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SUPPLEMENT ARTICLE

The Relationship Among Range Adaptation, Social Anhedonia, and Social Functioning: A Combined Magnetic Resonance Spectroscopy and Resting-State fMRI Study

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***Background and Hypothesis*: Social anhedonia is a core feature of schizotypy and correlates significantly with social functioning and range adaptation. Range adaptation refers to representing a stimulus value based on its relative position in the range of pre-experienced values. This study aimed to examine the resting-state neural correlates of range adaptation and its associations with social anhedonia and social functioning. *Study Design*: In study 1, 60 participants completed resting-state magnetic resonance spectroscopy and fMRI scans. Range adaptation was assessed by a valid effort-based decision-making paradigm. Self-reported questionnaires was used to measure social anhedonia and social functioning. Study 2 utilized 26 pairs of participants with high (HSoA) and low levels of social anhedonia (LSoA) to examine the group difference in range adaptation's neural correlates and its relationship with social anhedonia and social functioning. An independent sample of 40 pairs of HSoA and LSoA was used to verify the findings. *Study Results*: Study 1 showed that range adaptation correlated with excitation–inhibition balance (EIB) and ventral prefrontal cortex (vPFC) functional connectivity, which in turn correlating positively with social functioning. Range adaptation was specifically determined by the EIB via mediation of ventral-medial prefrontal cortex functional connectivities. Study 2 found HSoA and LSoA participants exhibiting comparable EIB and vPFC connectivities. However, EIB and vPFC connectivities were negatively correlated with social anhedonia and social functioning in HSoA participants. *Conclusions*: EIB and vPFC functional connectivity is putative neural correlates for range adaptation. Such neural correlates are associated with social anhedonia and social functioning.**

Key words: range adaptation/social anhedonia/social functioning/magnetic resonance spectroscopy/resting-state fMRI

Introduction

Schizotypy is a personality organization that reflects vulnerability to develop schizophrenia (SCZ).[1] Social anhedonia is a core feature of schizotypy[2–4] and a promising indicator of liability to SCZ-spectrum disorders.[5,6] Social anhedonia is defined as reduced ability to experience pleasure and reduced motivation to pursue goal-directed behavior in the social domains.[7] It strongly determines social functioning.[5,8–11] Individuals with HSoA experience more social isolation,[12,13] more dysfunction within the family,[8] and less social support.[3,8] Understanding the neurobiological mechanisms of social anhedonia is important in elucidating its relationship with conversion risk to psychosis, and may facilitate the development of possible preventive interventions.[14,15]

The extant literature has focused on the role of value representation upon social anhedonia and social functioning.[16–18] Range adaptation refers to the

representation of a stimulus value based on its relative position in the range of pre-experienced values.[19] Importantly, range adaptation enhances value discriminability. Impaired range adaptation could lead to altered value discrimination, reduced motivation, and eventually social dysfunctions.[20] Indeed, a previous behavioral study has demonstrated the association of range adaptation with social anhedonia/motivation in individuals with SCZ and HSoA.[21] Range adaptation also correlates with an individual's social choices and social perceptions,[22] implicating its potential association with social functioning. Thus, range adaptation could be potential neurobiological mechanisms of social anhedonia. Previous studies located several brain regions such as the anterior cingulate cortex (ACC) which were activated when individuals performed tasks requiring range adaptive behavior.[23] Studies also showed that these task-based range adaptation activation patterns can predict SCZ patients' negative symptoms.[24,25] However, the resting-state neural correlates of range adaptation remains unknown.

Range adaptation is a type of canonical neural computations which applies to various problems including sensory perception, social perception, and value representation.[26] It depends on the interaction between prior beliefs and the current sensory information signals, such that prior beliefs could guide the representation of signals and then normalize them within an embedded range.[27–30] The "background" neural correlates of range adaptation is believed to be active and constantly monitors the previous experience and the current information. Such neural correlates ought to combine prior belief with sensory information, and connect lower-level sensory regions with higher-level regions, and therefore represent a type of functional connectivity of the brain.[27,31,32] The ventral prefrontal cortex (vPFC) resting-state functional connectivity could be involved in range adaptation, for several reasons. First, vPFC has one of the highest resting metabolic base-rate[33] and is involved in integrating external with internal information.[34,35] Researchers have observed that patients with vPFC lesion showed impairments in decision-making, and postulated that vPFC may be involved in integrating previous experience via functional connectivity.[36–38] Additionally, vPFC is activated during adaptation process.[32,39] Range adaptation may also depend on the balance between excitatory (glutamate, Glu) and inhibitory (gamma-aminobutyric acid, GABA) neurotransmitters, termed as the excitation–inhibition balance (EIB).[40–43] Indeed, the resting-state EIB predicts range adaptation[44] and alterations of EIB can result in adaptation deficits.[45] However, no study to-date has directly assessed the role of EIB and vPFC connectivity in range adaptation. Moreover, these two components do not function separately. EIB strongly determines the resting-state functional connectivity,[43,46] especially the ones between vPFC and other regions.[47–50] Nevertheless, no study has clarified these hypotheses using empirical data.

