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The neural basis of academic achievement motivation

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ABSTRACT

We have used functional magnetic resonance imaging to study the neural correlates of motivation, concentrating on the motivation to learn and gain monetary rewards. We compared the activation in the brain obtained during reported high states of motivation for learning, with the ones observed when the motivation was based on monetary reward. Our results show that motivation to learn correlates with bilateral activity in the putamen, and that the higher the reported motivation, as derived from a questionnaire that each subject filled prior to scanning, the greater the change in the BOLD signals within the putamen. Monetary motivation also activated the putamen bilaterally, though the intensity of activity was not related to the monetary reward. We conclude that the putamen is critical for motivation in different domains and the extent of activity of the putamen may be pivotal to the motivation that drives academic achievement and thus academic successes.

Introduction

Motivation is an abstract term to describe a characteristic possessed by most humans to varying degrees and at different times. It acts as a stimulus for action towards a desired goal, and may be limited in scope, as in the motivation for high monetary rewards, or more general, as is found with those who are "driven" to achieve in a multiplicity of fields. It has certain definite corollaries, as well as more general ones. The former can be summarized as the initiation of action, whether motor or otherwise, to achieve the desired goal; an expectation related to the goal; and a reward, which is the goal. In addition, motivation must engage the working memory system to relate what has been achieved to the ultimate goal. This is especially so during learning, which serves to maintain "on tap" a limited amount of currently relevant information so that it is available for immediate use (Baddeley, 1992; Eliassen et al., 2001). Hence one might expect that a study of motivation will result in widespread brain activity but especially in the brain systems that have been shown to be related to reward and expectation, and possibly in the motor system as well.

Motivation is one of the most important psychological concepts in education. It can be classified into intrinsic and extrinsic motivations; intrinsic motivation refers to doing something because it is inherently interesting or enjoyable, while extrinsic motivation refers to doing something because it leads to a separable outcome (Deci et al., 1991). It has been shown that intrinsic academic motivation (academic achievement motivation) results in better educational outcomes, such as higher academic performances, better quality of learning, increased persistence and effort in studies, and better psychological adjustment of learners, in comparison to extrinsic motivation (Deci et al., 1996; Ryan and Deci, 2000). In addition, it has been reported that academic achievement motivation is heightened by academic reward which induce a sense of competence and achievement (Maehr, 1984). In this study, we accordingly focused on the neural substrates of academic achievement motivation linked to academic reward. Linear relationships between strength of subjective feelings and cortical activity measured by the BOLD signal or cerebral blood flow have been observed before (Breiter et al., 2001; Callan and Schweighofer, 2008;

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Kawabata and Zeki, 2004; O'Doherty et al., 2001). Therefore, in order to clarify the neural substrates of academic achievement motivation, we performed the correlation analysis between the score of reported motivation as derived from an academic achievement motivation scale (Waugh, 2002) and the cortical activity associated with the academic reward.

Many studies have shown the neural substrates of extrinsic motivation induced by monetary reward (Breiter et al., 2001; Delgado et al., 2000, 2003; Elliott et al., 2004; Kirsch et al., 2003; Knutson et al., 2000). In addition, the neural substrates involved in the relationship between extrinsic motivation related to monetary reward and learning (Callan and Schweighofer, 2008) and long-term memory formation (Wittmann et al., 2005) have been shown. Therefore, we compared the neural substrates of motivation linked to academic reward to those linked to monetary reward. In this study, we tried to chart the neural activity produced by motivational states to learn, by imaging activity in the brain using a 3.0 T functional magnetic resonance (fMRI) in 14 college students, and compared the activity produced to that produced by motivation for monetary reward. Such restriction has advantages in that it makes the study more manageable, as well as charting the brain's motivational system, against which we hope in the future to study other motivational states.

As expected, we found that activity in part of the brain traditionally associated with reward, the putamen, correlated positively with the (baseline) academic achievement motivation score and performance of working memory task. Although motivation related to monetary reward also produced activity in the putamen, no correlation was observed with the degree of monetary reward, leading us to conclude that there are different motivational systems in operation, linked to different kinds of reward.

Materials and methods

Subjects

Fourteen college students [22.4 ± 1.2 years of age (mean ± SD), 7 females and 7 males] participated in the present study. The subjects were recruited from Osaka City University. They had normal or corrected-to-normal visual acuity, no history of medical illness, and were right-handed according to the Edinburgh handedness inventory (Oldfield, 1971). The protocol was approved by the Ethics Committee of the National Institute for Physiological Sciences, and all subjects gave written informed consent for participation in the study.

Motivation scale

Waugh's academic achievement motivation scale consists of 24 motivation-related questions (Waugh, 2002). We recently developed a Japanese version of this scale (Yoshida et al., in press). The questions are defined to reveal the students' desire to learn, their personal incentives, as well as standards and goals. Each subject could score anywhere between 0 and 72, the former reflecting low rates of motivation and the latter high ones, and giving us 14 points (from the 14 subjects) overall, through which we could relate the change in the BOLD signal to the scores for our population of subjects. All subjects recorded this scale just before the fMRI experiments.

Experimental paradigm

Before scanning, subjects practiced a series of working memory tasks for 10 min, since working memory speeds up learning and hence constitutes a means of achieving the desired purpose. The working memory task that we used was a digit *n*-back task (Braver et al., 1997), in which the working memory load could be varied incrementally. In the version that we used, there were three incremental levels (Fig. 1). In 0-back trials, subjects were asked to press a right button with their right middle finger if the target digit "2" was presented at the centre of a personal computer screen (Fig. 1a). If any other digits ("1", "3", or "4") appeared, subjects were to press the left button with their right index finger. In the 3-back trials, subjects had to remember for 3 s the last 3 digits while being continuously presented with a new order of digits. They had to judge whether the target digit presented at the centre of the screen was the same as the one that had appeared 3 presentations

