Supplementary Information

Attribute-Balancing Task

Task Overview

Subjects completed a total of 96 trials of the attribute-balancing task, split across four runs. The task was framed as a decision among stocks that varied in two attributes. The attribute values were shown by the to the percentage rankings of that stock within the set of all stocks on the major US markets. The identities of the stocks and of the attributes were hidden from the subjects until the end of the experiment, so that prior knowledge about stocks and market behavior could not influence the results.

Each trial began by showing the subject three stocks (see **Figure 1**). One stock was a <u>balanced option</u> whose attribute ratings were similar (i.e., they were either equal or differed by fewer than three points). The other two stocks were <u>extreme options</u> which had a better rating on one attribute and a poor rating on the other. Then, following a brief delay, one of the extreme options was eliminated, and the subject chose between the balanced option and the remaining extreme option.

There were three types of conditions: <u>congruent</u>, <u>incongruent</u>, and <u>equal</u>, defined based on the expected value relationship (i.e., the sum of the two attributes) between the balanced and extreme options. In the incongruent condition, the expected value of the balanced option was 8 (low-incongruence) or 16 (high-incongruence) points lower than that of the alternative extreme option while in the congruent condition, the expected value of the balanced option was 8 (low-congruence) or 16 (high-congruence) points higher. In the equal condition, the balancing and extreme options had equal expected value.

Stock attribute rankings for the balanced option ranged from 16 to 79 and the extreme alternative varied from 7 to 98, depending on trial type. For the choice trials, the extreme alternatives always had a higher score on one of the attributes and a lower score on the other compared to the balanced option. The attribute ratings for the two extreme alternatives were not identical but reversed: the numbers always varied slightly such that no two stocks on any given trial had identical ratings on any attributes. Subjects completed 18 equal trials, 36 congruent trials (half low-congruence, half high-congruence), and 36 incongruent trials (half low-incongruence, half high-incongruence) for a total of 90 main choice trials. For the strategy-control analysis, we included the low-congruent and low-incongruent trials in addition to the equal trials for greater experimental power. Finally, there were 6 randomly intermixed catch trials in which the extreme alternative had higher ratings than the balanced option on both attributes and thus was the more desirable option. These trials thus served to ensure that subjects attended to the task.

Subject instructions

Prior to the scanning session, subjects were informed that they would make a series of choices between different stocks and their task was to predict the stock that is likely to be more profitable based on the normalized ratings on the two attributes. It was emphasized that each trial involved information about real stocks, and the attributes represented information that a financial analyst might use when making investing decisions (e.g., normalized ratings of a company's financial reserves). Subjects were told that the particular stock or attribute in each trial would not be identified while they made decisions to ensure that their prior knowledge did not influence their choice. However, as an incentive to perform well, subjects were informed that a portion of their payment would depend on their performance (see Subject Payments below).

Stock Selection

All stock information presented in the task represented real stocks and their performance in a historical market (October, 2007). Stocks and their attribute rankings were identified using the website "The Motley Fool CAPS". For each stock, the two attribute rankings were their 30-day and one-year performance, among all stocks on US markets; these corresponded to normalized attributes a1 and a2, respectively. At the end of the session, we revealed the ticker name for each available stock as well as the more profitable of the two stocks, based on its performance at the end of the identified market period. Subjects received a monetary bonus if they had selected the more profitable of the two stocks (see below).

Subject Payments

Subjects were informed at the beginning of the session that they would be paid a fixed amount for participation ($40) plus a variable component that would depend on their choices. For this variable component, they were given a hidden cash endowment ($10) in a sealed envelope prior to the scan; its value was unknown to the subject until the end of the session. For each of two randomly selected trials from the attribute-balancing task, an additional $5 was added to the endowment if they successfully predicted the higher performing stock. If they did not select the higher performing stock, $5 was subtracted from the endowment. Finally, subjects had the opportunity to win an additional $5 based if their performance on the counting Stroop task reached a criterion level: accuracy greater than 95% and average response time faster than 600 ms.

Behavioral Results

Subjects’ choices were sensitive to manipulations of expected value. In the congruent condition, where the balanced alternative was associated with higher expected value, the proportion of balanced choices was the greatest at 0.89 **(Supplementary Table 1)**. In the incongruent condition, however, this value dropped to 0.23 indicating that subjects preferred the extreme alternative when it was associated with significantly greater expected value. For the equal condition, subject still showed a small, but significant, bias towards the balanced alternative preferring it in 65% of the trials. Post-experiment questionnaires indicated that subjects treated our manipulations of expected value in a logical manner consistent with our experimental design.

