

Bidirectional Associations Between Stress and Reward Processing in Children and Adolescents: A Longitudinal Neuroimaging Study

Supplemental Information

Reward Paradigm: Piñata Task

The task included one practice run followed by six task runs, with each run consisting of 22 trials, for a total of 132 task trials. Trials were equally divided among each of four incentive levels (0 stars, 1 star, 2 stars, or 4 stars), with 33 trials of each potential reward value. Each trial consisted of three stages: the anticipation stage, where participants saw part of the piñata at the top of the screen (cue), containing the number of stars inside the piñata for that trial, followed by an anticipation period with no cue visible; the response stage, where the piñata descended to the middle of the screen (target) and the participant “hit” the piñata with a quick button press; and the feedback stage, where the piñata either broke open (indicating a successful hit) and the participant “collected” the stars inside, or the piñata swung away intact, indicating that the hit was not successful. **Figure S1** shows an example of the time course of a trial of the Piñata task.

The cue appeared for 1500 ms and was followed by an anticipation period with no cue visible that varied between 1000 and 2000 ms. The target duration varied using a dynamic algorithm that maintained a successful hit rate of approximately 66%. When the participant’s cumulative success rate for all trials was <66%, the response window increased by 50 ms and when the success rate was >66%, the response window decreased by 50 ms. The response window was followed by a delay period such that the target response window plus the delay period totaled 1500 ms combined. The feedback duration was 1500 ms. A white fixation cross on a black background appeared between trials for a variable period of 1000 to 2000 ms.

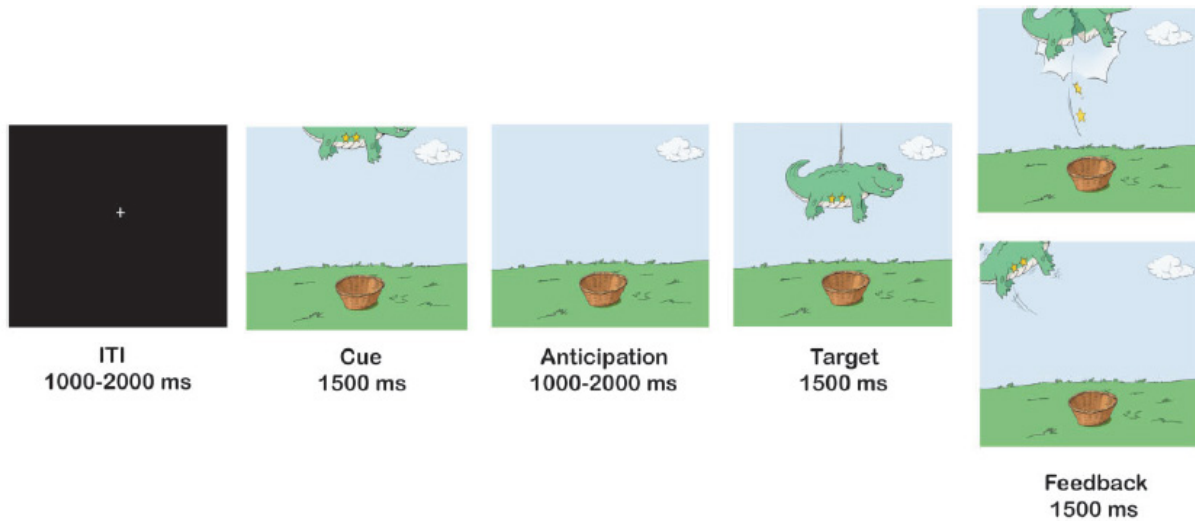


Figure S1. Trial structure of the Piñata task.

Acute Stress Laboratory Paradigm: Speech Task

In this experiment, participants entered a room with a one-way mirror and sat in a table with one unfamiliar peer at age 10 and two unfamiliar peers at age 13. After a 5-minute task in which children are introduced for the first time, participants were instructed to prepare a 5-minute speech on a topic to be presented to an audience composed of two experimenters and the other/s unfamiliar peer/s. Two topics were randomly assigned at age 10: “Why we should vote for you for class president” and “Why homework is good or bad for you”. The topic of the speech at age 13 was “What makes you a good person?”. Participants were given 2 minutes to prepare the speech and the option to write notes, although these could not be used during the speech. During the preparation period, the unfamiliar peer/s and one experimenter remained in the room. Following the preparation period, a video camera visible to the participant was brought into the room by a second experimenter with the aim of increasing self-consciousness and social evaluative threat. After that, the participant delivered the speech to the audience. Participants were prompted to

continue their speeches for a minimum of two minutes but were allowed to conclude after two minutes. All the procedure was videotaped with a camera located in the next room, on the other side of the one-way mirror.