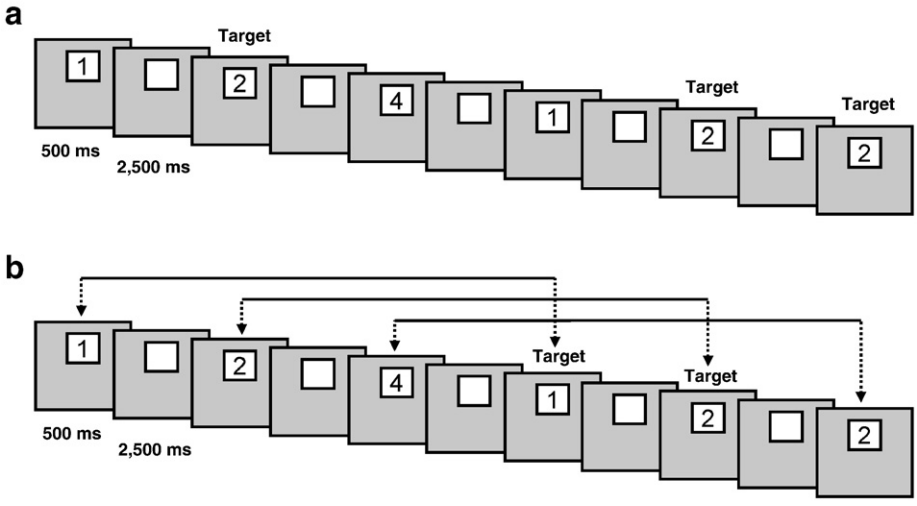

Fig. 1. Time course of stimulus display sequences of the 0-back (a) and 3-back (b) trials. In the 0-back trials, subjects were asked to press a right button with their right middle finger if the target digit "2" was presented at the centre of a personal computer screen. If any other digits ("1", "3", or "4") appeared, subjects were to press the left button with their right index finger. In the 3-back trials, subjects had to remember for 3 s the last 3 digits while being continuously presented with a new order of digits. They had to judge whether the target digit presented at the centre of the screen was the same as the one that had appeared 3 presentations before. If it was, they were to press the right button with their right middle finger and the left button if it was different. In contrast, in the 0-back trials there was no need to remember since it consisted of a single digit, and thus constituted a control task without working memory processes.

before (Fig. 1b). If it was, they were to press the right button with their right middle finger and the left button if it was different. In contrast, in the 0-back trials there was no need to remember since it consisted of a single digit, and thus constituted a control task without working memory processes.

We used 2 types of rewards, academic and monetary ones. The academic reward [AR(+)] was set to induce a sense of competence and achievement. In it, since academic achievement motivation is heightened by a sense of competence and achievement (Maehr, 1984), subjects were instructed, before the fMRI experiments, that the test was an intelligence test (Larisch et al., 1999). When they answered correctly, some of the white lattices in a square (30×30 lattices) were randomly changed to blue (Fig. 2a). When they answered incorrectly, the number of blue lattices did not change. If they answered 9 successive trials correctly, all lattices changed to blue. The lattices then reverted to white for the next presentation. If subjects answered correctly again, blue lattices were increased in number. For the control condition in this task [AR(−)], when subjects answered correctly in the first trial, some of the white lattices were randomly made blue (Fig. 2b). However, if they gave a correct answer in the next trial, the blue lattices were not increased in number. Thus, although the white-to-blue ratio remained the same, the location of each lattice was randomly altered. If subjects could not answer correctly, the location of each lattice was left unchanged.

In the monetary reward condition [MR(+)], subjects were instructed that "200 points" implied 200 yen. In this condition, they obtained "200 red colored points" for each correct response (Fig. 2c). The points with red color were added when subjects answered correctly. When they responded incorrectly, they did not obtain the points, and the total number of points with blue color was presented. Subjects were not informed about the precise amount of money associated with points, in order to avoid mental calculation of gains. They could earn up to 8000 yen (approximately 70 U.S. dollars) if they achieved correct scores of 75% or more. For the control condition in this task [MR(−)], only the point (00000) with red color was presented (Fig. 2d) and subjects could not obtain points even if they answered correctly. If, however, their response was incorrect, they could not obtain 200 red colored points, and the point (00000) turned blue.

The fMRI experiments consisted of 2 reward (academic and monetary) and 2 non-reward conditions, i.e. the AR(+) and AR(−), and the MR(+) and MR(−) conditions. Before the presentation of each stimulus, information appeared for 4 s on the screen, to inform subjects what the task will be, i.e., whether it was an intelligence test or whether it was a monetary test and whether it would be of a "0-back task" or "3-back task" one (Fig. 2). Each condition consisted of 20 trials which lasted for 500 ms followed by a blank which lasted 2500 ms, a total of 3000 ms. The probability of a digit appearing in each trial was 50%. Thus, the total for each condition was 60 s. Each condition was repeated 3 times in counter-balanced order. The time interval between conditions was 20 s. After the fMRI experiments, subjects were asked to rate their subjective experience of motivation on a