Meta Analysis

Selection of studies

Studies for use in the meta-analyses were identified by keyword searches through comprehensive databases (e.g., PubMed). Keywords included “cingulate”, “response”, “conflict”, “neuroimaging”, and “Stroop” for response-related control studies and “cingulate”, “decision”, “choice”, “medial frontal”, and “fMRI” for decision-related control studies. We emphasize that this meta-analysis was not intended to be a comprehensive review of all prior literature, but a way to corroborate the loci of activation identified in our experiments.

Studies selected from the search results met the following criteria. The cognitive control studies (a) utilized a task considered to elicit robust response-related control demands, such as the Stroop or Go/No-Go tasks; (b) provided three-dimensional coordinates of peak voxel activation during the response portion of the task; (c) showed peak activation in the DMPFC (BA 6, 9, 24, or 32); and (d) used fMRI or PET to acquire functional brain images from neurologically healthy individuals. The decision-related control studies (a) engaged subjects in a task requiring them to decide between multiple options, (b) provided three-dimensional coordinates of peak voxel activation during the decision-making portion of the task, (c) reported areas of activation in the DMPFC (BA 6, 9,24, or 32), and (d) used fMRI to acquire functional brain images from neurologically healthy individuals. This process resulted in the selection of 28 studies for inclusion in the response-related control condition **(Supplementary Table 4)** and 25 studies for inclusion in the decision-related control condition **(Supplementary Table 5)**, yielding 48 and 38 activation foci, respectively.

ALE Methods

Three separate activation likelihood estimate (ALE) based meta-analyses were carried out using the GingerALE software (Turkeltaub et al., 2002; Laird et al., 2005). The first consolidated response-related control studies, the second consolidated decision-related control studies, and the third generated a contrast between the first two analyses. All activation foci originally reported as MNI coordinates in the manuscript tables were converted to Talairach coordinates. ALE values were computed in Talairach space and activation foci were plotted using a full-width half maximum (FWHM) of 10.0 mm. To evaluate statistical significance, permutation testing was subsequently performed with 5000 iterations. A false discovery rate level of 0.05 was used to compute the ALE map threshold. The subtraction meta-analysis provided a map of regions where the two groups of foci are significantly different. Thresholded ALE maps were overlaid onto the colin1.1.nii anatomical template **(Supplementary Fig. S7)** provided by BrainMap (Turkeltaub et al., 2002). We also transformed the peak activations for each contrast to MNI coordinates to allow direct comparisons with the functional activations in our current study **(Fig. 6, squares)**.

Supplementary Tables

Supplementary Table 1: Mean proportion of balanced choices and response times across all subjects (N=20) for each of the condition types in our attribute-balancing task: *congruent*, such that the balanced option had higher expected value (EV); *incongruent*, such that the balanced option had lower EV; and *equal,* such that the balanced and extreme options were matched for expected value. Subjects' choice percentages tracked our EV manipulation, confirming that they were attending to the stock attribute values. Moreover, there was a significant bias toward the balanced option in the equal condition, consistent with prior work and our hypotheses. The pattern of response time data supported our planned manipulation of decision-related control, with slowest response times in the Equal condition, intermediate in the Incongruent condition, and fastest in the Congruent conditions. All pairs of response-times significantly differ from each other ($p < 0.01$).

	Prop. of Balanced Choices (%)		**Response Time (s)**	
	Mean	**S.E**	**Mean**	**S.E.**
Congruent	88.81	1.77	0.72	0.04
Incongruent	22.65	3.51	0.87	0.08
Equal	64.95	3.56	1.13	0.13

Supplementary Table 2: Summary of regions activated during the Counting Stroop task. Provided are coordinates and *z*-values of the peak activated voxel within the region.

