.W., Creswell, J.D., Ryan, R.M., editors. (2015). *Handbook of Mindfulness: Theory, Research, and Practice*. New York: Guilford.
- Brown, K.W., Goodman, R.J., Inzlicht, M. (2013). Dispositional mindfulness and the attenuation of neural responses to emotional stimuli. *Social Cognitive and Affective Neuroscience*, 8(1), 93–9.
- Brown, K.W., Ryan, R.M. (2003). The benefits of being present: mindfulness and its role in psychological well-being. *Journal of Personality and Social Psychology*, 84(4), 822–48.
- Brown, K.W., Ryan, R.M., Creswell, J.D. (2007). Mindfulness: theoretical foundations and evidence for its salutary effects. *Psychological Inquiry*, 18(4), 211–37.
- Craig, A.D. (2002). How do you feel? Interoception: the sense of the physiological condition of the body. *Nature Reviews. Neuroscience*, 3, 655–66.
- Craig, A.D. (2009). How do you feel - now? The anterior insula and human awareness. *Nature Reviews. Neuroscience*, 10, 59–70.
- Creswell, J.D., Way, B.M., Eisenberger, N.I., Lieberman, M.D. (2007). Neural correlates of dispositional mindfulness during affect labeling. *Psychosomatic Medicine*, 69(6), 560–5.
- De Araujo, I.E., Rolls, E.T., Velasco, M.I., Margot, C., Cayeux, I. (2005). Cognitive modulation of olfactory processing. *Neuron*, 46(4), 671–9.
- Deci, E.L., Koestner, R., Ryan, R.M. (1999). A meta-analytic review of experiments examining the effects of extrinsic rewards on intrinsic motivation. *Psychological Bulletin*, 125(6), 627–68.
- Deci, E.L., Ryan, R.M., Schultz, P.P., Niemiec, C.P. (2015). Being aware and functioning fully: mindfulness and interest-taking within Self-Determination Theory. In: Brown, K.W., Creswell, J.D., Ryan, R.M., editors. *Handbook of Mindfulness: Theory, Research, and Practice*. New York: Guilford.
- Deichmann, R., Gottfried, J.A., Hutton, C., Turner, R. (2003). Optimized EPI for fMRI studies of the orbitofrontal cortex. *Neuroimage*, 19(2), 430–41.
- Downar, J., Geraci, J., Salomons, T.V., et al. (2013). Anhedonia and reward-circuit connectivity distinguish nonresponders from responders to dorsomedial prefrontal repetitive transcranial magnetic stimulation in major depression. *Biological Psychiatry*, 76, 176–85.
- Farb, N.A., Segal, Z.V., Mayberg, H., et al. (2007). Attending to the present: mindfulness meditation reveals distinct neural modes of self-reference. *Social Cognitive and Affective Neuroscience*, 2(4), 313–22.
- Friston, K.J., Buechel, C., Fink, G.R., Morris, J., Rolls, E., Dolan, R.J. (1997). Psychophysiological and modulatory interactions in neuroimaging. *Neuroimage*, 6, 218–29.
- Friston, K.J., Williams, R., Howard, R.S., Frackowiak, R.S.J., Turner, R. (1996). Movement-related effects in fMRI time-series. *Magnetic Resonance in Medicine*, 35, 346–55.
- Friston, K.J., Fletcher, P., Joseph, O., Holmes, A., Rugg, M.D., Turner, R. (1998). Event-related fMRI: characterizing differential responses. *Neuroimage*, 7, 30–40.
- Glaser, D., Friston, K.J. (2004). Variance components. In: Frackowiak, R.S.J., Friston, K.J., Frith, C.D., Dolan, R.J., Price, C.J., Zeki, S., editors. *Human Brain Function*. Amsterdam, NL: Elsevier, pp. 781–93.
- Gotlib, I.H., Hamilton, J.P., Cooney, R.E., Singh, M.K., Henry, M.L., Joormann, J. (2010). Neural processing of reward and loss in girls at risk for major depression. *Archives of General Psychiatry*, 67(4), 380–7.
- Hagger, M.S., Chatzisarantis, N.L.D. (2011). Causality orientations moderate the undermining effect of rewards on intrinsic motivation. *Journal of Experimental Social Psychology*, 47, 485–9.
- Hare, T.A., Camerer, C.F., Rangel, A. (2009). Self-control in decision-making involves modulation of the VMPFC valuation system. *Science*, 324, 646–8.
- Harvey, A.H., Kirk, U., Denfield, G.H., Montague, P.R. (2010). Monetary favors and their influence on neural responses and revealed preference. *The Journal of Neuroscience*, 30, 9597–9602.
- Hofmann, S.G., Sawyer, A.T., Witt, A.A., Oh, D. (2010). The effect of mindfulness-based therapy on anxiety and depression: a meta-analytic review. *Journal of Consulting and Clinical Psychology*, 78, 169–83.
- Holzel, B.K., Ott, U., Gard, T., et al. (2008). Investigation of mindfulness meditation practitioners with voxel-based morphometry. *Social Cognitive and Affective Neuroscience*, 3, 55–61.
