Neuropsychologia 144 (2020) 107502

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: http://www.elsevier.com/locate/neuropsychologia

Metacognition-related regions modulate the reactivity effect of confidence ratings on perceptual decision-making

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ARTICLE INFO

Keywords:
Decision confidence
Reactivity effect
Metacognition
Functional magnetic resonance imaging
Decision-making

ABSTRACT

Prompting confidence ratings following perceptual decision-making could significantly affect the decision-making per se, a phenomenon known as the reactivity effect. The current study aimed to explore the neural substrates underlying the reactivity effect by comparing behavioral and functional magnetic imaging data between when participants making decisions with prompted confidence ratings (DCR+) and when without providing confidence ratings (DCR−). The results showed that DCR+ was associated with longer decision response times (RTs) and higher accuracy than DCR−. The analysis of fMRI data revealed significantly increased activation in the DCR+ condition, relative to the DCR− condition, in multiple metacognition-related regions including the left supplementary motor area, left dorsal anterior cingulate cortex, left opercular part of the inferior frontal gyrus, and bilateral precuneus. Changed beta values ($Beta_{DCR+}$ minus $Beta_{DCR-}$) of these clusters were correlated with the changed decision RTs between the two conditions ($\Delta RT = RT_{DCR+} - RT_{DCR-}$). Psychophysiological interaction analysis revealed increased functional connectivity between the left supplementary motor area and the right inferior parietal lobe in the DCR+ condition than the DCR− condition. Further multiple regression analysis found that ΔRTs was significantly associated with activities in the bilateral dorsal anterior cingulate cortex and supplementary motor area. Together, this study found that provide confidence ratings significantly changed online decision-making while activating multiple metacognition-related regions. The activity of metacognition-related regions may be a crucial part of the neural mechanisms underlying the reactivity effect of confidence ratings on perceptual decision-making.

1. Introduction

Providing metacognitive judgments (e.g., retrospective confidence ratings) while performing a cognitive task could reactively change the online performance, a phenomenon known as the *reactivity effect* (Mitchum et al., 2016). Robust reactivity effect has been found in a board range of cognitive domains, such as memory retention (Double et al., 2018; Mitchum et al., 2016), cognitive reasoning (Dinsmore and Parkinson, 2013; Double and Birney, 2017) and perceptual decision-making (Baranski and Petrusic, 2001; Kiani and Shadlen, 2009; Petrusic and Baranski, 2003). For instance, make judgments of learning (JOLs) after the presentation of the to-be-learned stimuli could significantly change the performance of recall (Mitchum et al., 2016); while performing confidence ratings after perceptual decision-making could lead to longer decision response times (RTs) and higher accuracy than when confidence ratings are not performed (Baranski and Petrusic, 2001; Petrusic and Baranski, 2003; Schoenherr et al., 2010; Yang et al., 2018). Both JOLs and confidence ratings require metacognitive

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https://doi.org/10.1016/j.neuropsychologia.2020.107502
Received 10 March 2020; Received in revised form 20 May 2020; Accepted 22 May 2020
Available online 28 May 2020

introspection of one's cognitive processing. The reactivity effect hence could reflect the impact of metacognitive monitoring on the online cognitive processing (Double and Birney, 2019a). In terms of decision-making, the reactivity effect has at least two important implications: 1) Self-report measures that collected while a participant is performing a task could either facilitate or impair the task performance via the reactivity effect, which could cause an inaccurate measure of the performance (Double et al., 2018; Mitchum et al., 2016). Given that self-report measures are widely used in psychology studies, a better understanding of the mechanism of the reactivity effect could help improve the design of such measures. 2) Exploring the mechanism of the reactivity effect could deepen our understanding of decision-making. Decision-making and confidence are closely correlated (Pleskac and Busemeyer, 2010). While confidence rating relies on the information provided by decision-making processing, it could also modulate the decision-making through error monitoring (Yeung and Summerfield, 2012), motivation and self-regulated learning (Efklides, 2011), allocating cognitive resources (Son and Metcalfe, 2000), and strategy selection (Karpicke, 2009) and so on. However, so far, little is known about how confidence ratings would affect online decision-making processing.