The relationship between neural correlates of range adaptation with social anhedonia and social functioning remains unclear. Our earlier study examined range adaptation in HSoA individuals using behavioral measures, and found that, although HSoA group exhibited comparable range adaptation behavior to LSoA group, their range adaptive behavior were positively correlated with reduced willingness to expend effort for a suboptimal option.[21] Such association concurs with the notion that high OV adaptation may lead to better value discrimination.[24] It is plausible that the putative neural correlates of range adaptation, as measured by resting-state MRI technique, may be associated with social anhedonia and social functioning. Indeed, previous studies have found a negative correlation between the vPFC connectivity and negative symptoms in individuals with high schizotypy.[51] Moreover, GABA levels were correlated negatively with negative symptoms in high-risk populations.[52] However, to-date, no study has investigated the relationship between resting-state neural correlates of range adaptation with social anhedonia and social functioning in individuals with HSoA.

This study aimed to bridge this knowledge gap by combining resting-state fMRI with magnetic resonance spectroscopy (MRS) techniques. We hypothesized that range adaptation behavior would be predicted by EIB via mediation of vPFC functional connectivity. Moreover, we hypothesized that HSoA individuals would exhibit impaired neural correlates compared to LSoA participants. We also expected that range adaptation and its neural correlates would be positively correlated with reduced social anhedonia and social functioning in HSoA individuals. Figure 1 illustrates the flow of study design.

Study 1

Method

Participants. Study 1 recruited 60 healthy participants from universities in Shanghai, China. The exclusion criteria included a history of head injury, drug or alcohol abuse and a history or family history of psychiatric disorder. This study was approved by the Ethics Committees of the Institute of Psychology, the Chinese Academy of Sciences (H15031 and H21043).

Measures

Behavioral Task We used the effort-based pleasure experience task to measure participants' range adaptation behavior. This task has been detailed elsewhere.[21] In brief, participants were first asked to choose between a high-effort and a low-effort task based on the offered reward magnitude and probability. The reward value range was fixed for the low-effort task, while the high-effort

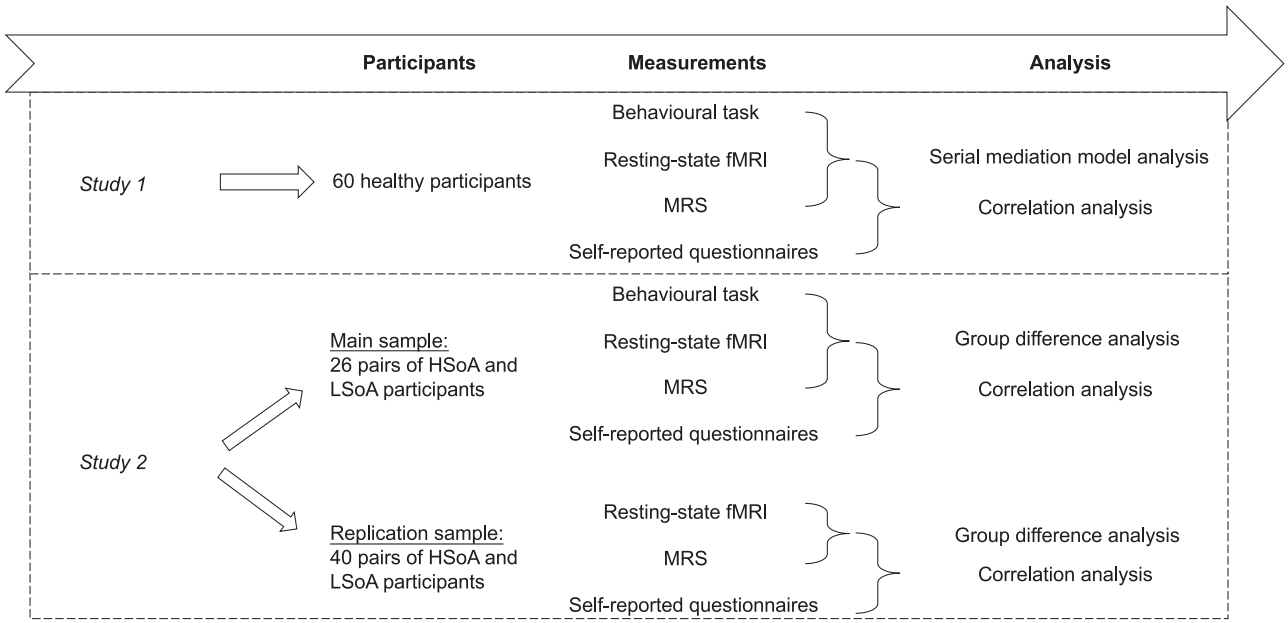


Fig. 1. The research framework of studies 1 and. MRS = Magnetic Resonance Spectroscopy; HSoA = High social anhedonia group; LSoA = Low social anhedonia group.

task has two value ranges (narrow: ¥1.5–¥2.4; wide: ¥5–¥8). During the presentation of reward value range in each task, participants were asked to make choice between high- vs low-effort tasks. After executing the chosen tasks, they were required to rate their anticipatory pleasure. Then, they were presented with the outcome value and then rated their consummatory pleasure on a 9-point Likert scale.