- Kirk, U., Skov, M., Nygaard, N., Christensen, M.S. (2009). Brain correlates of aesthetic expertise: a parametric fMRI study. *Brain and Cognition*, 69, 306–15.

- Kirk, U., Harvey, A.H., Montague, P.R. (2011a). Domain expertise insulates against judgment bias by monetary favors through a modulation of ventromedial prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, 108(25), 10332–6.
- Kirk, U., Downar, J., Montague, P.R. (2011b). Interoception drives increased rational decision-making in meditators playing the ultimatum game. *Frontiers in Neuroscience*, 5, 49.
- Kirk, U., Gu, X., Harvey, A.H., Fonagy, P., Montague, P.R. (2014). Mindfulness training modulates value signals in ventromedial prefrontal cortex through input from insular cortex. *Neuroimage*, 100C, 254–62.
- Knutson, B., Adams, C.M., Fong, G.W., Hommer, D. (2001). Anticipation of increasing monetary reward selectively recruits nucleus accumbens. *The Journal of Neuroscience*, 21, RC159.
- Knutson, B., Fong, G.W., Bennett, S.M., Adams, C.M., Hommer, D. (2003). A region of mesial prefrontal cortex tracks monetarily rewarding outcomes: characterization with rapid event-related fMRI. *Neuroimage*, 18, 263–72.
- Knutson, B., Westdorp, A., Kaiser, E., Hommer, D. (2000). fMRI visualization of brain activity during a monetary incentive delay task. *Neuroimage*, 12, 20–7.
- Kringelbach, M.L., O'Doherty, J., Rolls, E.T., Andrews, C. (2003). Activation of the human orbitofrontal cortex to a liquid food stimulus is correlated with its subjective pleasantness. *Cerebral Cortex*, 13, 1064–71.
- Lebreton, M., Jorge, S., Michel, V., Thirion, B., Pessiglione, M. (2009). An automatic valuation system in the human brain: evidence from functional neuroimaging. *Neuron*, 63, 431–9.
- Levesque, C., Brown, K.W. (2007). Mindfulness as a moderator of the effect of implicit motivational self-concept on day-to-day behavioral motivation. *Motivation and Emotion*, 31(4), 284–99.
- Lutz, A., Dunne, J.D., Davidson, R.J. (2007). Meditation and the neuroscience of consciousness: an introduction. In: Zelazo, P.D., Moscovitch, M., Thompson, E., editors. *The Cambridge Handbook of Consciousness*. New York: Cambridge University Press, pp. 499–551.
- Lutz, K., Pedroni, A., Nadig, K., Luechinger, R., Jancke, L. (2012). The rewarding value of good motor performance in the context of monetary incentives. *Neuropsychologia*, 50, 1739–47.
- Ma, Q., Jin, J., Meng, L., Shen, Q. (2014). The dark side of monetary incentive: how does extrinsic reward crowd out intrinsic motivation. *Neuroreport*, 25, 194–8.
- McClure, S.M., Li, J., Tomlin, D., et al. (2004). Neural correlates of behavioral preference for culturally familiar drinks. *Neuron*, 44, 379–87.
- Murayama, K., Matsumoto, M., Izumab, K., Matsumoto, K. (2010). Neural basis of the undermining effect of monetary reward on intrinsic motivation. *Proceedings of the National Academy of Sciences of the United States of America*, 107(49), 20911–16.
- Ogawa, S., Lee, T.M., Kay, A.R., Tank, D.W. (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *Proceedings of the National Academy of Sciences of the United States of America*, 87(24), 9868–72.
- Pizzagalli, D.A., Holmes, A.J., Dillon, D.G., et al. (2009). Reduced caudate and nucleus accumbens response to rewards in unmedicated individuals with major depressive disorder. *The American Journal of Psychiatry*, 166(6), 702–10.
- Plassmann, H., O'Doherty, J., Shiv, B., Rangel, A. (2008). Marketing actions can modulate Neural representations of experienced pleasantness. *Proceedings of the National Academy of Sciences of the United States of America*, 105, 1050–4.
- Rangel, A., Camerer, C., Montague, P.R. (2008). A framework for studying the neurobiology Of value-based decision making. *Nature Reviews Neuroscience*, 7, 545–56.
- Sahdra, B.K., Shaver, P.R., Brown, K.W. (2010). A scale to measure nonattachment: a Buddhist complement to western research on attachment and adaptive functioning. *Journal of Personality Assessment*, 92(2), 116–27.
- Samanez-Larkin, G.R., Gibbs, S.E., Khanna, K., Nielsen, L., Carstensen, L.L., Knutson, B. (2007). Anticipation of monetary gain but not loss in healthy older adults. *Nature Neuroscience*, 10(6), 787–91.
- Sanfey, A.G., Rilling, J.K., Aronson, J.A., Nystrom, L.E., Cohen, J.D. (2003). The neural basis of economic decision-making in the ultimatum game. *Science*, 300, 1755–8.