

Supplementary Information

Title

Neural determinants of human goal-directed vs. habitual action control and their relation to trait motivation

Authors

Hamdi Eryilmaz¹

Anais Rodriguez-Thompson¹

Alexandra S. Tanner¹

Madeline Giegold¹

Franklin C. Huntington¹

Joshua L. Roffman¹

¹Department of Psychiatry, Massachusetts General Hospital and Harvard Medical School, Boston, MA

Corresponding author information

Name: Hamdi Eryilmaz

Address: Massachusetts General Hospital, 149 13th St, Room 2602-D,
Charlestown, MA 02129, USA.

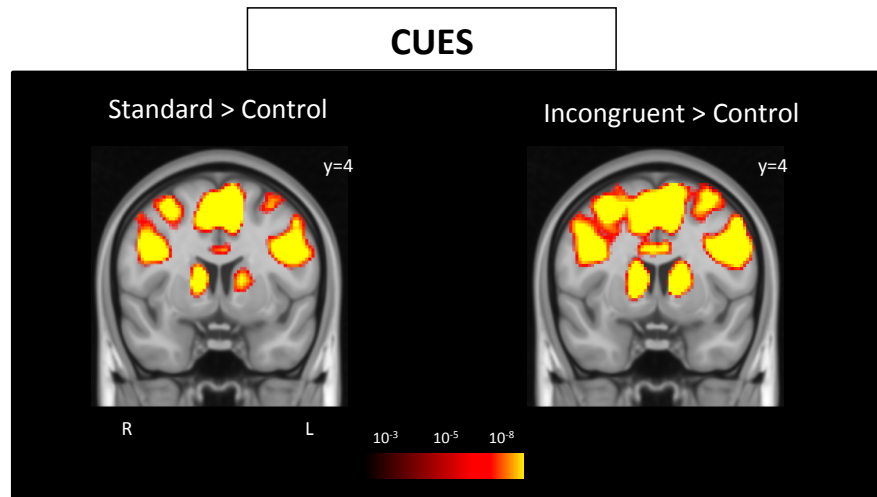
Email address: hamdi.eryilmaz@mgh.harvard.edu

Phone: +1 617 643 7462

Fax: +1 617 726 4078

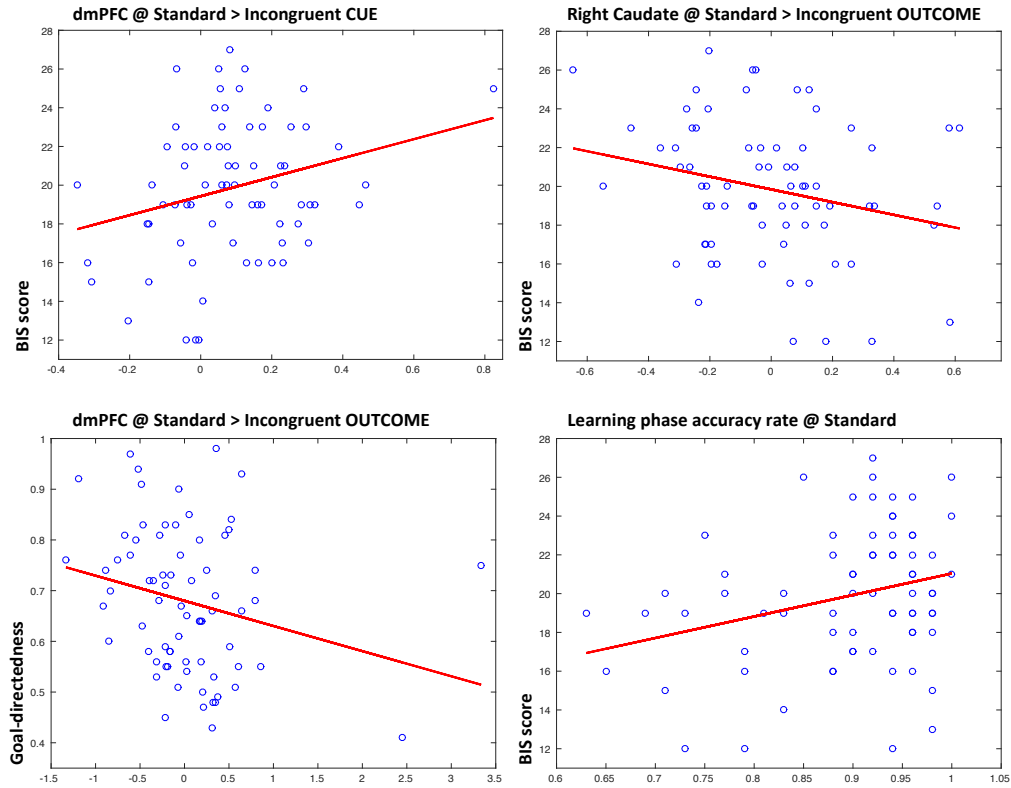
Supplementary Figures

Figure S1. General effect of learning.