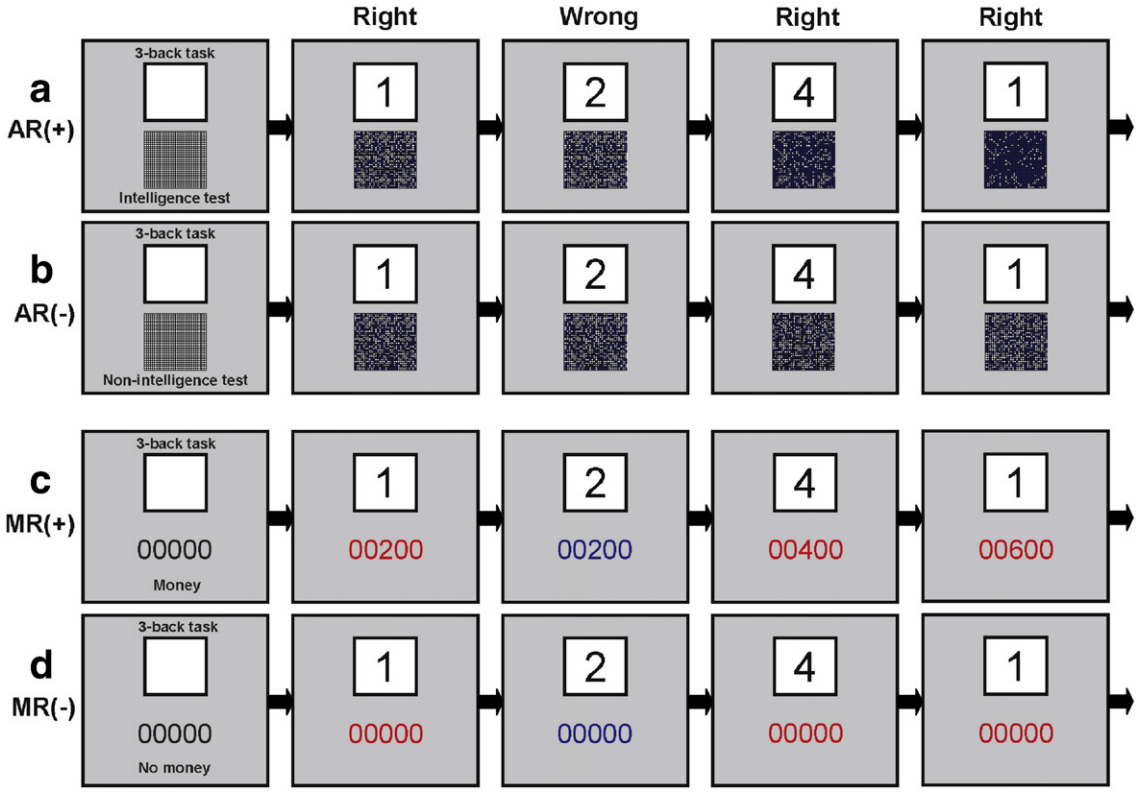

Fig. 2. Schematic representation of academic reward condition [AR(+)] (a), control condition for academic reward [AR(−)] (b), monetary reward condition [MR(+)] (c), and control condition for monetary reward [MR(−)] (d). For the [AR(+)], when they answered correctly, some of the white lattices in a square were randomly changed to blue. When they answered incorrectly, the number of blue lattices did not change. If they answered 9 successive trials correctly, all lattices changed to blue. For the [AR(−)], when subjects answered correctly in the first trial, some of the white lattices were randomly made blue. However, if they gave a correct answer in the next trial, the blue lattices were not increased in number. For the [MR(+)], subjects obtained "200 red colored points" for each correct response. They were instructed that "200 points" implied 200 yen. The points with red color were added when subjects answered correctly. When they responded incorrectly, they did not obtain the points, and the total number of points with blue color was presented. For the [MR(−)], only the point (00000) with red color was presented and subjects could not obtain points even if they answered correctly. If, however, their response was incorrect, they could not obtain 200 red colored points, and the point (00000) turned blue.

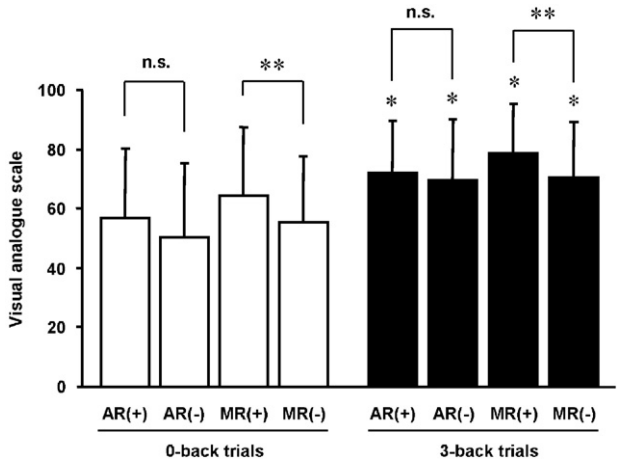

Fig. 3. Reported subjective experience of motivation to succeed in 0- and 3-back trials in academic reward condition [AR(+)], control condition for academic reward [AR(−)], monetary reward condition [MR(+)], and control condition for monetary reward [MR(−)]. Just after the fMRI experiments, subjects were asked to rate their subjective experience of motivation on a visual analogue scale for each task condition. Open columns, 0-back trials; closed columns, 3-back trials. *$P<0.05$, significantly different from the 0-back trials in each condition (two-tailed paired t-test). **$P<0.01$, significant difference between MR(+) and MR(−); n.s., no significant difference between AR(+) and AR(−). Values are the mean and SD.

visual analogue scale from 0 (complete lack of motivation) to 100 (maximum motivation) for each task condition. Such subjective reports have been used successfully to assess subjective states against BOLD signals (see for example the use of the Passionate Love Scale (PLS)) (Bartels and Zeki, 2000).

Functional imaging and data analyses

All images were obtained using a 3.0 T MR scanner (Allegra; Siemens, Erlangen, Germany). For functional imaging, a series of 900 volumes was acquired using T2-weighted, gradient-echo, echo planar imaging (EPI) sequences. Each volume consisted of 32 transaxial slices, each having a thickness of 3.5 mm with a 0.5 mm gap between slices to include the entire cerebrum and cerebellum [repetition time (TR), 2000 ms; echo time, 30 ms; flip angle (FA), 75°; field of view (FOV), 19.2 cm; in-plane matrix size, 64×64 pixels]. Oblique scanning was used to exclude the eyeballs from the images. Tight but comfortable foam padding was placed around the subjects' head to minimize head movement. For anatomical reference, T1-weighted magnetisation-prepared rapid-acquisition gradient-echo (MP-RAGE) images, scanned at the same location as those used for EPI, were obtained for each subject [TR, 1460 ms; TE, 4.88 ms; FA, 8°; FOV, 19.2 cm (one slab); distance factor, 50%; number of slices per slab, 32; voxel dimension, 0.9×0.8×4.0 mm]. In addition, high-resolution structural whole-brain MRI images were obtained using a MP-RAGE sequence [TR, 2500 ms; TE, 4.38 ms; FA, 8°; FOV, 23.0 cm (one slab); voxel dimensions, 0.9×0.9×1.0 mm].

The first 12 volumes acquired in each MRI session were discarded due to unsteady magnetisation, and the remaining 288 volumes per session were used for analyses. Data were analysed using Statistical Parametric Mapping 2 (Wellcome Department of Cognitive Neurology, London, UK) (Friston et al., 1995) implemented in MATLAB 6.5.1 (Mathworks, Sherbon, MA). Following realignment for motion correction of all EPI images, the same-slice-positioned anatomical images and high-resolution whole-brain T1-weighted images were co-registered with the first volume of EPI images. Then, the whole-head MP-RAGE images were normalized to the Montreal Neurological Institute (MNI) T1 image template (Evans et al., 1994). These parameters were then applied to all EPI images which were spatially smoothed in 3 dimensions using a 8 mm full-width half-maximum Gaussian kernel.