Robust reactivity effect of confidence ratings on decision-making has been documented in several studies (Baranski and Petrusic, 2001; Petrusic and Baranski, 2003; Schoenherr et al., 2010; Yang et al., 2018). For example, Petrusic and Baranski (2003) used a perceptual decision paradigm, in which the participants were randomly assigned to the confidence condition (the decisional responses were followed by confidence ratings) and to a no-confidence condition (confidence ratings were not requested), and found that eliciting confidence ratings resulted in slower decision RTs. Similarly, in the study of Schoenherr et al. (2010), the decision-making processing was significantly slower and sometimes more accurate when confidence rating was required than when it was not required.

The cognitive mechanism of the reactivity effect is currently unclear. Double and Birney (2019a) recently proposed a tentative framework to explain available findings. This framework suggests that prompt self-reporting leads participants to attend to particular cues, which facilitate or impair the metacognitive monitoring on the cognitive processing and eventually alter the performance. There are two sets of cues: the experience-based cues refer to cues that are drawn from the experience of the task, e.g. task characteristics and difficulty; the information-based cues, on the other hand, refer to cues that are drawn from pre-existing beliefs about one's competence, e.g. self-confidence and self-efficacy (Koriat et al., 2008). Depend on the task setting (e.g. the self-report measures adopted), one or several of these cues will be salient and alter performance. For example, Double and Birney (2017) found that performing confidence ratings facilitated the performance of high self-confidence participants but impaired the performance of low self-confidence participants, suggesting that eliciting confidence ratings may have activated preexisting self-confidence. Relatively, a recent study found that human observers take attention-dependent uncertainty into account when categorizing visual stimuli and reporting their confidence (Denison et al., 2018), suggesting that metacognitive awareness of uncertainty could be a crucial locus for both the confidence-rating and the reactivity effect.

Exploring the neural underpinnings could be a crucial step toward deepening our understanding of the cognitive mechanisms underlying the reactivity effect. If the reactivity effect is indeed an effect of metacognitive monitoring on online cognitive processing, it is logical to expect that neural representation of this effect would to some extent overlap with the metacognition-related network. According to previous neuroimaging studies, confidence ratings provoke activations in regions of the frontoparietal and cingulo-opercular networks, particularly the dorsal anterior cingulate cortex (dACC), the supplementary motor area (SMA), the anterior prefrontal cortex, the inferior parietal lobe (IPL), precuneus, and the anterior insula (Chen et al., 2013; Fleming et al., 2012; Hilgenstock et al., 2014; Lemaitre et al., 2018; Qiu et al., 2018; Rouault et al., 2018). However, it is unclear if these regions also involved in the reactivity effect.

The present study aimed to investigate the neural substrates underlying the reactivity effect of confidence ratings on decision-making using functional magnetic resonance imaging (fMRI). Based on previous studies, we expected that confidence ratings could induce enhanced metacognitive monitoring on the decision-making process and correspondingly trigger fMRI signal changes in the metacognition-related network.

2. Material and methods

2.1. Subjects

Forty-two undergraduates free of neurological or psychiatric history (mean age: 21.5 ± 1.48 years; range: 19–26 years; 19 females) were recruited from the Southwest University (Chongqing, China). All subjects were right-handed and reported normal or corrected-to-normal vision. They provided written consent and received monetary compensation depending on their task performance. This study was approved by the Institutional Review Board of Southwest University and was conducted following the latest revision of the Declaration of Helsinki.