	MNI Coordinates			Brodmann Area	*z*-value
	x	**y**	**z**		
Main Effect: Incongruent > Neutral					
Dorsomedial Prefrontal Cortex	0	17	51	8	4.34
L. Dorsolateral Prefrontal Cortex	-46	13	33	9	4.61
	-40	11	24	9	4.49
L. Superior Parietal Lobule	-28	-67	43	7	4.22
L. Posterior Parietal Cortex	-37	-47	48	40	4.31
L. Middle Frontal Gyrus	-39	1	54	6	4.21
R. Middle Frontal Gyrus	36	5	54	6	3.71
Response-related control: (Incongruent – Neutral) * (Response Time)					
Dorsomedial Prefrontal Cortex	-5	10	51	32	3.41
L. Dorsolateral Prefrontal Cortex	-55	9	34	9	3.06

Supplementary Table 3: Summary of regions activated during the attribute-balancing task. Provided are coordinates and *z*-values of the peak activated voxel within the region.

	MNI Coordinates			**Brodmann Area**	**z-value**
	X	**y**	**z**		
Decision: Equal > Incongruent					
R. Dorsolateral Prefrontal Cortex	42	38	32	9	2.81
R. Posterior Parietal Cortex	46	-41	37	40	2.91
Dorsomedial Prefrontal Cortex	-6	24	38	32	2.62
R. Inferior Frontal Gyrus	44	50	10	46	2.50
Decision: Incongruent > Congruent					
R. Inferior Frontal Gyrus	44	31	14	46	2.99
R. Precuneus	30	-50	44	9	3.42
Dorsomedial Prefrontal Cortex	-10	28	34	32	2.50
Anterior Insula	33	25	1	13	3.01
	-36	26	8	13	2.97
Choices: Extreme > Balanced					
L. Lateral Prefrontal Cortex	-46	24	12	46	3.01
R. Lateral Prefrontal Cortex	42	26	22	46	2.73
R. Anterior Insula	26	27	6	13	2.86
R. Precuneus	28	-59	54	7	2.71
L. Precuneus	-31	-50	42	7	2.51

Supplementary Table 4: Summary of response-related control studies used in the ALE meta-analysis along with the Talairach coordinates of the reported peak activations.

Response-related Control Studies	Talairach Coordinates		
	x	y	z
1. Bench et al. 1993	4	-4	20
	10	-4	24
	18	40	4
	20	42	8
	22	42	12
2. George et al. 1994	-22	24	32
3. Carter et al. 1995	10	8	48
	12	44	20
4. Kawashima et al. 1996	6	-11	52
	-4	-44	33
	8	-23	49
	8	6	42
	-4	9	38
	-4	5	30
5. George et al. 1997	-22	8	28
6. Bush et al. 1998	12	9	34
7. Carter et al. 1998	4	25	43
8. Derbyshire et al. 1998	-2	14	40
	0	2	48
9. Botvinick et al. 1999	-2	28	31
10. Brown et al. 1999	8	23	35
	-4	14	35
11. Bush et al. 1999	6	0	40
	6	15	43
	-3	21	37
12. Konishi et al. 1999	-5	29	32
13. Peterson et al. 1999	-7	18	26
14. Carter et al. 2000	0	15	41
15. Casey et al. 2000	-8	22	32
16. Macdonald et al. 2000	4	1	43
17. Barch et al. 2001	8	9	42
	8	21	24
	11	3	42
	5	15	39
18. Kerns et al. 2004	1	10	40
19. Erickson et al. 2004	2	18	40
20. Egner and Hirsch, 2004	18	8	46

21.	Milham and Banich, 2005	0	30	22
22.	Critchley et al. 2005	6	22	38
23.	Weissman et al. 2005	-2	5	43
24.	van Veen and Carter, 2005	7 1	18 26	42 28
25.	Evers et al. 2006	0	36	22
26.	Kerns, 2006	-3	8	41
27.	Lau et al. 2006	6 10	16 24	34 34
28.	Roelofs et al. 2006	-4 -8	30 36	36 28

Supplementary Table 5: Summary of decision-related control studies used in the ALE meta-analysis along with the Talairach coordinates of the reported peak activations.