Subjects demonstrated strong activation in bilateral dorsal caudate and in the dorsal attention network (bilateral dorsolateral and dorsomedial prefrontal cortex, superior parietal lobule) in both learning conditions relative to the control condition.

Figure S2. Correlations among BIS/BAS-Drive, Goal-directedness, brain activation, and learning performance.



Correlations between behavioral scales and brain activation are depicted only for illustration purpose and they did not survive correction for multiple comparisons. BIS scores showed a nominally significant positive correlation with activation in dmPFC during standard cues and a negative correlation with activation in right caudate during standard outcomes. Goal-directedness measured in the Slip Test showed a nominally significant inverse correlation with dmPFC activation during standard outcomes. Finally, BIS scores significantly correlated with accuracy rates during acquisition of standard pairs.

Supplementary Tables

Table S1. List of brain regions showing significant activation during early versus late phases of learning at standard and incongruent cues. Cluster size indicates the number of voxels surviving Monte Carlo corrected threshold. Coordinates and the p value are shown for the peak voxel in each region.

Region (ROI)	Side	Coordinates			p-value	Cluster size (N)
		x	y	z		
Standard EARLY > Standard LATE						
Caudate	L	-12	-5	19	2.3x10 ⁻¹¹	970
Caudate	R	11	7	13	5x10 ⁻⁹	1226
Insula	R	34	21	-3	5.2x10 ⁻¹⁰	630
dIPFC	R	52	10	35	2x10 ⁻⁸	1988
dmPFC	R	2	35	41	3.4x10 ⁻⁸	855
Insula	L	-30	19	-3	4.9x10 ⁻⁸	422
PrCG	L	-48	1	39	5.6x10 ⁻⁵	144
Standard LATE > Standard EARLY						
STG	R	66	-13	-1	2.1x10 ⁻⁷	470
PoCG	L	-14	-31	79	5.5x10 ⁻⁷	405
PCC	L	-4	-43	23	10 ⁻⁶	1278
PoCG	R	16	-31	77	1.3x10 ⁻⁶	251
Incongruent EARLY > Incongruent LATE						
dmPFC	R	4	37	41	1.6x10 ⁻¹⁰	1376
dIPFC	R	46	15	51	2.1x10 ⁻⁸	708
IFG	R	56	11	18	3.1x10 ⁻⁸	800
Caudate	R	10	-3	15	1.1x10 ⁻⁷	638
Caudate	L	-8	5	9	1.7x10 ⁻⁷	514
Insula	R	34	21	-11	1.8x10 ⁻⁶	336
Insula	L	-32	25	-5	10 ⁻⁵	368

Abbreviations: dmPFC: dorsomedial prefrontal cortex, dIPFC: dorsolateral prefrontal cortex, IFG: inferior frontal gyrus, PCC: posterior cingulate cortex, PoCG: postcentral gyrus, PrCG: precentral gyrus, STG: superior temporal gyrus.

Table S2. List of brain regions showing significant activation during early versus late phases of learning at standard and incongruent outcomes. Cluster size indicates the number of voxels surviving Monte Carlo corrected threshold. Coordinates and the p value are shown for the peak voxel in each region.

Region (ROI)	Side	Coordinates			p-value	Cluster size (N)
		x	y	z		
Standard EARLY > Standard LATE						
SMA	L	-2	3	61	8.1x10 ⁻⁸	734
dACC		0	13	28	1.6x10 ⁻⁶	492
dIPFC	R	32	41	35	2.6x10 ⁻⁵	323
Standard LATE > Standard EARLY						
Putamen	L	-16	5	-9	7.9x10 ⁻⁹	426
Caudate	R	12	9	-3	3.7x10 ⁻⁷	288
MOcc	L	-28	-89	17	1.4x10 ⁻⁵	324
Incongruent EARLY > Incongruent LATE						
dIPFC	R	34	41	29	1.5x10 ⁻⁷	529
dACC	L	-8	21	37	6.2x10 ⁻⁶	758
PrCG	L	-48	3	39	3.2x10 ⁻⁵	398
Incongruent LATE > Incongruent EARLY						
Putamen	L	-20	5	-7	4.2x10 ⁻⁷	388

Abbreviations: dACC: dorsal anterior cingulate cortex, dIPFC: dorsolateral prefrontal cortex, MOcc: middle occipital cortex, PrCG: precentral gyrus, SMA: supplementary motor area.

Supplementary Results

GLM results. In order to verify that the conditions *standard* and *incongruent* induced the predicted learning effects, we contrasted these two conditions with the activation during the control condition, which consisted of the visual and motor properties of the learning conditions.

General learning effects. The contrast ‘Standard Cue vs. Control Cue’ showed strong activation in distributed brain areas including the dorsal attention network (bilateral dlPFC, dmPFC, superior parietal lobule), bilateral insula, bilateral dorsal caudate and thalamus and lateral occipital cortex (Fig. S1). Widespread cortical activation suggests that learning conditions required more attentional resources than the control condition, whereas substantial striatum activation hints at learning effects. ‘Incongruent Cue vs. Control Cue’ activated similar brain areas as above with slightly larger clusters in the striatum and in the dorsal attention network.