To fill the gap of empirical knowledge on neural mechanisms underlying cognitive dissonance, we used a modified free-choice paradigm and scanned healthy young Chinese adults as they rated a set of CDs both before and after making a series of choices between these CDs. During the choice, the CDs were paired in such a way that the two CDs in each pair were equally attractive, as previous work shows that dissonance arises only when choices are difficult (Brehm, 1956; Sharot et al., 2009; Jarcho et al., in press). Moreover, in order to increase choice justification during the post-choice sessions, subjects were reminded which choice they had made earlier. We had two primary aims.

First, we aimed to investigate the brain regions recruited when subjects justified their choices. Previous research has found that choice justification is eliminated when one's sense of the self is affirmed after making a difficult choice (Hoshino-Browne et al., 2005; Steele, 1988). This supports the proposal that individuals justify their choice in order to eliminate a threat to the self. On the basis of this literature, we predicted that self-related brain areas such as the ventral MPFC (Kelley et al., 2002) and the dorsal/ventral lateral prefrontal cortex (Liberman, 2010) would be engaged in post-decisional choice justification. Q1 Furthermore, because the public sense of the self involves taking the perspectives of others (Imada and Kitayama, 2010; Kitayama et al., 2004), we anticipated that brain areas implicated in mind reading such as temporal–parietal junction (TPJ, e.g., Saxe and Kanwisher, 2003) and dorsal MPFC (e.g., Gallagher et al., 2000) might also be related to choice justification. In addition, since individuals justify their choices by inhibiting choice-inconsistent information while augmenting choice-consistent information (Jarcho et al., in press), we predicted that the brain areas implicated in regulation, such as the dorsal MPFC (Venkatraman et al., 2010), the dorsal LPFC (Ochsner and Gross, 2008), and the inferior frontal gyrus (Jarcho et al., in press), would also be involved.

Second, we aimed to examine whether, similar to the Sharot et al. (2009) study, choice justification might be tracked by neural activity that is related to subjectively experienced preferences. We expected that neural activities reflecting subjects' preferences, such as caudate (Sharot et al., 2009), ventral MPFC (McClure et al., 2004), and/or PCC (Kawabata and Zeki, 2008), would be altered by choice justification. In addition, given cultural differences in cognitive dissonance (Hoshino-Browne et al., 2005; Imada and Kitayama, 2010) and considerable variation within cultures in the extent to which they endorse their cultural norms, we assessed the relationship between change in the neural signatures related to subjects' preference and individual differences in independent self-construals (i.e., the view the self as an autonomous entity separate from others) and interdependent self-construals (i.e., the view of the self as interconnected with others as well as the social contexts; Markus and Kitayama, 1991).

Materials and methods

Subjects

Sixteen undergraduate and graduate students from Peking University, China (5 males, 11 females; 19–26 years of age, mean 22.3 ± 1.91, values are given as mean ± SD throughout), participated in this study as paid volunteers. All subjects were right-handed, had normal or corrected-to-normal vision, and had no neurological or psychiatric history. Informed consent was obtained prior to scanning. This study was approved by a local ethics committee.

Stimuli

Stimuli consisted of 60 popular music CDs, including 48 Chinese CDs and 12 European/American CDs. The artists of the CDs were known to college students. The cover of each CD was scanned and saved as a .jpg file.

Pre-scanning procedure

Subjects were asked to rank 60 CDs according to their degree of liking by categorizing the CDs into10 boxes with 6 CDs in each box. The ten boxes were marked with numbers from 1 to 10 (1 = slightly like the CD, 10 = extremely like the CD).

fMRI Scanning sessions and "free-choice" session

After the pre-scanning CD categorization task, subjects were scanned to get anatomical structures. This was followed by eight functional scanning sessions and intervened by a "free-choice" session.

Pre-choice session

The pre-choice session consisted of four event-related functional scanning sessions. On each trial, subjects were presented with a picture of a CD cover. They were then asked to either indicate "How much do you like the CD?" (preference judgment task) or "How new is the CD?" (recency judgment task) on a 4-point scale (1 = slightly like/slightly new; 2 = somewhat like/somewhat new; 3 = like/new; 4 = extremely like/extremely new). Subjects responded to each stimulus by pressing one of the four buttons as accurately and quickly as possible using the index and middle fingers of their left and right hands. Thirty preference judgments and 15 recency judgments were conducted in a random order in each scanning session.