2.2. Materials

Using the Computer-Aided Design (https://www.autodesk.com/products/autocad/overview) software, perceptual stimuli were made by split rectangles of 112 × 82 pixels with a random jagged line (6 variable points) into two areas filled by either orange or blue color (Fig. 1). The principal stimuli were 36 images, for which the average judgment accuracy was 55%–85%. These images were selected from 150 stimuli in total, based on a behavioral pilot study with an independent group of subjects ($N = 200$).

2.3. Experimental design and procedure

The current experiment involved a within-subjects design. Subjects performed a post-decision confidence rating task while taking an fMRI scan. The task consisted of two conditions with identical decision stage but different confidence stage: i.e. a *DCR+ condition* involves perceptual decision-making followed by retrospective confidence ratings, and a control *DCR− condition* involves perceptual decision-making followed by digit selecting. Fig. 1A illustrated the example trials of these two conditions. Particularly, in the decision stage, participants were required to make a binary decision regarding which color (Orange/Blue) had a larger area. The confidence stage occurred immediately following the decision stage. During the confidence stage, subjects either reported their confidence level regarding the correctness of their decision on a rating scale ranging from 1 (not confident at all) to 4 (extremely confident) in the DCR+ condition or press one of four number keys (1–4) randomly marked out by the computer in the DCR− condition.

Before the fMRI experiment, 20 trials were practiced to familiarize participants with the task. In the scanner, participants completed four blocks (2 DCR+ and 2 DCR−) of 18 trials. The stimuli and order of blocks were counterbalanced across subjects to avoid any order effects. For each trial, a correct response in the decision stage would gain 100 points whereas an incorrect one was counted as zero. At the end of the task, the bonuses were awarded according to the total amount of earned points (1000 points = 2 RMB). The participants were instructed that their compensation would depend on the points they earned, but they were not informed how the compensation was calculated. No feedback was given during the task.