Other Measures The revised Chinese version of the Chapman Social Anhedonia Scale (RCSAS[53,54]) was used to measure the participants' level of social anhedonia. The Chinese version of the Social Functioning Scale (SFS)[55,56] was used, which contains 27 items to measure 6 domains of social functioning including living skills, family and friends, intimacy, interpersonal, school, and balance. Higher scores indicate better self-reported social functioning. The short form of the Chinese version of the Wechsler Adult Intelligence Scale[57] was used to estimate participants' IQ.

MR Image Acquisitions Data were acquired with a 3T Siemens-Trio Tim MRI scanner using a 32-channel head coil. A T1-weighted MPRAGE sequence was obtained from each participant (TR = 2530, TE = 2.34, flip angle = 7, matrix size = 256 × 256, slice thickness = 1.0 mm, voxel size = 1 mm × 1 mm × 1 mm). Functional images were obtained using a T2-weighted EPI sequence (TR = 2000, TE = 30, flip angle = 80, matrix size = 64 × 64, slice thickness = 4.5 mm, interleaved order, voxel size = 3.8 mm × 3.8 mm × 4.5 mm, Measurement = 220).[1] H point-resolved spectroscopy (PRESS) sequence was used to measure levels of Glu and other major metabolites (TR = 2000, Measurements = 32, Average = 4, Bandwidth = 2500 HZ, Resonance frequency = 123 MHZ). We used 32 TE-averaged spectra with the TE ranging from 35 to 221 ms with 6-ms increments. For GABA, MEGA-PRESS (Mescher–Garwood point-resolved spectroscopy) sequence was used (TR = 2000, TE = 68, Average = 128, Bandwidth = 2500HZ). The editing pulses were applied at 1.9 and 7.5 ppm. The Region of Interest (ROI) was located at the ACC with a 30 × 20 × 18 voxel. We chose the ACC as the target brain region because of its high signal-to-noise ratio[58] and it is enriched in glutamate and other neurotransmitters.[59] Moreover, the association of ACC with vmPFC may be involved in the integration process of previous and current information.[60,61] We took Glx (Glu + Gln) as the measure of Glu and GABA + (GABA + macromolecule) to indicate GABA levels.

Data Analysis

Behavioral Data Analysis

We estimated range adaptation to expected value (EV) and outcome value (OV) separately. For OV, range adaptation was calculated by taking the difference of the response slopes from the two reward ranges for the high-effort task as in our previous study.[21] We used three regressors (value range, OV, and value range × OV interaction) to predict the consummatory rating scores of each trial on a participant-by-participant basis. The regression coefficient for the interaction variable reflected

the slope difference between two ranges and was used as the OV adaptation index.

Given that the decision-making phase involved a range of values in each trial, we could not estimate range adaptation to EV in the same way as we estimated the OV adaptation. Thus, EV adaptation was operationalized as the interaction effect between participants' previous hold EV and the current EV on their choices for high-effort or low-effort tasks.[28–30,62] The interaction effect concurs with computation process of range adaptation which concerns the interaction between prior belief and current stimulus input.[28–30,62] We fit the binary choice data (high vs low effort) into generalized linear mixed-effects regression (GLMER) models using the package "lme4" in R.[63] In the GLMER model, the dependent variable would be the participant's chosen task in each trial (0 = low-effort task, 1 = high-effort task), while the independent variables were previous EV, current EV, and the interaction effect between them. A random slope for the interaction effect was included to indicate the strength of interaction effect. The random slope for each participant was regarded as the EV adaptation index. Details of the model can be found in Supplementary Materials.

MRS Data Analysis

MRS data were analyzed using the LCModel version 6.3-1R. Default processing steps were adopted. Quantification results with estimation errors (% standard deviation [SD]) below 25% were excluded from further analysis (2 participants excluded) (Supplementary Figure S1).[64–66] We scaled the metabolite ratios Glx and GABA + relative to tNAA (NAA + NAAG). Then, the Glx/GABA + ratio, indices of EIB, was computed by dividing the GABA+/tNAA from Glx/tNAA.[67] The Glx/GABA ratios were correlated with participants OV and EV adaptation as well as their social anhedonia and social functioning scores.

Resting-State fMRI Data Analysis. The functional images were preprocessed using the DPABI toolbox.[68] First 10 volumes were removed. Slice timing, realign and reorientation to ACPC were executed. Then, the processes of coregistration, segmentation, and normalization using the DARTEL toolbox were performed. We regressed out the nuisance covariates using the Friston 24-parameter model together with the global mean signal, the white-matter signal, and the cerebrospinal fluid signal. Images were smoothed using a Gaussian kernel of 4-mm FWHM. A band pass filter of 0.01–0.1 Hz was applied. To control for motion effects, we adopted Jenkinson's frame-wise displacement (FD) larger than 0.2 and 6 motion parameters larger than 2.5 mm/2.5° as the exclusion criterion. Four participants were excluded. Nine seeds belonging to vPFC (including 5 from vmPFC, 2 from ventral-later prefrontal cortex [vlPFC] and 2 from vPFC) were defined as ROIs based on the Dosenbach's 160 functional ROIs, since these functional ROIs were identified as part of the default mode network.[69]

We built the second-level model for range adaptation to EV and OV separately. For EV, the EV adaptation was included to identify its functional correlates. For OV, we included the OV adaptation and the Glx/GABA + ratios in the model, because of the significant correlation between the two variables. For both models, the FD Jenkinson parameter was entered as a covariate. The clusters were considered significant if they reached a threshold of $P < 0.001$ at uncorrected voxel level and $P < 0.05$ at family wise error corrected cluster level. We extracted the eigenvariate for significant clusters and then correlated them with participants' anhedonia and social functioning scores.