Each trial started with the presentation of an instruction for 1000 ms, which defined the task (i.e., preference or recency judgments). Then the cover of a CD was presented for 3000 ms followed by an inter-stimulus interval that varied randomly among 1500, 2000, 2500 ms. Sixty CDs were used for the preference judgment task and, of those, 30 CDs were randomly selected for the recency judgment task. In order to collect enough data, these tasks consisted of two functional scanning sessions and were repeated once in an additional two scanning sessions.

Free choice

After the pre-choice session, subjects engaged in 30 free-choice trials. On each trial, two CD covers were presented on either side of the screen (i.e., right or left). Each CD was shown only once. Subjects were instructed to indicate which CD they wanted more by pressing one of the two buttons using the left or the right index finger. Prior to this, subjects were informed that one CD would be randomly selected from the CDs they chose and given to them as a token of appreciation for their participation at the end of the study. CDs pairs were determined by each subject's ranking of the CDs during the pre-scanning categorization task. That is, each pair was randomly selected from one of the 10 boxes so that each pair was equal in liking. Choices made during the free-choice session were used to classify the 60 CDs into the chosen and rejected items in the post-choice sessions.

Post-choice session

The post-choice session also consisted of four functional scanning sessions. All aspects of the post-choice session were identical to those in the pre-choice session except that each CD was shown with a color frame (i.e., red = chosen; green = rejected; gray = used in the recency judgment task) to indicate the status of the CD.

Post-scanning procedure

After the scanning procedure, each subject was asked to rate his/her independent/interdependent self-construal (Singelis, 1994) on a 7-point Likert-type scale (1 = strongly disagree to 7 = strongly agree). Q2

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fMRI Data acquisition

Scanning was performed at Peking University First Hospital on a GE 3-T scanner with a standard head coil. Thirty-two transverse slices of functional images covering the whole brain were acquired using a gradient-echo echo-planar pulse sequence ($64 \times 64 \times 32$ matrix with a spatial resolution of $3.75 \times 3.75 \times 4$ mm, repetition time = 2000 ms, echo time = 30 ms, FOV = 24×24 cm, flip angle = 90°). Anatomical images were obtained using a 3D FSPGR T1 sequence ($256 \times 256 \times 128$ matrix with a spatial resolution of $0.938 \times 0.938 \times 1.4$ mm, TR = 7.4 ms, TI = 450 ms, TE = 3.0 ms, flip angle = 20°). Subjects' heads were immobilized during the scanning sessions using pieces of foam. Stimuli were presented via a mirror mounted on the head coil.

Data analysis

The mean rating scores of the preference judgments were calculated during the pre-choice and post-choice sessions were calculated for chosen and rejected CDs. The results were then submitted to a 2 (Choice: chosen/rejected) × 2 (Session: pre-choice/post-choice) repeated measures analysis of variances (ANOVA).

SPM2 (Wellcome Department of Cognitive Neurology, London, UK) was used for the imaging data analysis. The time-series for the voxels within each slice were realigned temporally to the acquisition of the middle slice. The functional images were realigned to the first scan to correct for the head movement between scans, and the anatomical image was co-registered with the mean functional image produced during the process of realignment. All images were normalized to a $2 \times 2 \times 2$ mm Montreal Neurological Institute (MNI) template using bilinear interpolation. Functional images were spatially smoothed using a Gaussian filter with a full-width at half maximum (FWHM) parameter set to 8 mm.

We first conducted whole-brain exploratory analysis. The image data were modeled using a canonical hemodynamic response function (HRF) and a general linear model (GLM). The time derivatives and the head motion parameters were included to account for extra variance of onset and residual movements (the three rigid-body translations and rotations determined from the realignment stage). All data were globally normalized with proportional scaling of the image means. High-pass filtering was used with a cutoff of 128 s. Effects at each voxel were estimated, and regionally specific effects were compared using linear contrasts.

There were six types of trials in our experiment. There were four types of preference judgment trials, each classified according to the subjects' choices during the "free-choice" session: (1) preference judgments for chosen CDs during pre-choice session, (2) preference judgments for rejected CDs during pre-choice session, (3) preference judgments for chosen CDs during post-choice session, and (4) preference judgments for rejected CDs during post-choice session. There were also two types of recency judgment trials: (1) recency judgment during pre-choice session and (2) recency judgment during post-choice session. We contrasted and reversely contrasted blood oxygenation level-dependent (BOLD) signal of the preference judgment trials for the chosen CDs with those for the rejected CDs, and BOLD signal of preference judgment trials of chosen/rejected CDs with recency judgment trials, during both pre-choice and post-choice sessions. Areas of significant activation were identified using threshold of $p < 0.001$ (uncorrected) and a spatial extent threshold of $k = 100$.