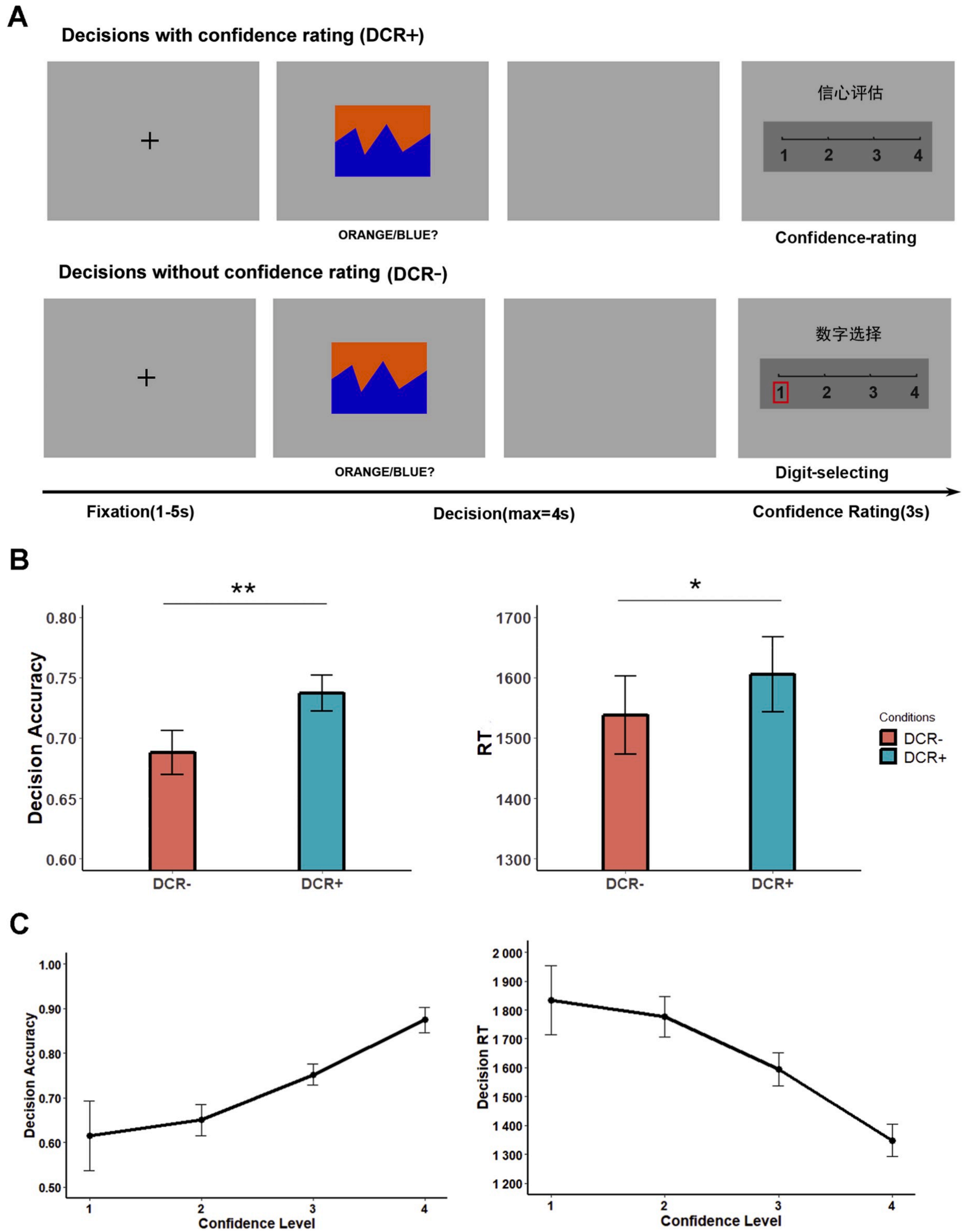

Fig. 1. **(A)** The post-decision confidence rating task. Each trial started with a fixation presented for 1–5s randomly. Then the decision-making stage initiated, during which subjects determined which part (Orange/Blue) of the presented stimuli had a greater area, and they reported their decision using one of two buttons on a response box (maximum RT = 4s; stimuli disappeared once a response was made, and a blank screen was presented for the rest of the 4s to equate the duration of each trial). Following a decision, subjects either reported their confidence level regarding their decision correctness (confidence ratings) or press a number key that was randomly marked out by the computer (digit selecting). The maximum RT for confidence ratings and digit selecting was 3s. For each trial, there was a brief instruction present above the rating scale, in the DCR+ condition the instruction was "信心评估" (Chinese for 'confidence rating'), while in the DCR− condition the instruction was "数字选择" (Chinese for 'digit selecting'). (B) Comparisons of decision accuracy and RTs between the DCR+ and the DCR− condition. (C) Comparisons of decision accuracy and RTs between different confidence levels in the DCR+ condition. *$p < .05$; **$p < .01$. Error bar represents ± standard error. Abbreviations: RT, response time; DCR+, Decisions with confidence rating; DCR−, Decisions without confidence rating. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.4. Behavioral data analysis

Paired *t*-tests were conducted to compare RTs and decision accuracy between the DCR+ and DCR− conditions. The reactivity effect was characterized by two indexes, ΔRT and Δaccuracy, using the following two formulas:

$$\Delta RT = RT_{DCR+} - RT_{DCR-}$$
$$\Delta accuracy = accuracy_{DCR+} - accuracy_{DCR-}$$

To assess if the reactivity effect was derived from alterations in decision criterion or discriminability, the decision criterion (c′) and discriminability index (d′) of each condition were calculated for each subject using signal detection theory analysis and compared between conditions.