Mediation Analysis. We performed serial-mediation analysis using the SPSS PROCESS macro, version 4.0.[70] Model 6 was chosen because it assumed a causal chain linking the mediators, with a specified direction of causal flow.[71] The OV adaptation was the dependent variable, while the Glx/GABA + ratio was the independent variable. We searched for vPFC functional connectivity that were significantly correlated with OV adaptation and Glx/GABA + ratios. The identified two functional connectivities were defined as two possible mediators (Supplementary Figure S2). We used 5000 bootstrapping to provide bias-corrected 95% confidence intervals (CI) for the estimation of effects.

Results

Relationship Between Range Adaptation Behavior With EIB and Functional Connectivity

Table 1 summarizes the demographics of participants. We found a significant correlation between the OV adaptation and the Glx/GABA + ratio ($r_{57} = 0.31$, $P = .02$, Figure 2a). We found a significant negative correlation between vmPFC–left calcarine connectivity with OV adaptation, and a significant positive correlation between vlPFC–left calcarine connectivity with EV adaptation (Figure 2b). The vmPFC–inferior frontal gyrus (IFG) connectivity was correlated with the Glx/GABA + ratio (Figure 2b). Such association remained significant after controlling for gender and IQ effects (see Supplementary Results).

Mediation Analysis Results

Table 2 shows the mediation analysis results. The total effect of Glx/GABA + ratios on OV adaptation was significant ($t = 2.17$, $P = .04$). The bootstrapped results of all 3 mediation models revealed that the serial-mediation model (M3) differed significantly from zero effect (95% CI = −0.28, −0.03). This pathway partially accounted for the overall impact of Glx/GABA + ratios

Table 1. Demographic Summary for Participants in Studies 1 and 2

	Study 1	Study 2									
		Main sample					Replication sample				
	Participants (n = 60)	HSoA Group (n = 26)	LSoA Group (n = 26)	t/χ^2	df	P	HSoA Group (n = 40)	LSoA Group (n = 40)	t/χ^2	df	P
Age (year)	20.13 (1.93)	21.46 (2.35)	24.5 (20.14)	1.46	43.22	.15	20.78 (2.25)	20.98 (2.34)	−0.39	78	.70
Length of education (year)	14.08 (1.63)	14.17 (1.9)	13.6 (1.58)	1.14	47.00	.26	14.68 (1.76)	14.88 (1.96)	-0.48	78	.63
IQ Estimates	124.03 (9.56)	126.27 (7.23)	124.04 (6.81)	1.13	49	.26	123.49 (8.23)	121.79 (10.49)	0.78	74	.44
Sex (Male: Female)	7:53	8:18	7:19	0.09	1	.76	10:30	14:26	0.95	1	.33
RCSAS score	10.97 (6.69)	22.46 (2.92)	5.27 (2.93)	21.20	50.00	<.001	24.05 (3.52)	6.23 (2.25)	27.02	78	<.001

Note: RCSAS = Revised Chinese version of the Chapman Social Anhedonia Scale; HSoA = High social anhedonia group; LSoA = Low social anhedonia group.

on OV adaptation, since the direct effect remained significant (c = 0.42, P <.01). The M2 which originated from Glx/GABA + ratios, across vmPFC–calcarine functional connectivity to OV adaptation, was also significant (95% CI = 0.003, 0.23). We also tested 6 other alternative models but found nonsignificant results (see Supplementary results and Supplementary Table S1).

Relationship Between MultiModal Range Adaptation, Anhedonia Trait, and Social Functioning