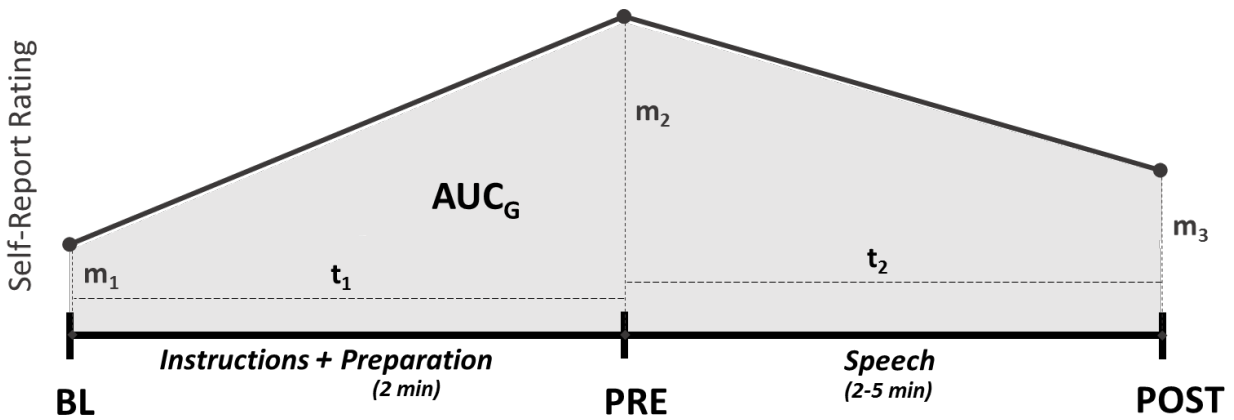


Figure S2. Time course of the Speech task with an example of measurements at baseline (BL), after preparing and before giving speech (PRE), and after giving speech (POST). The shaded area represents the area under the curve with respect to ground (AUC_G).

Table S1. Whole-brain analyses results for the association between stress and reward anticipation

Association between exposure to stress at age 7 and reward anticipation at age 10					
k	Region	x	y	z	t
240	L caudate head	4.8	-7.1	-2.2	-3.12
131	L inferior parietal lobule	38.2	35.2	52.0	-3.97
Association between reward anticipation and stress reactivity at age 10					
k	Region	x	y	z	t
204	L precuneus	26.2	64.5	40.5	-4.04
201	R fusiform gyrus	-36.8	55.6	-12.6	-3.93
Association between reward anticipation at age 10 and stress reactivity at age 13					
k	Region	x	y	z	t
924	R fusiform gyrus	-34.4	61.9	-5.4	-2.41
521	L medial frontal gyrus	1.9	-56.2	20	-3.59
370	L posterior cingulate	0.8	43.4	18.6	-3.19
190	L precuneus	21.8	70.9	33.7	-4.46
172	R middle temporal gyrus	-41.4	56.6	20	-4.33
157	L superior frontal gyrus	10.9	-26.3	49.0	-3.67
137	L fusiform gyrus	48.9	60.9	-10.6	-3.27
133	L fusiform gyrus	46.8	2.7	-22.8	-3.80
124	L middle frontal gyrus	26.7	-10.3	33.9	-3.36
111	L anterior cingulate	11.2	-48.2	-3.8	-3.11

k, number of voxels; L, left; R, right.

Cluster thresholds for the whole brain corrected at alpha level of $p < 0.05$.

Table S2. Whole-brain analyses results for the association between stress and reward anticipation adjusted for motion

Association between exposure to stress at age 7 and reward anticipation at age 10					
k	Region	x	y	z	t
262	L caudate head	8.8	-13.8	1.2	-4.65
141	L inferior parietal lobule	38.2	38.8	53.8	-4.38
Association between reward anticipation and stress reactivity at age 10					
k	Region	x	y	z	t
123	L precuneus	26.2	61.2	41.2	-4.60
Association between reward anticipation at age 10 and stress reactivity at age 13					
k	Region	x	y	z	t
299 ^a	R fusiform gyrus	-31.2	48.8	-11.2	-5.11
90 ^a	L medial frontal gyrus	6.2	-46.2	21.2	-4.27

k, number of voxels; L, left; R, right.