Conjunction analysis implemented in SPM2 (ANOVA with inclusive masking) was used to determine areas of activation common to preference judgment of chosen CDs during pre-choice and post-choice sessions, areas of activation common to preference judgment of rejected CDs during pre-choice and post-choice sessions, areas of activation common to preference judgment of chosen and rejected CDs in pre-choice session, and areas of activation common to preference judgment of chosen and rejected CDs in the post-choice session. All inclusive masking analyses used an uncorrected p value of 0.05 for their masks.

To examine brain areas linked with attitude change during choice justification, we first conducted parametric modulation analysis using an independent GLM model for post-choice session that used change in the preference rating score for each trial as the regressor. Then we constructed a simple regression analysis. Parametric maps contrasting preference judgment of chosen CDs vs. that of rejected CDs during post-choice session were taken as the dependent variables for each subject, and the corresponding attitude change scores (the absolute amount of preference increase for chosen items plus the absolute amount of preference decrease for rejected items) served as covariates. The resulting maps were identified using a threshold of $p < 0.001$ (uncorrected) and a spatial extent threshold of $k = 100$.

To assess the relationship between change of neural activities (post-choice session minus pre-choice session) in the brain areas that are likely to reflect subjects' preferences (i.e., ventral mPFC, PCC, and caudate) and individual differences in attitude change and self-construal, we also conducted another parametric modulation analysis for pre-choice and post-choice session respectively using participants' rating score on each preference judgment trial as the regressor. Conjunction analysis (ANOVA with inclusive masking) was used to identify the areas of activation generally related to subject's preference. A relatively stringent threshold, cluster level $p < 0.05$ (corrected), was used because this analysis included 120 trials. We then calculated correlations between change of activities in the brain areas reflecting subjects' preferences and their attitude change. A similar analysis was conducted on the brain areas that were shown to be linked to subjects' preference in previous studies, the vMPFC ($x = 8$/

$p<0.001$), suggesting that the preference for chosen over rejected CDs was larger during the post-choice than pre-choice sessions. Post hoc analysis confirmed that the rating scores for chosen CDs were higher in the post-choice than pre-choice sessions ($t(15)=2.93$, $p<0.05$), whereas rating scores for rejected CDs did not differ significantly between the post-choice than pre-choice sessions ($t(15)=2.03$, $p=0.06$).

fMRI Results

To identify neural activities associated with post-choice attitude change, we calculated the change in preference rating by subtracting the rating score of each CD in the pre-choice sessions from the rating score of the same CD in the post-choice sessions. We then conducted parametric modulation analysis during post-choice session using the change in preference rating as a regressor. We found that attitude change was associated with activations in the ventral MPFC ($x=-12/y=54/z=0$, $Z=3.53$; cluster size = 165 voxel), right temporal–parietal junction (TPJ) ($x=48/y=-60/z=12$, $Z=3.02$; cluster size = 205 voxel), anterior insula ($x=42/y=-2/z=6$, $Z=3.05$; cluster size = 66 voxel), and bilateral cerebellum ($x=28/y=-64/z=-30$, $Z=3.42$; cluster size = 131 voxel; $x=-38/y=-66/z=-30$, $Z=3.12$; cluster size = 121 voxel) (Fig. 2a).

We also conducted a regression analysis using the individual attitude change score (increase of preference for the chosen items minus decrease of preference for the rejected items) as the regressor. We found that activities in left LPFC($x=-24/y=56/z=8$, $Z=3.73$; cluster size = 133 voxel), dorsal MPFC ($x=-4/y=14/z=54$, $Z=3.23$; cluster size = 111 voxel), and right precentral cortex ($x=54/y=-8/z=44$, $Z=3.09$; cluster size = 212 voxel) positively correlated with subjects' attitude change scores (Fig. 2b).