Decision-related Control Studies	Talairach Coordinates		
	x	y	z
1. Elliot and Dolan, 1998	-4	28	30
2. Critchley et al. 2001	8	28	24
	-6	28	20
3. Bush et al. 2002	-2	23	20
4. Paulus et al. 2002	8	44	3
	1	27	31
	6	39	10
5. Sanfey et al. 2003	4	20	36
	-8	25	26
6. O'Doherty et al. 2003	-3	21	39
	6	21	39
7. Volz et al. 2003	4	30	46
8. Rogers et al. 2004	-3	37	15
	1	38	19
9. Volz et al. 2004	1	33	41
	4	21	47
10. Walton et al. 2004	-7	16	38
	0	12	36
11. Ernst et al. 2004	-6	24	42
12. Cohen et al. 2005	5	36	29
13. Coricelli et al. 2005	-3	25	41
14. Deppe et al. 2005	-7	38	17
	6	46	11
15. Huettel et al. 2005	7	14	39
16. Fishbein et al. 2005	-8	34	15
	14	32	17
17. Paulus and Frank, 2005	8	23	28
18. Blair et al. 2006	3	16	46
19. De Martino et al. 2006	0	17	46
20. Hampton et al. 2006	6	22	40
	-3	25	26
21. Krain et al. 2006	-20	39	14
	-4	32	-2
22. Marsh et al. 2006	2	25	37
23. Moll et al. 2006	-4	20	43
24. Behrens et al. 2007	-6	26	34
25. Pochon et al. 2008	-3	20	43
	-6	39	23

Supplementary Figure Captions

Figure S1. **Variability in preference for the balanced option in the attribute-balancing task**. Subjects showed a significant bias towards the balanced option, and away from the extreme option, with substantial inter-individual variability. Some subjects nearly always preferred the balanced option, while others preferred the extreme option in the majority of the trials.

Figure S2. **Incongruent trials in the Stroop task activated lateral frontal, medial frontal, and parietal regions**. We found increased activation for incongruent trials over neutral trials in bilateral dorsolateral prefrontal cortex, posterior parietal cortex and dorsomedial prefrontal cortex, consistent with previous studies using a similar task. Shown here and in subsequent figures are active clusters that surpassed a threshold of $z > 2.3$ with cluster-based Gaussian random field correction.

Figure S3. **Activation in pDMPFC predicts individual differences in motor impulsiveness across subjects**. (A) When response time variability was used a covariate for incongruent versus neutral trials, we found increased activation within the left dorsolateral prefrontal cortex and pDMPFC. (B) Within pDMPFC region (indicated with arrow; see also **Fig. 3**), we found a significant positive correlation between activation for incongruent trials and an independent trait measure of motor impulsiveness. Subjects with greater values on the impulsiveness scale exhibited increased activation for incongruent trials in this region.

Figure S4. **Activation associated with decision-related control demands**. Activation in right inferior frontal gyrus, posterior parietal cortex and middle DMPFC increased with decision-related control. (B) We also found that extreme choices were associated with increased activation in bilateral dorsolateral PFC (indicated with arrow), anterior insula and parietal regions, relative to balanced choices. No regions showed significantly greater activation for balanced choices over extreme choices at the pre-selected threshold of $p<0.05$ (corrected).

Figure S5. **Activation in aDMPFC predicts individual differences in the need for cognition trait across subjects**. Within the anterior DMPFC region that tracks strategy-related control (indicated with arrow; see also **Fig. 5**), we found a significant positive correlation of activation difference between extreme and balanced options with an independent *need for cognition* trait measure. Subjects with greater need for cognition exhibit a greater difference between extreme and balancing choices in this region.

Figure S6. **Anterior and middle DMPFC are associated with strategy and decision-related control respectively**. To verify that the clusters implicated in strategy and decision-related control were functionally distinct, we conducted a post hoc ROI analysis within the aDMPFC (green) and mDMPFC (red) regions indicated in **Fig. 4** and **Fig. 5** of the main manuscript. We found that the anterior region, unlike the middle region, did not show a linear relationship with increasing decision conflict. Similarly, mDMPFC, unlike aDMPFC, did not show a significant correlation with strategic variability across subjects

Figure S7. **Meta-analysis reveals functional segregation between studies involving decision-related and response-related control**. We conducted a meta-analysis of 53 past studies that reported DMPFC activation in tasks cognitive control. We classified each study as involving either decision-related or response-related control, based on task properties, and included the reported coordinates of activation in an Activation Likelihood Estimation (ALE) analysis. We found an anterior-to-posterior functional segregation between the decision-related and response-related control studies. We have also included, for reference, a second cluster in the rostral cingulate cortex associated with decision making. This cluster, which is more ventral than the DMPFC regions considered in this paper, specifically may reflect affective content of some of the decision-making studies used in our meta-analysis.

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