Statistical analyses were performed at 2 levels. First, individual task-related activation was evaluated. The percent signal change was proportionally scaled by setting the whole-brain mean value to 100 arbitrary units in order to normalize the global signal change. Expected signal changes caused by the tasks were modeled with a box-car function convolved with a hemodynamic response function and high-pass filtering (cut off frequency at 128 s). An autoregressive model was used for whitening the residuals so as to meet the assumptions for application of a general linear model (GLM). Then, the effect of each condition was evaluated with GLM. The weighted sum of the parameters estimated in the individual analyses consisted of "contrast" images. Next, the contrast images corresponding to each condition in each subject were used for group analyses with a random-effects model to obtain population inferences (Friston et al., 1999). The resulting set of voxel values for each comparison constituted a statistical parametric map of t statistics (SPM{t}). The SPM{t} was transformed to the unit of normal distribution (SPM{Z}). The threshold for the SPM{Z} of individual analyses was set at $Z>3.09$ for each voxel and P

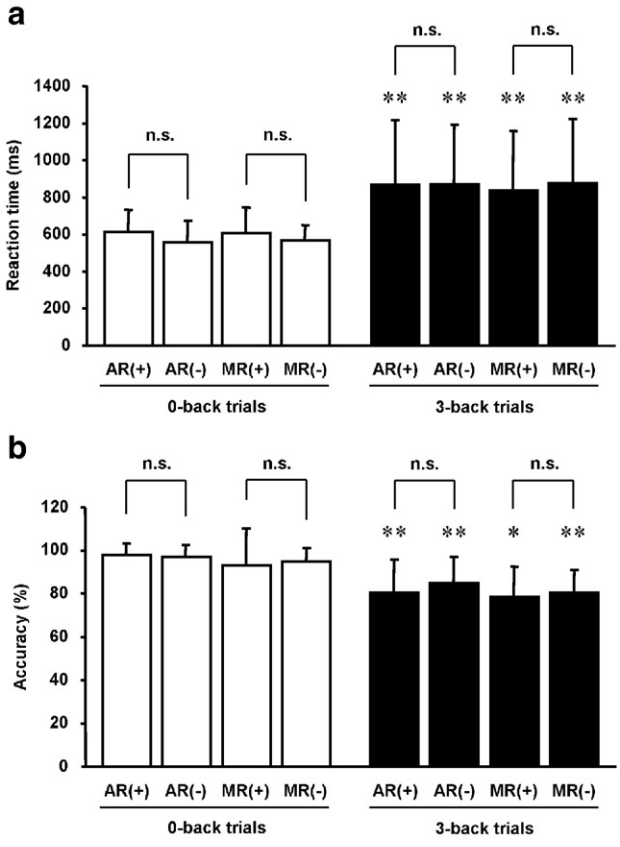

Fig. 4. Reaction time (a) and accuracy (b) in 0- and 3-back trials in academic reward condition [AR(+)], control condition for academic reward [AR(−)], monetary reward condition [MR(+)], and control condition for monetary reward [MR(−)]. Open columns, 0-back trials; closed columns, 3-back trials. *$P<0.05$, **$P<0.01$, significantly different from the 0-back trials in each condition (two-tailed paired t-test). n.s., no significant difference between reward condition and control condition for reward. Values are the mean and SD.

value less than 0.05 with a correction for multiple comparisons at the cluster level for the entire brain (Friston et al., 1996). The threshold for the SPM{*Z*} of group analyses was also set at $Z>3.09$, and the threshold in terms of number of voxels was set at more than 10. Comparison of 3-back trials to 0-back trials (3-back trials *minus* 0-back trials) was performed in order to obtain the activation pattern of working memory processing (Koppelstaetter et al., 2008; Pochon et al., 2002). Anatomic localization of significant voxels within clusters was done using the Talairach Demon software (Lancaster et al., 2000) with the nearest gray matter option enabled.

Behavioral performance was assessed as time to respond (reaction time) and percentage of correct responses (accuracy). The effects of monetary or academic reward on reaction time and accuracy in the 0- and 3-back trials were analysed using repeated-measured analysis of variance (ANOVA). All analyses were performed with SPSS 11.0 software package (SPSS Inc, Chicago, IL).

Results

Subjective motivation

Visual analogue scale values for the reported subjective experience of motivation to succeed in each task condition for all subjects are shown in Fig. 3. Three-way (2×2×2) repeated-measures ANOVA of visual analogue scale scores revealed significant main effects of task [$F_{(1,13)}=6.13$, $P=0.028$], reward [$F_{(1,13)}=10.06$, $P=0.007$], and type of reward (academic or monetary) [$F_{(1,13)}=8.55$, $P=0.012$]. However, no other significant interaction effects were found. The visual analogue scale scores for 3-back trials were significantly higher than those for 0-back trials in all of the conditions, suggesting higher levels of motivation. As noted in previous studies (Goldberg et al., 1998; Jaeggi et al., 2003), levels of motivation during task trials may be affected by difficulty or intensity of memory load. Although visual analogue scale values of 0- and 3-back trials in the monetary reward condition [MR(+)] were significantly higher than those in the control condition for monetary reward [MR(−)], visual analogue scale scores in the academic reward condition [AR(+)] were not significantly different from those in the control condition [AR(−)], in either the 0- or 3-back trials.

Behavioral results

The results for task performance are summarized in Fig. 4. Although 3-way (2×2×2) repeated-measures ANOVA revealed significant main effects of task on reaction time [$F_{(1,13)}=21.04$, $P<0.001$] and accuracy [$F_{(1,13)}=29.69$, $P<0.001$], it revealed no significant main effects of reward on reaction time [$F_{(1,13)}=0.27$, $P=0.612$] or accuracy [$F_{(1,13)}=1.37$, $P=0.264$], type of reward in reaction time [$F_{(1,13)}=0.05$, $P=0.831$] or accuracy [$F_{(1,13)}=3.69$, $P=0.077$], or interactions among them in reaction time or accuracy. The reaction times in 3-back trials were significantly longer than those of 0-back trials in all conditions

Table 1
Activated brain regions associated with working memory processing (3-back trials *minus* 0-back trials) in the academic reward condition, control condition for academic reward, monetary reward condition, and control condition for monetary reward