Similar to the previous research (Sharot et al., 2009), we assessed whether neural activities can predict individual differences in preference. To do this, we identified preference related neural activity by conducting parametric modulation analysis for pre-choice and post-choice sessions, respectively, using participants' rating score of each preference judgment trial as the covariate. We found significant positive correlations between BOLD signal and subjects' preference in the PCC ($x=-2/y=-56/z=22$, $Z=3.95$; cluster size = 1240 voxel) and right cerebellum ($x=-46/y=-26/z=48$, $Z=5.50$; cluster size = 1137 voxel) in pre-choice sessions. The same analysis performed on the post-choice sessions showed significant positive correlations between BOLD signal and subjects' preference in the precuneus/PCC ($x=24/y=-54/z=-34$, $Z=4.97$; cluster size = 2568 voxel) and ventral MPFC ($x=2/y=64/z=-2$, $Z=4.07$; cluster size = 919 voxel). The conjunction analysis of the data in pre-choice and post-choice sessions identified the PCC ($x=4/y=-62/z=12$, $Z=4.48$; cluster size = 1039 voxel) as the common brain areas related to subject's preference.

We also examined whether changes in PCC activity between post-choice and pre-choice sessions could predict subjects' attitude change. We also carried out comparable analyses to see if changes in neural activities might be related to self-construals. These analyses, however, failed to show any significant correlations between changes in brain activities and attitude change. We then conducted similar correlation analysis on two additional ROIs that have been associated with behavioral preference (ventral MPFC, $x=8/y=56/z=0$, McClure et al., 2004) and hedonic rating scores (caudate, $x=10/y=22/z=0$, Sharot et al., 2009) in previous studies. Interestingly, we found that changes in the ventral MPFC activity between post-choice and pre-choice sessions were negatively correlated with interdependent self-construal ($r=-0.569$, $p=0.027$ for 15 subjects without an outlier subject; $r=-0.480$, $p=0.060$ for all 16 subjects, Fig. 3).

To assess which brain regions were involved in subjects' preference for the chosen and rejected CDs, we contrasted the neural activity linked to preference judgment for chosen CDs versus rejected CDs. These revealed activations in the PCC/precuneus and middle cingualte cortex (Table 1: Pre-choice). The reverse contrast showed activations in the right postcentral/paracentral cortex, left paracentral cortex/precuneus, left superior temporal cortex, and right insula. Similar results were found for the same contrasts during post-choice session (Table 1: Post-choice). The conjunction analysis for the pre-choice and post-choice sessions identified that the PCC/precuneus

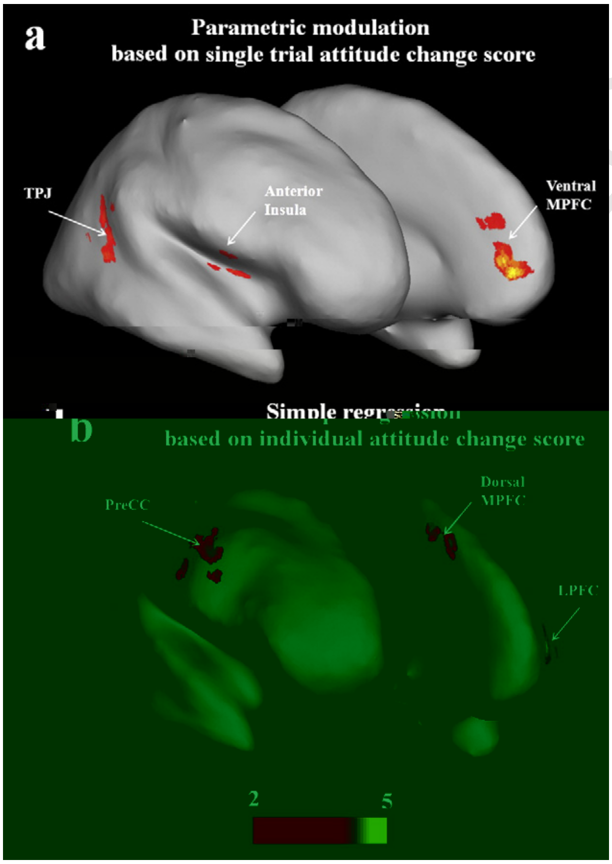

Fig. 2. (a) Parametric analysis revealed neural activities related to subjects' attitude change. (b) Simple regression analysis revealed neural activities positively correlated with individual attitude change score. Ventral MPFC = ventral medial prefrontal cortex; TPJ = temporal–parietal junction; dorsal LPFC = dorsal lateral prefrontal cortex; dorsal MPFC = dorsal medial prefrontal cortex; PreCC = precentral cortex.