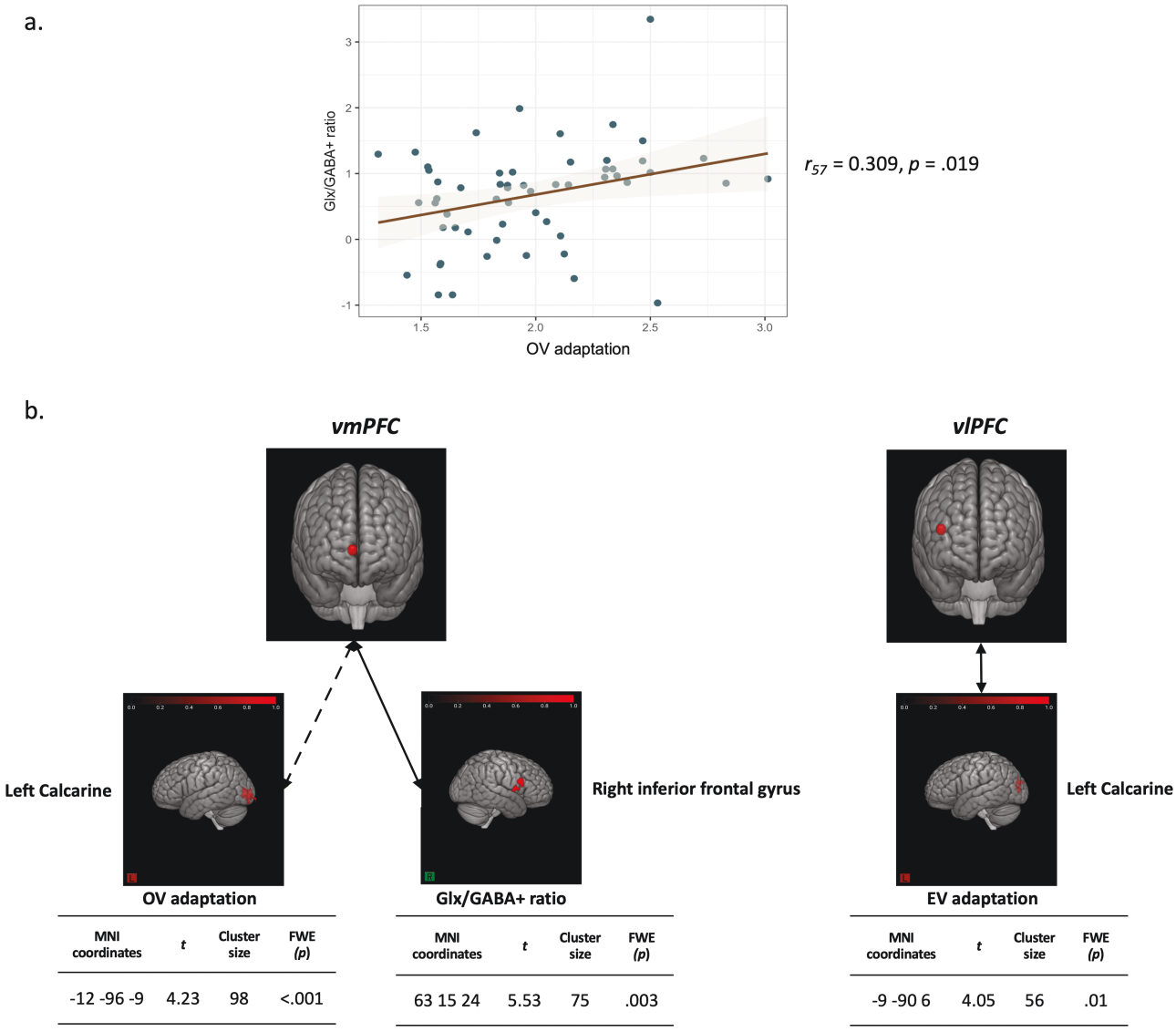
No significant correlation was found between EV or OV adaptation with anhedonia and social functioning. However, partial correlation analysis with OV adaptation as a covariate showed significant correlations between Glx/GABA + ratios and the SFS scores among the family–friends, school, and balance domain (r_{50} = 0.33, P = .02; r_{50} = 0.30, P = .01; r_{50} = 0.34, P = .01; see Supplementary Figure S3). The vmPFC–calcarine connectivity was also significantly correlated with SFS total scores (r_{50} =0.32, P = .02; see Supplementary Figure S3) after controlling for OV adaptation.

Discussion

Study 1 investigated the resting-state neural correlates for individual difference in range adaptation behavior and its relationship to social anhedonia and social functioning. The findings showed that range adaptation was related to EIB and vPFC functional connectivities. EIB specifically predicted range adaptation to OV by the serial-mediation effect of vmPFC functional connectivities. As expected, the EIB and vmPFC functional connectivities were both correlated with social functioning.

Our pioneer study examined the resting-state functional circuit correlates of individual difference in range adaptation. We found that vmPFC–calcarine connectivity was correlated with OV adaptation, while the vlPFC–calcarine connectivity was correlated with EV adaptation. The calcarine is strongly associated with the visual cortex.[72] This connectivity may implicate early range adaptation process which integrates prior beliefs (as represented by vmPFC/vlPFC) with current visual value input (as represented by calcarine). Interestingly, we found the OV adaptation correlated with vmPFC connectivity; whilst the EV adaptation correlated with vlPFC connectivity. It is plausible that vmPFC and vlPFC have different roles in value representation processing. At the neurochemical level, the brain's EIB was significantly correlated with OV adaptation. Recent studies have shown that EIB ties with the range adaptation related phenomena like context-integration and value discriminability ability.[45,73] Our findings provide direct evidence for the dependency of range adaptation to EIB.[26]

Evidence suggested our speculation that EIB influences range adaptation behavior via functional connectivities. Indeed, we revealed a distinct pathway from EIB to vmPFC–IFG and vmPFC–calcarine connectivity in determining OV adaptation. A previous study proposed that IFG's connection with vmPFC could suggest its role as an information filter with a specific threshold: assessing whether there is sufficient information for vmPFC to conclude the meaning of that stimulus.[74] The vmPFC receives multiple inputs from various accessory regions to establish that meaning.[75] Taken together, it is possible that the visual information of the current value may be represented by calcarine and then pass on to vmPFC and IFG. The IFG would