Location	Side	BA	AR(+)				AR(−)				MR(+)				MR(−)			
			Coordinates (mm)			*Z* value	Coordinates (mm)			*Z* value	Coordinates (mm)			*Z* value	Coordinates (mm)			*Z* value
Middle frontal gyrus	R	10	34	50	−3	3.25	32	54	1	4.33	34	57	6	4.68	36	59	10	4.21
	L	10	−36	54	8	4.31	−36	56	3	4.81	−34	58	6	4.77	−32	51	10	3.30
Middle frontal gyrus	R	46	46	38	20	3.78	46	40	20	5.20	44	42	27	3.89	44	40	20	4.36
	L	46	−46	30	13	3.49	−53	25	25	3.81	−50	40	15	5.08	−50	36	13	4.69
Middle frontal gyrus	L	11									−22	38	−15	3.23				
Middle frontal gyrus	R	9	40	21	32	3.19	51	17	30	4.42	34	41	33	3.43	48	21	30	3.33
Middle frontal gyrus	L	8	−53	12	38	3.47	−51	8	40	4.02	−48	9	35	4.56	−52	8	40	4.00
Middle frontal gyrus	R	6	32	6	51	4.15	32	7	53	5.02	30	6	44	5.66	32	8	53	5.55
	L	6	−36	6	49	3.83	−30	3	51	3.89	−28	12	53	5.13	−32	3	51	4.48
Superior frontal gyrus	R	10									26	58	−3	3.68				
	L	10									−38	51	16	4.66	−36	48	23	3.88
Superior frontal gyrus	R	6	24	14	49	4.22	16	15	60	3.52	20	11	57	4.84	24	12	51	5.19
	L	6	−4	11	68	3.45	−4	15	58	4.53	−6	9	66	4.83	−12	15	60	3.89
Inferior frontal gyrus	R	44	50	12	14	3.83	51	14	18	4.07	53	14	12	3.91	51	14	18	3.69
	L	44									−57	6	18	3.69	−51	5	18	3.71
Inferior frontal gyrus	L	9	−50	11	27	4.04	−46	13	25	4.64	−50	11	31	4.50	−46	15	25	4.81
Cingulate gyrus	R	32	10	21	41	3.64	8	23	38	4.30	10	25	37	4.85	8	20	41	4.38
	R	23									2	−32	27	3.66				
Insula	R		36	20	3	3.81	34	19	1	4.23	36	21	1	4.55	32	23	1	4.39
	L		−40	14	7	4.12	−36	18	14	3.96	−34	16	12	4.13	−38	14	9	4.35
Thalamus	R		16	−22	18	3.47	8	−5	11	4.61	6	−15	12	4.92	16	−21	16	4.32
	L		−10	−17	16	3.60	−8	−17	12	4.42					−12	−9	15	4.76
Superior parietal lobule	R	7									28	−64	49	5.65	26	−65	51	4.63
	L	7					−22	−70	44	4.78	−30	−49	63	4.99	−22	−68	44	4.66
Precuneus	R	7					6	−62	47	5.53	12	−76	42	5.15	10	−64	49	5.18
	L	7	−12	−70	42	4.74	−16	−72	42	4.95	−18	−72	44	4.96	−24	−66	38	4.89
Inferior parietal lobule	R	40	38	−47	41	4.57	38	−50	47	5.51	40	−44	46	4.83	38	−48	43	5.31
	L	40	−44	−31	42	4.81	−46	−35	44	5.47	−40	−42	45	5.48	−44	−33	42	6.29
Inferior parietal lobule	R	39									34	−60	40	5.90				
Middle temporal gyrus	R	20	55	−43	−13	3.48	61	−45	−11	3.60	53	−36	−12	4.13	55	−41	−13	3.28
Cerebellum	R		28	−64	−27	4.66	38	−59	−24	3.99	22	−59	−21	5.54	−28	−61	−26	4.59
	L		−30	−60	−34	3.38	−10	−79	−20	5.28	−32	−56	−26	4.65	−36	−56	−31	4.11

AR(+), academic reward condition; AR(−), control condition for academic reward; MR(+), monetary reward condition; MR(−), control condition for monetary reward; BA, Brodmann's area.
Random-effect analysis of 14 subjects ($P<0.001$, uncorrected for the entire search volumes).
x, *y*, *z*: Talairach coordinates of activated clusters.

(Fig. 4a). In addition, the accuracy of 3-back trials was significantly lower around 15% than that of 0-back trials in all conditions (Fig. 4b).

Interaction of neural substrates of working memory processing with motivation

In control conditions for AR and MR, working memory was associated with activation of large part of cortex, as expected (Braver et al., 1997; Pochon et al., 2002; Ravizza et al., 2004) (see Table 1). These included subdivisions of the frontal cortex, right cingulate gyrus (BA 32), bilateral insula, right thalamus, left superior parietal lobule (BA 7), bilateral precuneus (BA 7), bilateral inferior parietal lobule (BA 40), right middle temporal gyrus (BA 20), and bilateral cerebellum were activated (Table 1). The brain areas activated during MR(+) completely overlapped those activated during MR(−) (Table 1 and Figs. 5c, d). However, the regions of brain activated in MR(+), particularly in bilateral prefrontal cortex [right superior frontal gyrus (BA 10) and left middle frontal gyrus (BA 11)], were larger than in MR(−). In contrast, brain areas activated during AR(+) overlapped completely those during AR(−), and no additional active brain regions were found in AR(+) (Table 1 and Figs. 5a, b).

Academic motivation-based regression analyses

In order to find brain regions related specifically to motivation associated with academic reward involving working memory processing, we performed correlation analyses. In AR(+), activities of both left and right putamen were positively correlated with academic achievement motivation scores (Fig. 6). In order to evaluate the interaction between motivation score and reward condition (i.e. monetary or academic) in these brain regions, we performed repeated-measures analysis of covariance (ANCOVA) with reward and type of reward as within-subject factors and academic achievement motivation scores as a potential confounding covariate. ANCOVA of left putamen activity exhibited significant reward×type of reward interaction [$F_{(1,12)}$=11.14, P=0.006] and reward×type of reward×academic achievement motivation score interaction [$F_{(1,12)}$=6.36, P=0.027]. Activity of the left putamen exhibited significant correlation with academic achievement motivation score in AR(+), but not in AR(−) (R=0.183, P=0.532), MR(+) (R=0.388, P=0.171), or MR(−) (R=0.518, P=0.058). ANCOVA of right putamen activity revealed no reward×type of reward interaction [$F_{(1,12)}$=2.08, P=0.175] or reward×type of reward×academic achievement motivation score interaction [$F_{(1,12)}$=6.36, P=0.248]. No significant correlation was found between academic achievement motivation score and activity of the right putamen in AR(−) (R=0.398, P=0.159), MR(+) (R=0.400, P=0.157), or MR(−) (R=0.458, P=0.100).

In order to determine whether the correlation observed in the activity of bilateral putamen with the academic achievement motivation score under AR(+) condition was specific for the working memory processing, we performed correlation analyses between the activities of left and right putamen during the 0-back trials in each task condition [AR(+), AR(−), MR(+), or MR(−)] and the academic achievement motivation score. No significant correlation was found between the activity of the putamen in both hemispheres and the academic achievement motivation score [AR(+) (R=−0.127, P=0.664), AR(−) (R=−0.036, P=0.903), MR(+) (R=−0.310, P=0.281), or MR(−) (R=−0.117, P=0.690) in left and AR(+) (R=−0.222, P=0.445), AR(−) (R=−0.074, P=0.802), MR(+) (R=−0.343, P=0.230), or MR(−) (R=−0.036, P=0.903) in right].