2.5. fMRI data acquisition

Task-based fMRI data were collected using a 3T MRI scanner (Siemens Magnetom Trio TIM, Erlangen, Germany) with a single shot echo-planar imaging sequence: TR = 2000 ms, TE = 30 ms, flip angle = 90°, FOV = 192 × 192 mm^2, matrix size = 64 × 64, slice thickness = 3 mm, interslice gap = 1 mm, slices = 32, voxel-size = 3 × 3 × 3 mm. High resolution T1-weighted images were also recorded with a total of 176 transverse slices at a thickness of 1 mm (no gap) and in-plane resolution of 0.98 × 0.98 mm^2 (TR = 1900 ms; TE = 2.52 ms; flip angle = 9°; FOV = 250 × 250 mm^2).

2.6. fMRI data preprocessing and analysis

fMRI data were preprocessed using SPM12 (http://www.fil.ion.ucl.ac.uk/spm). Preprocessing steps included (in this order): discarded five volumes to achieve magnet-steady images, slice timing, realignment, coregistration to the T1-weighted image, spatial normalization to the Montreal Neurological Institute (MNI) space using the nonlinear deformation fields derived from segmentation of T1-weighted images and interpolated to 3 × 3 × 3 mm voxels, and spatial smooth using an 8 mm Gaussian kernel.

Statistical analyses of task-based fMRI data include three parts: a whole-brain localization analysis, a psychophysiological interaction (PPI) analysis, and a multiple regression analysis. In the whole-brain localization analysis, we targeted fMRI signal differences during the decision stage between the DCR+ and DCR− conditions, which reflect the neural substrates underlying the reactivity effect. In the first-level analysis, four regressors were created, two correspondings to the onset of the stimuli of the two conditions (i.e. DCR+ and DCR−), two corresponding to the onset of the confidence stage of the two conditions (named Confidence-rating and Digit-selecting). The six head movement parameters were included as covariates. The resulted design matrix was then convolved with a canonical hemodynamic response function in the context of the general linear model. We identified voxels involved in the reactivity effect using the contrast of DCR+ *vs.* DCR−. The contrast of Confidence-rating *vs.* Digit-selecting during the confidence stage was also performed to identify voxels involved in the confidence evaluation. Then a random-effect group analysis of these individual contrasts was performed in the second-level analysis using one-sample *t*-tests.

To examine whether providing confidence ratings cause changes in functional connections, a PPI analysis was performed using the gPPI toolbox (McLaren et al., 2012). Three variables were entered into the PPI analysis, with the two experimental conditions (DCR+ vs. DCR−) as the psychological variable, the time course in a given seed region as the physiological variable, and the cross-product of these two variables as the PPI term. The seed regions were defined based on the results of whole-brain localization analysis (see Table 1) as spheres of 6 mm radius centered around the peak voxel of each cluster. The PPI analysis was carried out for each seed region and each subject separately. Brain regions showing changed functional connectivity with the seed regions were evaluated by one-sample *t*-tests in the second-level analysis.

Table 1
Task-based fMRI results associated with the reactivity effect of confidence ratings on decision-making.

Brain regions	Voxels	peak *t*-value	x y z
DCR+ > DCR−			
Supplementary Motor Area-L	127	5.36	-9 9 63
Precuneus-R	55	4.95	9 -69 57
dorsal Anterior Cingulate Cortex-L	41	4.36	-9 27 36
Precuneus-L	35	4.15	-12 -66 57
opercular Inferior Frontal Gyrus-L	36	3.54	-48 15 21
DCR+ < DCR−			
Middle Cingulate Cortex-L	92	4.50	3 -18 45
Confidence-rating > Digit-selecting			
Primary Visual Cortex-R	137	6.14	18 -81 -9
dorsolateral Prefrontal Cortex-R	77	4.51	24 57 30
Primary Visual Cortex-L	94	4.49	-12 -99 0
dorsal Anterior Cingulate Cortex-R	66	3.76	9 33 27
Confidence-rating < Digit-selecting			
Extrastriate Areas-R	491	6.92	33 -93 -6
Postcentral Gyrus-R	30	4.87	45 -33 54
Extrastriate Areas-L	57	4.87	-30 -99 -12
Postcentral Gyrus-R	73	4.78	60 -18 45
Angular Gyrus-L	54	4.25	-36 -69 45
PPI: Seed at Supplementary Motor Area-L			
Inferior Parietal Lobe-R	53	4.18	36 -39 45
Multiple regression of ΔRT with DCR+ > DCR−			
Precentral Gyrus-L	270	5.63	-27 0 45
dorsal Anterior Cingulate Cortex -L/R	414	5.59	9 18 45
Caudate-R	70	5.29	15 -12 21
Extrastriate Areas-R	74	4.70	36 -87 6
lateral Prefrontal Cortex-R	60	4.25	36 30 21
Inferior Parietal Lobe-R	46	4.16	36 -48 51
Extrastriate Areas-L	76	4.16	-24 -84 -9
Extrastriate Areas-L	26	4.14	-24 -99 9
Anterior insula-R	20	3.97	33 21 3
Anterior insula-L	32	3.89	-36 18 -3