Cluster thresholds for the whole brain corrected at alpha level of $p < 0.05$.

^aCluster thresholds for the whole brain corrected at alpha level of $p < 0.09$.

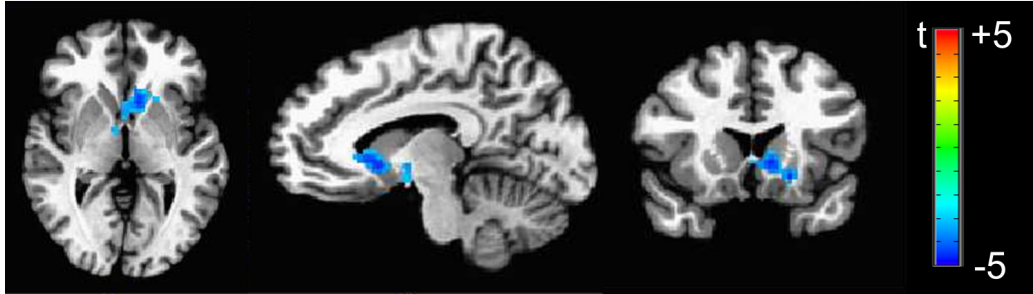


Figure S3. Voxel-wise t-test maps for the effect of past stress on reward anticipation adjusted for motion, corrected at cluster-level with a threshold of $p < 0.05$ and a minimal cluster size of 110 voxels, $k=262$ $xyz=+9 -14 +1$. (Note: R is L).

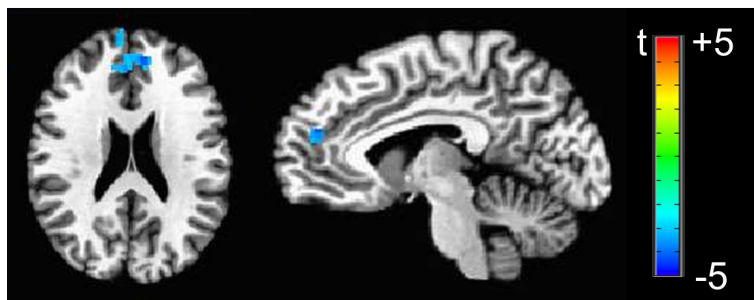


Figure S4. Voxel-wise t-test maps for the association between neural activity during reward anticipation at age 10 and self-reported stress reactivity at age 13 adjusted for motion, corrected at cluster-level with a threshold of $p < 0.085$, $k=90$ $xyz=6 -46 21$. (Note: R is L).

Table S3. Association between stress and reward anticipation in unadjusted and adjusted *single* path analytical models

Association between exposure to stress at age 7 and reward anticipation at age 10																				
ROI	Unadjusted				Adjusted for motion				Adjusted for maternal depression				Adjusted for peer rejection				Adjusted for depressive symptoms			
	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value
ACC	-0.31	0.16	-1.98	0.048	-0.32	0.15	-2.05	0.040	-0.32	0.15	-2.06	0.039	-0.31	0.16	-2.01	0.045	-0.33	0.15	-2.13	0.033
Amy	-0.35	0.15	-2.39	0.017	-0.34	0.15	-2.30	0.022	-0.36	0.15	-2.48	0.013	-0.35	0.15	-2.37	0.018	-0.35	0.15	-2.39	0.017
DC	-0.34	0.15	-2.30	0.022	-0.35	0.15	-2.35	0.019	-0.37	0.14	-2.60	0.009	-0.34	0.15	-2.23	0.026	-0.34	0.15	-2.30	0.022
GP	-0.51	0.13	-3.85	<0.001	-0.51	0.13	-3.95	<0.001	-0.51	0.13	-3.86	<0.001	-0.50	0.13	-3.81	<0.001	-0.51	0.13	-3.86	<0.001
Ins	-0.28	0.20	-1.40	0.161	-0.36	0.20	-1.80	0.072	-0.29	0.19	-1.56	0.119	-0.27	0.20	-1.36	0.174	-0.30	0.20	-1.53	0.125
mPFC	-0.31	0.16	-1.98	0.048	-0.31	0.16	-1.99	0.047	-0.33	0.15	-2.14	0.032	-0.31	0.16	-1.98	0.048	-0.30	0.16	-1.96	0.050
NAcc	-0.40	0.14	-2.93	0.003	-0.41	0.14	-2.97	0.003	-0.42	0.14	-3.08	0.002	-0.41	0.14	-2.97	0.003	-0.41	0.14	-2.97	0.003
Put	-0.39	0.14	-2.77	0.006	-0.41	0.14	-2.95	0.003	-0.40	0.14	-2.84	0.005	-0.39	0.14	-2.74	0.006	-0.40	0.14	-2.81	0.005
VC	-0.49	0.13	-3.83	<0.001	-0.49	0.13	-3.84	<0.001	-0.51	0.12	-4.11	<0.001	-0.49	0.13	-3.83	<0.001	-0.49	0.13	-3.83	<0.001