Activities of the left and right putamen in each condition are summarized in Fig. 7. Two-way (2×2) repeated-measures ANOVA of left putamen activity revealed a significant main effect of type of reward [$F_{(1,13)}$=6.68, P=0.023] and reward×type of reward interaction [$F_{(1,13)}$=8.19, P=0.013]. However, it did not reveal a significant main effect of reward [$F_{(1,13)}$=0.27, P=0.612]. Two-way (2×2) repeated-measures ANOVA of right putamen activity also revealed a significant main effect of type of reward [$F_{(1,13)}$=9.10, P=0.010]. But it also did not reveal a significant main effect of reward [$F_{(1,13)}$=3.58, P=0.081] or reward×type of reward interaction [$F_{(1,13)}$=1.01, P=0.333]. Activity of the left putamen in MR(+) was significantly higher than that in AR(+) and MR(−) and tended to be higher than that in AR(−) (Fig. 7a). Likewise, activity of the right putamen in MR(+) was significantly higher than that in AR(+) and AR(−) and tended to be higher than that in MR(−) (Fig. 7b).

Task performance-based regression analyses

We performed correlation analyses between activities of the left and right putamen during working memory processing (3-back trials *minus* 0-back trials) and difference in reaction time from 0-back trials to 3-back trials. The difference in reaction time from 0-back trials to 3-back trials was calculated as mean reaction time of each task condition [AR(+), AR(−), MR(+), or MR(−)] in 3-back trials *minus* that in 0-back trials. No significant correlation was found between the activity of the left

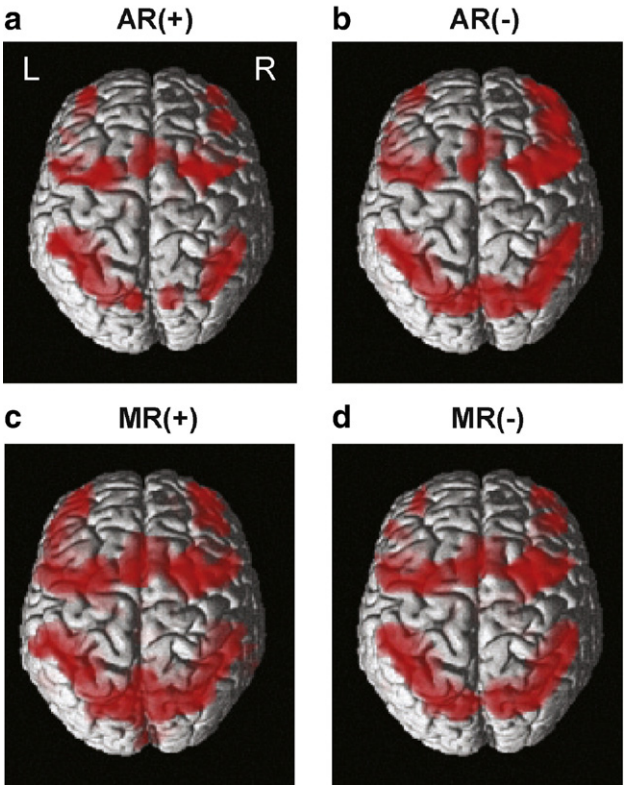

Fig. 5. Statistical parametric maps of activation by working memory processing (3-back trials *minus* 0-back trials) in the academic reward condition (a), control condition for academic reward (b), monetary reward condition (c), and control condition for monetary reward (d) (random-effect analyses of 14 subjects, P<0.001, uncorrected). Statistical parametric maps are superimposed on surface-rendered high-resolution MRIs. Right (R) and left (L) sides are indicated.

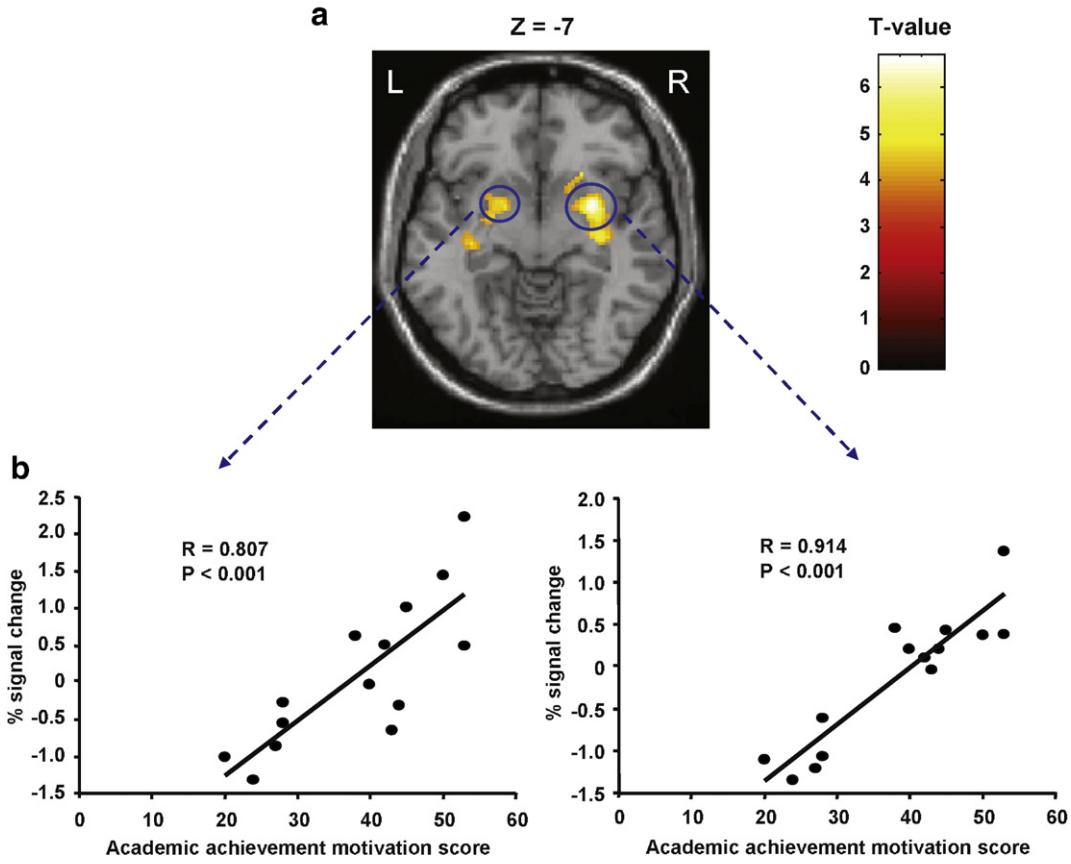

Fig. 6. Correlations between activities of brain regions related to working memory processing (3-back trials *minus* 0-back trials) during academic reward condition and academic achievement motivation score. Statistical parametric maps of activation in the academic reward condition were positively correlated with academic achievement motivation score (random-effect analyses of 14 subjects, $P<0.001$, uncorrected) (a). Right (R) and left (L) sides are indicated. Correlations between activities in the left (x, y, z: −20, 4, −7) and right (x, y, z: 30, 2, −7) putamen and academic achievement motivation score are shown (b). Z value indicates the z-axis value of standard brain according to the Talairach coordinate system. The linear regression line, P value, and Pearson's correlation coefficient are shown.