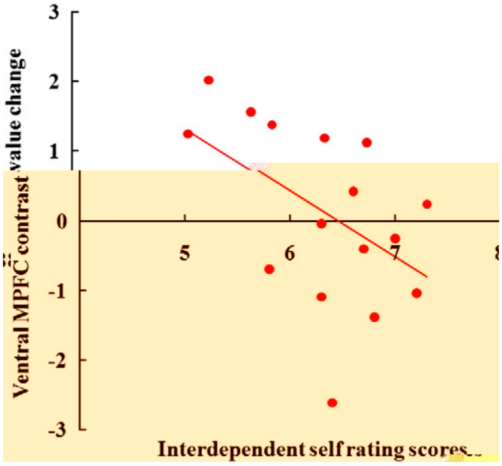

Fig. 3. Correlation between ventral MPFC activation level (contrast values) change and

activity was linked to preference judgment for the chosen CDs, whereas the right insula and postcentral cortex were associated with preference judgment for the rejected CDs (Fig. 4a; Table 1: Conjunction). The neural activity linked to preference judgments was assessed by contrasting preference and recency judgment tasks. These revealed activations in the precuneus as well as the right PCC in the pre-choice session and in the ventral MPFC in the post-choice session (Fig. 4b; Table 1: Conjunction).

Discussion

Neural mechanisms of choice justification

Our behavioral measurements showed, consistent with the hypothesis that choice justification may require regulation processes that are mediated by the dorsal MPFC and left LPFC (Venkatraman et al., 2010; Ochsner and Gross, 2008). However, the activations in the dorsal MPFC, left LPFC, and right precentral cortex did not overlap with regions that correlated with the trial-by-trial attitude change score. It is possible that there is a relatively stable individual difference in the degree to which the self-regulatory processes are engaged across all trials throughout the entire experimental session. The overall degree of choice justification may be expected to be greater for those who engage self-regulatory processes to justify their choices than those who do not. At the same time, however, across the 30 choices, people may engage their self-appraisals (vMPFC) mediated by perspective tasking (TPJ) to varying extent. They may do so more on some trials than on some other trials. This may be expected to result in a trial-by-trial variation in choice justification. The two processes (i.e., self-regulation that varies across individuals and self-referential processing that varies within each individual) are distinct and, yet, we suspect within the specific experimental setting of the present study that they result in the same behavioral outcome of choice justification.

During the post-choice rating session of the present study, subjects were given an explicit marker of whether they had chosen or rejected each CD. This procedure might have resulted in top–down modulation of preference related brain response (de Araujo et al., 2005; Plassmann et al., 2008; Kirk et al., 2009). However, the brain areas that were associated with attitude changes in the present study included left LPFC (−24, 56, 8), dorsal MPFC (−4, 14, 54), and right precentral cortex (54, −8, 44). These brain regions are different from those involved in the top–down modulation of preference responses. For example, Kirk et al. (2009) found that neural activity in the right medial orbitofrontal cortex (12, 48, −20) and the ventral medial prefrontal cortex (−10, 60, 2) correlated with aesthetic ratings. Accordingly, it is unlikely that the present results were influenced by the top–down modulation of preference responses (Table 2).

Neural markers of preferences

Parametric modulation analysis showed that PCC activity was positively correlated with subjects' preference. Consistent with this, the previous studies have shown that activation in the PCC is positively (we)-2-3 correlated with the perceive desirability of objects (Kawabata and Zeki, 2008) or the subjective value of delayed monetary rewards (Kable and Glimcher, 2007). Because the PCC is also implicated in self-referential processing and autobiographic memory (Rameson et al., 2010; Say(KTf(S)15(/

One previous study (Sharot et al., 2009) found a similar effect, but the brain area that was implicated was very different. In this study, activity in the caudate nucleus predicted subsequent choices. Whereas our study tested incentive compatible choices of pop music CDs, Sharot et al. tested choices among various hypothetical vacation sites. Moreover, whereas our study tested Chinese subjects, Sharot et al. tested British subjects. These factors might prove to be important in explaining the different pattern of results.

Conclusion

While the phenomenon of cognitive dissonance was discovered five decades ago and different theories have been proposed to interpret this phenomenon (see Harmon-Jones and Harmon-Jones, 2007 for a review), the underlying neural mechanisms remain undefined. Our fMRI study suggests that self-reflection (the ventral MPFC) that is mediated by perspective taking (TPJ) is crucially involved in choice justification. This finding goes along with the existing behavioral data that suggest the significance of a threat to the public self in mediating choice justification in Asian, interdependent cultural contexts. As the current work tested only Chinese subjects and found a correlation between the variation of the ventral MPFC activity and subjective ratings of interdependent self-construals, future work should expand the current work to Western, more independent cultural contexts.

Q4 Uncited references

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Lebreton et al., 2009
Zeki and Romaya, 2008

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