Association between reward anticipation and stress reactivity at age 10																				
ROI	Unadjusted				Adjusted for motion				Adjusted for maternal depression				Adjusted for peer rejection				Adjusted for depressive symptoms			
	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value
ACC	-0.31	0.16	-1.94	0.052	-0.31	0.16	-1.92	0.054	-0.31	0.16	-1.94	0.052	-0.10	0.17	-0.56	0.579	-0.29	0.16	-1.79	0.073
Amy	-0.30	0.16	-1.87	0.061	-0.30	0.16	-1.89	0.059	-0.28	0.16	-1.75	0.079	-0.27	0.16	-1.67	0.094	-0.28	0.16	-1.73	0.083
DC	-0.32	0.15	-2.11	0.035	-0.32	0.15	-2.07	0.038	-0.30	0.16	-1.92	0.055	-0.31	0.16	-1.96	0.050	-0.31	0.16	-2.02	0.044
GP	-0.09	0.18	-0.50	0.614	-0.08	0.18	-0.45	0.650	-0.07	0.18	-0.37	0.709	-0.07	0.18	-0.39	0.699	0.06	0.17	0.33	0.742
Ins	-0.04	0.17	-0.21	0.834	-0.03	0.17	-0.19	0.853	-0.03	0.17	-0.18	0.857	-0.02	0.17	-0.11	0.912	-0.02	0.17	-0.10	0.918
mPFC	-0.39	0.15	-2.66	0.008	-0.39	0.15	-2.66	0.008	-0.39	0.15	-2.67	0.008	-0.38	0.15	-2.50	0.012	-0.38	0.15	-2.52	0.012
NAcc	-0.13	0.17	-0.73	0.463	-0.12	0.17	-0.70	0.482	-0.12	0.17	-0.69	0.493	-0.10	0.17	-0.57	0.571	-0.11	0.17	-0.64	0.524
Put	-0.17	0.17	-1.00	0.318	-0.16	0.17	-0.95	0.343	-0.15	0.17	-0.87	0.383	-0.16	0.17	-0.93	0.354	-0.15	0.17	-0.91	0.363
VC	-0.28	0.16	-1.76	0.078	-0.28	0.16	-1.73	0.083	-0.27	0.16	-1.66	0.096	-0.26	0.16	-1.61	0.107	0.27	0.16	-1.70	0.090

Association between reward anticipation at age 10 and stress reactivity at age 13																				
ROI	Unadjusted				Adjusted for motion				Adjusted for maternal depression				Adjusted for peer rejection				Adjusted for depressive symptoms			
	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value
ACC	-0.49	0.14	-3.43	0.001	-0.42	0.14	-3.07	0.002	-0.44	0.14	-3.13	0.002	-0.50	0.14	-3.44	0.001	-0.50	0.14	-3.44	0.001
Amy	-0.28	0.16	-1.81	0.070	-0.14	0.16	-0.89	0.375	-0.30	0.14	-2.12	0.034	-0.29	0.16	-1.83	0.067	-0.31	0.16	-1.97	0.049
DC	-0.27	0.16	-1.71	0.087	-0.24	0.15	-1.64	0.102	-0.39	0.15	-2.67	0.007	-0.27	0.16	-1.68	0.093	-0.29	0.16	-1.80	0.072
GP	-0.25	0.16	-1.57	0.116	-0.25	0.14	-1.80	0.073	-0.25	0.15	-1.72	0.085	-0.25	0.16	-1.51	0.132	-0.27	0.16	-1.69	0.091
Ins	-0.10	0.16	-0.63	0.532	-0.14	0.15	-0.94	0.347	-0.13	0.15	-0.87	0.386	-0.12	0.16	-0.74	0.460	-0.12	0.16	-0.76	0.447
mPFC	-0.54	0.13	-4.31	<0.001	-0.44	0.13	-3.33	0.001	-0.48	0.13	-3.71	<0.001	-0.55	0.13	-4.16	<0.001	-0.56	0.13	-4.36	<0.001
NAcc	-0.40	0.15	-2.69	0.007	-0.35	0.14	-2.52	0.012	-0.35	0.15	-2.41	0.016	-0.41	0.15	-2.80	0.005	-0.41	0.15	-2.82	0.005
Put	-0.23	0.15	-1.49	0.135	-0.28	0.14	-2.09	0.037	-0.26	0.14	-1.87	0.061	-0.23	0.16	-1.45	0.146	-0.23	0.15	-1.49	0.136
VC	-0.39	0.16	-2.37	0.018	-0.27	0.16	-1.65	0.100	-0.38	0.15	-2.46	0.014	-0.39	0.17	-2.36	0.019	-0.44	0.16	-2.74	0.006