putamen and difference in reaction time in AR(+) ($R=0.083$, $P=0.777$), AR(−) ($R=0.151$, $P=0.606$), MR(+) ($R=0.135$, $P=0.646$), or MR(−) ($R=0.317$, $P=0.269$). A significant correlation was also not found between the activity of the right putamen and difference in reaction time in AR(+) ($R=-0.174$, $P=0.552$), AR(−) ($R=-0.019$, $P=0.949$), MR(+) ($R=-0.116$, $P=0.692$), or MR(−) ($R=0.237$, $P=0.415$). However, the activities of the left (Fig. 8a) and right (Fig. 8b) putamen in AR(+) were negatively correlated

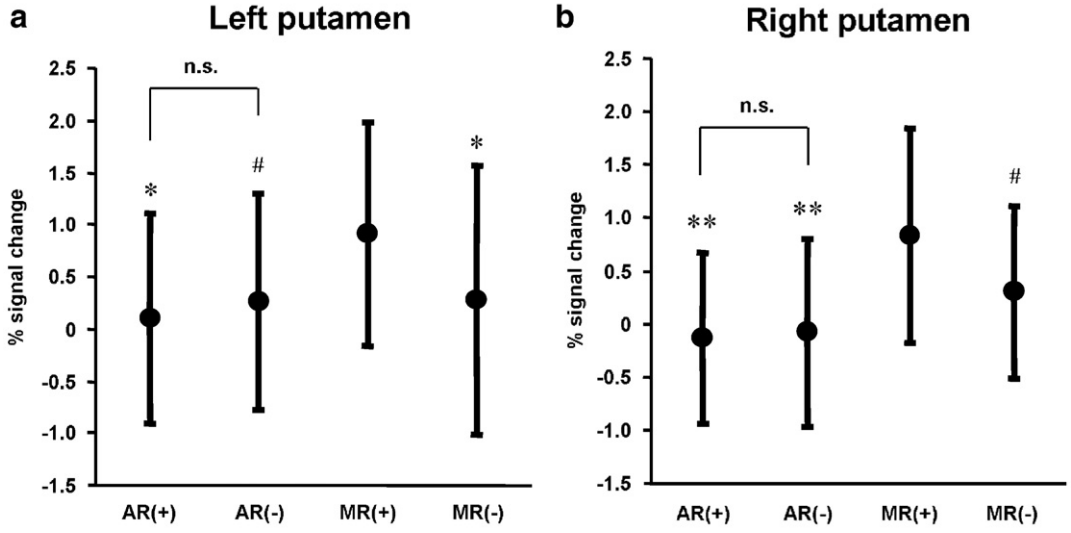

Fig. 7. Neural activities of the left (a) and right (b) putamen during working memory processing (3-back trials *minus* 0-back trials) in academic reward condition [AR(+)], control condition for academic reward [AR(−)], monetary reward condition [MR(+)], and control condition for monetary reward [MR(−)]. $^{*}P<0.05$, $^{**}P<0.01$, significantly different from MR(+) (two-tailed paired t-test). $^{\#}P<0.1$, different from MR(+). n.s., no significant difference between AR(+) and AR(−). Values are the mean and SD.

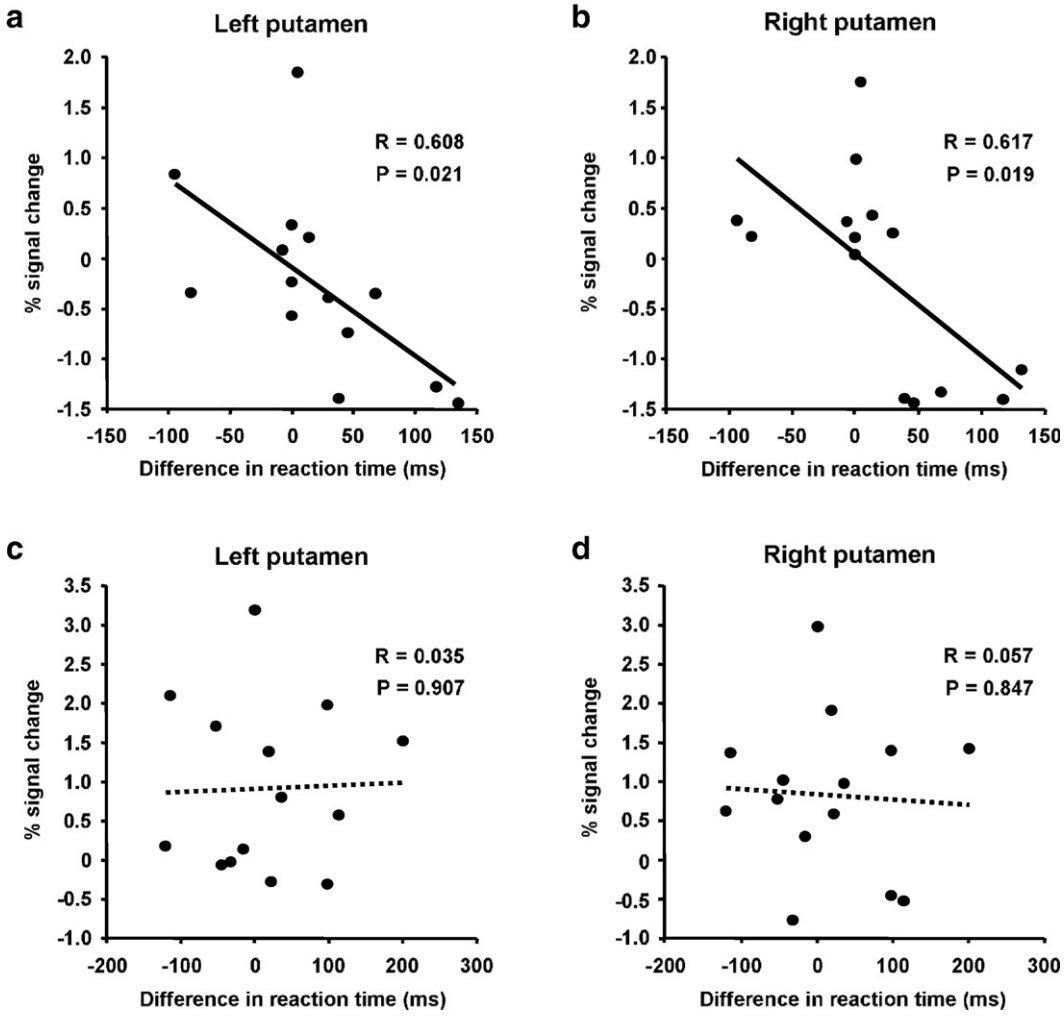

Fig. 8. Correlations between difference in reaction time and activities of left (a) and right (b) putamen during working memory processing (3-back trials *minus* 0-back trials) in the academic reward condition and those of left (c) and right (d) putamen in the monetary reward condition. Difference in reaction time was calculated as mean reaction time of 3-back trials in the academic or monetary reward condition subtracted by that in the control condition for academic or monetary reward condition. The linear regression line, *P* value, and Pearson's correlation coefficient are shown.