MNI coordinates	t	Cluster size	FWE (p)
-12 -96 -9	4.23	98	<.001

MNI coordinates	t	Cluster size	FWE (p)
63 15 24	5.53	75	.003

MNI coordinates	t	Cluster size	FWE (p)
-9 -90 6	4.05	56	.01

Fig. 2. The relationships between the excitation–inhibition balance, functional connectivity, and behavioral range adaptation. a. Correlations between Glx/GABA + ratios and range adaptation to OV. b. Three significant functional connectivities correlating with range adaptation. The vmPFC–Calcarine connectivity was correlated negatively with range adaptation to OV, the vmPFC–IFG connectivity correlated positively with Glx/GABA + ratios, and the vlPFC–calcarine connectivity correlated positively with range adaptation to EV. b.FC = functional connectivity; OV = outcome value; EV = expected value; vmPFC = ventral-medial prefrontal cortex; vlPFC = ventral-lateral prefrontal cortex; IFG = inferior frontal gyrus; Dashedline indicates a negative correlation; Straight line indicates a positive correlation.

evaluate the input from calcarine and decide whether it is enough for vmPFC to infer its meaning. The threshold of such filter could deviate toward either ends (extremely high or extremely low), and thus would depend on EIB.[74] Lastly, the vmPFC may integrate the current visual input with the prior belief regarding value range and establish the meaning of that value. Such postulation also aligns with the indication made by Friston that higher levels of a cortical hierarchy would provide contextual guidance to lower levels of processing.[76] Range adaptation may result from these multiple levels of neural functions.

Study 2

Methods

Participant . Study 2 recruited two independent samples of participants with HSoA and LSoA. The main sample comprised 26 pairs of participants with HSoA and LSoA, whereas the replication sample comprised 40 pairs of participants with HSoA and LSoA (see Figure 1). The main sample was recruited from a pool of 1270 college students; and the replication sample from another pool of 1127 college students. Participants were

Table 2. Results of the Serial-Mediation Model

Effect	Model Paths	B	SE	*t*	*P*	95% CI	
						Lower	Upper
Total effect	Glx/GABA + ratios --> OV adaptation	0.569	0.263	2.166	.035		
	Glx/GABA + ratios --> OV adaptation	0.865	0.267	3.243	.002		
Direct effect	Glx/GABA + ratios --> vmPFC–IFG FC	0.254	0.061	4.143	<.001		
	Glx/GABA + ratios --> vmPFC–calcarine FC	−0.152	0.103	−1.480	.145		
	vmPFC–IFG FC --> vmPFC–calcarine FC	0.857	0.203	4.231	<.001		
	vmPFC–IFG FC --> OV adaptation	-0.901	0.601	−1.498	.141		
	vmPFC–calcarine FC --> OV adaptation	−1.023	0360	−2.841	.007		
Indirect effect	M1. Glx/GABA + ratios --> vmPFC–IFG FC --> OV adaptation	−0.117	0.088			−0.300	0.050
	M2. Glx/GABA + ratios --> vmPFC–calcarine FC --> OV adaptation	0.079	0.057			0.003	0.227
	M3. Glx/GABA + ratios --> vmPFC–IFG FC --> vmPFC–calcarine FC --> OV adaptation	−0.114	0.066			−0.281	−0.031

Note. B = unstandardized coefficients; M1 = Model 1; M2 = Model 2; M3 = Model 3. IFG = inferior frontal gyrus; FC = functional connectivity; vmPFC = ventral-medial prefrontal cortex; OV = outcome value.

defined as having HSoA if they scored >= 20 (1.5 SD above the mean score of RCSAS), and as having LSoA if they scored <= 11 (mean score of RCSAS). The cutoff score was defined based on the RCSAS scores in a pool of 2241 college students. The exclusion criteria were the same as study 1. The study was approved by the Ethics Committees of the Institute of Psychology, the Chinese Academy of Sciences (H15031 and H21043).

Measures

Behavioral Task We used the Effort-Expenditure for Reward Task-adaptive version in the main sample (Supplementary Figure S4). This task was modified based on the Effort-Expenditure for Reward Task[77] and was specifically designed to unify both OV and EV adaptation calculation. It comprises of 2 phases (decision-making and consummatory rating). Participants were required to choose between low-effort and high-effort tasks. The reward magnitude of low-effort task was fixed to ¥5, while the reward magnitude of high-effort task was selected from 2 ranges (narrow: ¥5.4–¥6.4; wide: ¥5.4–¥9.4). In each trial, a reward value was randomly selected from the reward range designated in the high-effort task. After making choice, participants executed the task and rated their consummatory pleasure upon receipt of the outcome.

In study 2, we also administered the same set of measures as we used in study 1 to all participants. In addition, we administered the Motivation and Pleasure Scale–Self-Report (MAP-SR[78,79]) to measure participants' level of anhedonia and amotivation.

MR Image Acquisitions Detailed scanning information are provided in Supplementary Materials. In the replication sample, 4 HSoA participants and 1 LSoA participants were unable to complete the MRS scans, whilst 16 HSoA participants and 10 LSoA participants were unable to complete the resting-state MRI scan. The valid replication sample consisted of 36 HSoA participants and 39 LSoA participants with MRS data, and 24 HSoA participants and 30 LSoA participants with resting-state fMRI data.

Data Analysis

Behavioral Data Analysis for the Main Sample

OV adaptation was estimated in the same way as that in study 1. For EV, we quantified the degree of range adaptation by taking the difference of the response slopes from the two reward ranges. The dependent variable of the regression model is the proportion of high-effort task chosen by the participant. The value range, current EV, and the interaction effect between them were entered as predictors. We utilized the regression coefficient of the interaction effect variable as the EV adaptation index.