Note: p-values in **bold** survived Benjamini-Hochberg correction. ACC, anterior cingulate cortex; Amy, amygdala; DC, dorsal caudate; GP, globus pallidus; Ins, insula; mPFC, medial prefrontal cortex; NAcc, nucleus accumbens; Put, putamen; ROI, region of interest; SE, standard error.

Table S4. Association between stress and reward anticipation in unadjusted and adjusted *separate* path analytical models

Association between exposure to stress at age 7 and reward anticipation at age 10 (model 1)																				
ROI	Unadjusted				Adjusted for motion				Adjusted for maternal depression				Adjusted for peer rejection				Adjusted for depressive symptoms			
	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value
ACC	-0.32	0.15	-2.08	0.038	-0.33	0.15	-2.15	0.032	-0.29	0.16	-1.80	0.071	-0.33	0.16	-2.09	0.036	-0.37	0.15	-2.43	0.015
Amy	-0.35	0.15	-2.38	0.017	-0.34	0.13	-2.58	0.010	-0.38	0.15	-2.50	0.012	-0.39	0.15	-2.66	0.008	-0.33	0.15	-2.28	0.022
DC	-0.34	0.15	-2.28	0.023	-0.34	0.15	-2.31	0.021	-0.44	0.15	-2.94	0.003	-0.36	0.15	-2.37	0.018	-0.34	0.15	-2.29	0.022
GP	-0.51	0.13	-3.84	<0.001	-0.50	0.13	-3.83	<0.001	-0.53	0.14	-3.84	<0.001	-0.51	0.13	-3.81	<0.001	-0.51	0.13	-3.87	<0.001
Ins	-0.28	0.20	-1.39	0.165	-0.31	0.21	-1.48	0.139	-0.35	0.20	-1.81	0.070	-0.25	0.20	-1.24	0.215	-0.31	0.20	-1.55	0.120
mPFC	-0.32	0.15	-2.08	0.038	-0.31	0.14	-2.30	0.022	-0.25	0.16	-1.61	0.107	-0.37	0.15	-2.48	0.013	-0.30	0.15	-1.98	0.047
NAcc	-0.42	0.14	-3.05	0.002	-0.41	0.13	-3.07	0.002	-0.42	0.15	-2.90	0.004	-0.41	0.14	-2.95	0.003	-0.43	0.14	-3.16	0.002
Put	-0.39	0.14	-2.77	0.006	-0.40	0.14	-2.79	0.005	-0.45	0.15	-3.10	0.002	-0.40	0.14	-2.77	0.006	-0.42	0.14	-2.96	0.003
VC	-0.50	0.13	-3.96	<0.001	-0.50	0.12	-4.10	<0.001	-0.55	0.13	-4.12	<0.001	-0.50	0.13	-3.86	<0.001	-0.51	0.13	-4.01	<0.001