with differences in reaction time between AR(+) and AR(−), which was calculated as mean reaction time of 3-back trials in AR(+) *minus* that in AR(−). In contrast, the activities of left (Fig. 8c) or right (Fig. 8d) putamen in MR(+) were not significantly correlated with difference in reaction time between MR(+) and MR(−), which was calculated as the mean reaction time of 3-back trials in MR(+) *minus* that in MR(−).

The difference in reaction time between AR(+) and AR(−) also correlated with academic achievement motivation scores (R=0.629, P=0.016; data not shown). In contrast, the difference in reaction time between MR(+) and MR(−) was not significantly correlated with academic achievement motivation score (R=0.250, P=0.392; data not shown).

Discussion

Our principal finding is that activity in the putamen correlates with academic motivation levels and that the correlation is linearly related to reported levels of motivation. Motivation is a general term given for a characteristic that has other attributes from which it can nevertheless be conceptually separated. Among these are expectation, reward, and motor action. All three are attributes that can operate without a driving motivating force. But motivation itself cannot be divorced from them. Hence the involvement of the putamen is not only interesting but, in light of the published evidence, also not surprising. Both neurophysiological and imaging studies have linked it strongly to reward magnitude (Cromwell and Schultz, 2003), reward expectation (Knutson et al., 2001, 2003; O'Doherty et al., 2002), and predictability (Berns et al., 2001; McClure et al., 2003; O'Doherty et al., 2003; Wittmann et al., 2005). For example, ventral putamen has been found to be responsive to food preferences among humans (O'Doherty et al., 2006) while other experiments have shown that the putamen is important for the association between motor action and reward association (Haruno and Kawato, 2006; Knutson et al., 2001). Physiologically, several studies have shown the relationship between single-cell activity and reward expectation in the putamen. In an important study (Cromwell et al., 2005), it was shown that the responses of cells in the striatum, including the putamen, are strongly modulated when one reward was processed in the presence of alternative rewards, and that this shift was linked to arm movements and reward prediction, which would seem to constitute a direct link between motor control, reward and reward expectation, the characteristics that we have attributed

to motivation above. The putamen is associated not only with motivation but also with reward-related learning. Activity in it is reportedly related to prediction error during reward learning (Schultz et al., 1997). In the context of sequential motor learning, the putamen was found to be more active when a monkey was performing an already-learned motor sequence than when it was learning a new one (Hikosaka et al., 1999, 2002; Miyachi et al., 1997, 2002). Since the putamen is associated with motivation and learning, its bilateral activation during working memory processing may be crucial for progress in learning. Such links between expectation and motor action are not, however, confined to the putamen; they also seem to occur in other divisions of the striatum, thus raising the suggestion that different sections of the striatum may contribute differently during motivational tasks, in ways which still remain unknown. In our study, we also demonstrated that the responsiveness of bilateral putamen during working memory processing may be associated with the improvement of the motor preparation process in academic reward-related condition. This indicates that there is a motor component to academic reward-related activity in the putamen, presumably as a result of projections from the premotor cortex, supplementary motor area, and primary motor cortex (Alexander et al., 1990; Gerardin et al., 2003; Parthsarathy et al., 1992; Selemon and Goldman-Rakic, 1985; Takada et al., 1998).

One of the interesting, and perhaps surprising, findings in our study is the strong linear relationship between the reported motivational state as derived from the questionnaires that subjects completed and the change in the BOLD signal within the putamen. Linear relationships between strength of subjective feelings and cortical activity measured by the BOLD signal have been observed before. Notable among earlier studies has been the demonstration of a linear relationship between expectation for magnitude of monetary rewards and BOLD signal in the orbitofrontal cortex (Breiter et al., 2001; O'Doherty et al., 2001), the relationship between reward-induced anxiety and BOLD signals of the midbrain, hippocampus, and amygdala (Callan and Schweighofer, 2008), and the relationship between subjective beauty and BOLD signal in the orbitofrontal cortex (Kawabata and Zeki, 2004). Hence our study adds to the growing evidence of a quantitative relationship between subjective mental states and brain activity. Monetary reward and its expectation and the experience of beauty can both act as triggers to generate high motivational states, which suggests that many different subdivisions of the brain's reward and pleasure centres contribute in different ways to drive motivation. The putamen is part of the brain's reward system and is innervated with dopaminergic neurons which have been considered to mediate reward value (Wise, 1985). The mesolimbic and neostriatal dopamine systems could play a role in the anticipation of reward (Berridge, 1996; Berridge and Robinson, 1998), which is naturally intimately linked to motivation. The positive linear correlation between activity in the putamen and reported motivational levels suggests therefore that higher levels of motivation result in greater dopaminergic activity. This adds to the evidence that subjective states not only correlate with changes in BOLD signal, but with neuromodulator activity as well. For example, it has been shown that the early phase of passionate love correlates with a marked increase in nerve growth factor and a decrease in the levels of serotonin to level found in patients with obsessive-compulsive disorders (Emanuele et al., 2006).

It is also interesting to consider that although the extent of neural activity in the left and right putamen in the monetary reward condition was greater than that in the control and academic reward conditions, neural activities of none of the brain regions in that condition were correlated with motivation score or task performance. This finding is mirrored in other studies which have shown that activity in the brain correlates linearly with some subjective states and not others, thus raising the further important question of the determinants of such correlations (Callan and Schweighofer, 2008; Denton et al., 1999; Kawabata and Zeki, 2004; Patterson et al., 2002; Tanaka et al., 2006).

In this study, we have concentrated on motivation in the academic domain, but it seems likely that other motivational states will also be found to correlate with activity in the putamen. The extent of activity of the putamen may be pivotal to the motivation that drives academic achievement and thus academic successes. We believe that our neuroimaging findings provide information of great importance to the study of academic learning.

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