MRS Data Analysis

The same analysis techniques were used as that in study 1. For both the main and replication sample, we excluded 1 HSoA participant because of the quantification estimation errors > 25%. We examined the group difference in EIB, and then conducted the correlation of EIB with anhedonia and social functioning in HSoA and LSoA group separately. The analysis was first applied to the main sample, and then validated in the replication sample.

Resting-State fMRI Data Analysis

The same analysis procedures as study 1 were applied. However, for the main sample, no slice timing was

performed given the multiband scanning procedure we used. In both two samples, 1 LSoA participant was excluded due to excess motion movements (exceed 2.5 SD of group mean). Based on the group results in study 1, we saved the 3 significant clusters as masks. Then, we conducted an independent 2-sample *t* test while applying the masks to test the group difference in these specific functional connectivities. The functional connectivities were correlated with anhedonia and social functioning within HSoA and LSoA group, respectively.

Results

Demographic Information

The HSoA and the LSoA groups did not differ in gender, age, length of education, and estimated IQ (P >.05; see Table 1). HSoA participants showed more motivation and pleasure deficits than LSoA participants, except in MAP-SR recreation subscale. HSoA participants also showed social dysfunction mainly in social interaction related domains (interpersonal, family–friends, and intimacy) in both main and replication samples (P <=.01). Therefore, we performed subsequent analysis to examine the relationship between range adaptation with anhedonia and social functioning scores that showed significant group differences.

Group Difference in Multimodal Range Adaptation

We did not find significant group differences in the range adaptation behavior, the Glx/GABA+, and resting-state functional connectivities in both the main and replication sample.

Relationship Between MultiModal Range Adaptation, Anhedonia Trait, and Social Functioning

We found similar positive correlations between neural correlates of range adaptation with anhedonia trait and social functioning within the HSoA group just like study 1. The Glx/GABA + ratio was correlated with the RCSAS scores($r_{25} = -0.47$, $P = .02$),the MAP-SR total scores ($r_{23} = 0.56$, $P = .005$) in the HSoA group from the main sample. The Glx/GABA + ratio was correlated with the SFS interpersonal scores($r_{31} = 0.49$, $P = .005$) in the replication sample. However, we also found negative correlations between neural correlates of range adaptation with social functioning only within the HSoA but not the LSoA group. The vmPFC–IFG functional connectivity was negatively correlated with the SFS interpersonal domain scores ($r_{23} = -0.62$, $P = .002$, Figure 3a) in the main sample. Similarly, in the replication sample, the Glx/GABA + ratio was negatively correlated with SFS family–friends domain scores ($r_{31} = -0.40$, $P = .03$, Figure 3b). The vmPFC–calcarine connectivity was correlated with SFS family–friends domain scores ($r_{23} = 0.42$, $P = .05$).

Discussion

This multimodal study investigated the difference between HSoA and LSoA participants in neural correlates of range adaptation and its relationship to social anhedonia and social functioning. Contrary to our hypothesis, HSoA participants showed comparable neural correlates of range adaptation with LSoA participants. However, we found significant associations between range adaptation's neural correlates with social anhedonia and social functioning in HSoA participants using two independent datasets.

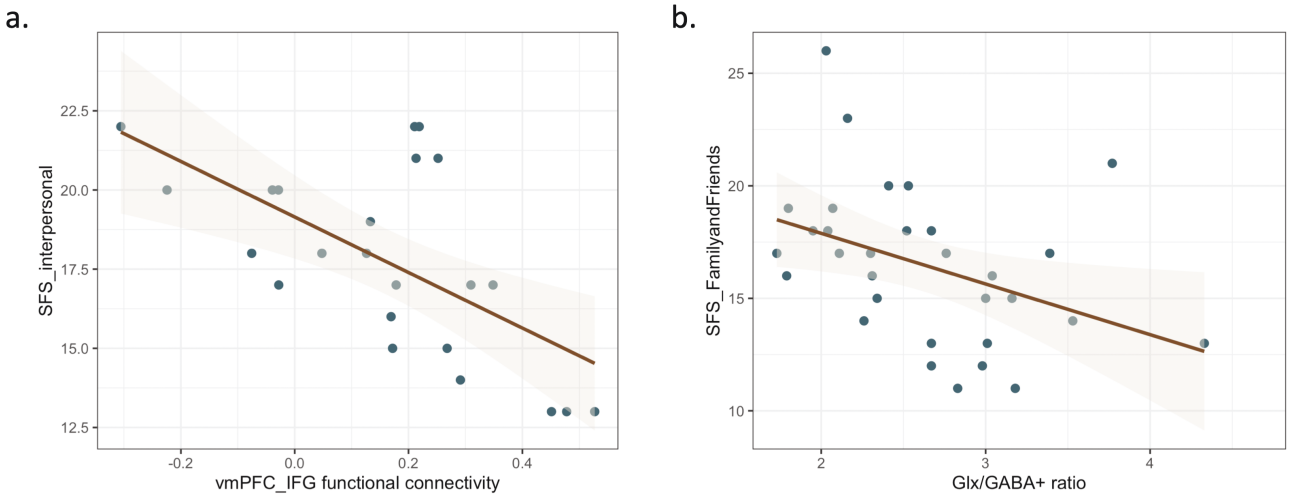


Fig. 3. Correlations between range adaptation's neural basis with social anhedonia and social functioning in high social anhedonia group. a = Correlation between vmPFC–IFG functional connectivity and SFS interpersonal domain scores in the high social anhedonia group from the main sample; b = Correlation between Glx/GABA + ratios and SFS family and friends domain scores in the high social anhedonia group from the replication sample. SFS = Social functioning scale; vmPFC = ventral-medial prefrontal cortex; IFG = inferior frontal gyrus.