Association between reward anticipation and stress reactivity at age 10 (model 2)																				
ROI	Unadjusted				Adjusted for motion				Adjusted for maternal depression				Adjusted for peer rejection				Adjusted for depressive symptoms			
	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value
ACC	-0.29	0.16	-1.77	0.077	-0.29	0.16	-1.78	0.075	-0.291	0.16	-1.82	0.069	-0.24	0.17	-1.44	0.149	-0.27	0.17	-1.60	0.109
Amy	-0.27	0.16	-1.65	0.100	-0.27	0.16	-1.69	0.092	-0.263	0.16	-1.63	0.102	-0.22	0.17	-1.33	0.185	-0.25	0.17	-1.50	0.133
DC	-0.30	0.16	-1.90	0.057	-0.30	0.16	-1.90	0.057	-0.289	0.16	-1.86	0.064	-0.26	0.16	-1.63	0.103	-0.28	0.16	-1.80	0.072
GP	-0.05	0.17	-0.29	0.771	-0.05	0.17	-0.28	0.778	-0.047	0.17	-0.27	0.785	-0.01	0.18	-0.04	0.970	-0.03	0.17	-0.18	0.859
Ins	-0.03	0.17	-0.17	0.868	-0.03	0.17	-0.17	0.865	-0.035	0.17	-0.21	0.834	0.00	0.17	0.01	0.989	-0.01	0.17	-0.05	0.960
mPFC	-0.36	0.15	-2.43	0.015	-0.37	0.15	-2.47	0.014	-0.371	0.15	-2.51	0.012	-0.33	0.16	-2.13	0.033	-0.35	0.15	-2.30	0.022
NAcc	-0.10	0.17	-0.58	0.564	-0.10	0.17	-0.58	0.561	-0.102	0.17	-0.60	0.548	-0.05	0.18	-0.31	0.757	-0.08	0.17	-0.46	0.644
Put	-0.14	0.17	-0.86	0.392	-0.14	0.17	-0.85	0.394	-0.14	0.17	-0.84	0.401	-0.11	0.17	-0.66	0.512	-0.13	0.17	-0.76	0.450
VC	-0.23	0.16	-1.40	0.162	-0.23	0.16	-1.40	0.162	-0.228	0.16	-1.42	0.157	-0.19	0.17	-1.11	0.269	-0.21	0.16	-1.30	0.194

Association between reward anticipation at age 10 and stress reactivity at age 13 (model 2)																				
ROI	Unadjusted				Adjusted for motion				Adjusted for maternal depression				Adjusted for peer rejection				Adjusted for depressive symptoms			
	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value	β	SE	z	p-value
ACC	-0.49	0.14	-3.43	0.001	-0.42	0.14	-3.07	0.002	-0.438	0.14	-3.13	0.002	-0.50	0.14	-3.44	0.001	-0.50	0.14	-3.44	0.001
Amy	-0.28	0.16	-1.81	0.070	-0.14	0.16	-0.89	0.375	-0.298	0.14	-2.12	0.034	-0.29	0.16	-1.83	0.067	-0.31	0.16	-1.97	0.049
DC	-0.27	0.16	-1.71	0.087	-0.24	0.15	-1.64	0.102	-0.394	0.15	-2.67	0.007	-0.27	0.16	-1.68	0.093	-0.29	0.16	-1.80	0.072
GP	-0.25	0.16	-1.57	0.116	-0.25	0.14	-1.80	0.073	-0.253	0.15	-1.72	0.085	-0.25	0.16	-1.51	0.132	-0.27	0.16	-1.69	0.091
Ins	-0.10	0.16	-0.63	0.532	-0.14	0.15	-0.94	0.347	-0.127	0.15	-0.87	0.386	-0.12	0.16	-0.74	0.46	-0.12	0.16	-0.76	0.447
mPFC	-0.54	0.13	-4.31	<0.001	-0.44	0.13	-3.33	<0.001	-0.482	0.13	-3.71	<0.001	-0.55	0.13	-4.16	<0.001	-0.56	0.13	-4.36	<0.001
NAcc	-0.40	0.15	-2.69	0.007	-0.35	0.14	-2.52	0.012	-0.351	0.15	-2.41	0.016	-0.41	0.15	-2.80	0.005	-0.41	0.15	-2.82	0.005
Put	-0.23	0.15	-1.49	0.135	-0.28	0.14	-2.09	0.037	-0.264	0.14	-1.87	0.061	-0.23	0.16	-1.45	0.146	-0.23	0.15	-1.49	0.136
VC	-0.39	0.16	-2.37	0.018	-0.27	0.16	-1.65	0.100	-0.378	0.15	-2.46	0.014	-0.39	0.17	-2.36	0.019	-0.44	0.16	-2.74	0.006

Note: p-values in **bold** survived Benjamini-Hochberg correction. ACC, anterior cingulate cortex; Amy, amygdala; DC, dorsal caudate; GP, globus pallidus; Ins, insula; mPFC, medial prefrontal cortex; NAcc, nucleus accumbens; Put, putamen; ROI, region of interest; SE, standard error.