Previous studies have observed aberrant range adaptation behavior and task-based brain activity in patients with first-episode and chronic SCZ.[21,24,25,80] By contrast, no such evidence have been found in HSoA individuals.[21] Nonetheless, using task-based fMRI, a previous study reported aberrant range adaptation related activation pattern among individuals with high schizotypy.[25] To our knowledge, this study is the first to examine the resting-state neural correlates of range adaptation behavior in HSoA and LSoA individuals. We did not find any significant group difference between the HSoA and the LSoA groups in EIB and vPFC connectivity. A meta-analysis of high-risk individuals showed that only half of the existing studies reported abnormal Glu concentrations, while another half of the studies reported negative results.[81] Our findings concur with the finding of comparable Glu levels in HSoA group.[82] One previous study has shown reduced vPFC connectivity in schizotypy,[83] while other studies found no difference between people with HSoA or schizotypy and controls.[84–86] On the other hand, aberrant EIB and vPFC connectivity in SCZ patients have been well-supported by several meta-analytic studies.[87–90] Impaired resting-state activity may lead to broad range adaptation impairments. In fact, SCZ patients showed extensive sensory-related range adaptive deficits, such as difficulty in distinguishing between objects and background.[91,92] In contrast, schizotypy individuals were found to exhibit a relatively intact range adaptation in perception.[93] Consistent with these prior evidence, our participants with subclinical HSoA may not have noticeable changes in resting-state neural correlates of range adaptation.

Taken together, our findings showed range adaptation was positively correlated with reduced social anhedonia, consistent with the notion that high OV adaptation may lead to better value discrimination and therefore milder anhedonia symptom.[21,24,25] However, our findings suggested that increased connectivity/EIB (i.e., resting-state neural correlate of range adaptation) is associated with poorer social functioning (such as social support from family and friends), and more range adaptation is associated with fewer social interactions with family and friends. The negative direction of such correlations appear to be counter-intuitive. However, it is plausible that range adaptation may be a compensatory mechanism. For instance, people having better range adaptation ability may adapt better to the environment and therefore rely less on social support from other people. By contrast, people having little range adaptation ability may adapt poorly to the environment and therefore rely more on social support.

In summary, it is plausible that altered range adaptation only emerges after psychosis onset, but the association of range adaptation with social anhedonia and social functioning is observable before onset of psychosis in subclinical individuals.

General Discussion

Overall, we identified the resting-state neural correlates of range adaptation and revealed its relationship with anhedonia and social functioning. The association of neural correlates of range adaptation with social functioning was found in the nonclinical sample of study 1, and the 2 subclinical samples of HSoA in study 2.

Together, studies 1 and 2 are complementary, and both support the relationships of range adaptation with anhedonia and motivation symptoms in SCZ patients and HSoA individuals.[21,24,25] In study 1, we found EIB and vmPFC connectivity correlated with social functioning in the nonclinical sample. Moreover, we found negative associations between EIB with social support from family and friends only within the HSoA group. These findings are consistent with the EIB hypothesis that aberrant EIB could result in impaired social functioning.[94–96] Our findings provide further support for the association between EIB and social deficits as well as the E/I imbalance hypothesis of SCZ.[97]

Our studies have several limitations. First, we only recruited college students, who do not reflect the full functional range of the general population, thus may undermine the generalizability of our findings. Second, social anhedonia is a core feature of schizotypy, but we did not utilize commonly used scales to measure schizotypal features, and therefore could not control for the effects of positive schizotypy on range adaptation and social functioning. Future studies should ascertain how different dimensions of schizotypy would affect one's range adaptation ability. Third, the association of range adaptation with neural measures was only limited to resting-state data. It remains unclear whether the pathway as revealed by serial-mediation model is involved during range adaptation process. A task-based fMRI design which directly taps into information integration and adaptation processes will be useful. Finally, we adopted a cross-sectional design. Future longitudinal studies should clarify the direction of the identified correlation in this study.

To conclude, our findings suggested that EIB and vPFC functional connectivity are putative resting-state neural correlates of range adaptation behavior. EIB and vPFC functional connectivities have a distinct role in social anhedonia and social functioning for HSoA individuals compared with LSoA individuals. Multimodal range adaptation can be a possible intervention target for improving the social anhedonia and social functioning in patients with SCZ-spectrum disorders and may play a role in preventing psychosis conversion.

Supplementary Material

Supplementary material is available at https://academic.oup.com/schizophreniabulletin/.

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Conflicts of Interest

The authors have declared that there are no conflicts of interest in relation to the subject of this study.

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