Abbreviations: L, left; R, right.

Finally, in the multiple regression analysis, we investigated whether changes in decision RTs and accuracy were related to fMRI signals of the reactivity effect. The ΔRT and Δaccuracy were included in two multiple regression models respectively as the independent variable, with the contrast images of DCR+ vs. DCR− as the dependent variable.

For all voxel-wise comparisons, an explicit gray matter mask constructed from all participants was applied to ensure that only voxels within the gray matter were analyzed. The threshold for all voxel-wise analyses was set at corrected $p < .05$. Correction for multiple comparisons was achieved by combining a voxel-level $p < .001$ and cluster-level AlphaSim corrected $p < .05$.

3. Results

3.1. Behavioral results

As shown in Fig. 1B, compared with DCR−, DCR+ significantly enhanced decision accuracy (0.74 ± 0.10 *vs.* 0.69 ± 0.11; $t = 2.84$, $p = .007$) and was associated with longer decision RTs (1604.63 ± 403.45 ms *vs.* 1537.40 ± 418.73 ms; $t = 2.47$, $p = .018$). In the DCR+ condition, confidence increased monotonically as decision accuracy increases ($F_{3, 164} = 8.38$, $p < .001$), while decision RTs linearly decreased as confidence increases ($F_{3, 164} = 8.85$, $p < .001$), suggesting an interaction of decision-making and confidence in this condition (Fig. 1C). On the contrary, decision RTs was not significantly influenced by the number selected in the DCR− condition ($F_{3, 164} = 1.10$, $p < .350$).

The signal detection theory analysis showed that d′ was significantly higher in the DCR+ condition than in the DCR− condition (1.40 ± 0.61 vs. 1.12 ± 0.73, $t = 2.53$, $p = .015$), while no significant difference found between c′ of the two conditions (0.07 ± 0.47 vs. 0.04 ± 0.46, $t = 0.76$, $p = .451$). We found a significant correlation between Δaccuracy and the changes of d′ (d'_{DCR+} minus d'_{DCR-}) ($r = 0.92$, $p < .001$), but not between Δaccuracy and the changes of c′ (c'_{DCR+} minus c'_{DCR-}) ($p = .839$), indicated that providing confidence ratings enhanced subjects' discriminability without changing their decision criterion.

Because these results could also reflect a speed-accuracy tradeoff that stressed accuracy in the DCR+ condition, we carried out a regression analysis with Δaccuracy as a dependent variable and ΔRT as an independent variable. This regression analysis found that the Δaccuracy cannot be significantly predicted by ΔRT (Beta = −0.17, $p = .275$). Moreover, Pearson's correlations between overall mean RTs and overall mean accuracy was non-significant ($r = 0.05$ $p = .735$). These results suggested that the changes of accuracy cannot account for by alternated speed-accuracy tradeoffs between the two conditions.

3.2. Neuroimaging results

Relative to the DCR− condition, the DCR+ condition induced significantly increased activations in the left SMA, left dACC, left opercular part of the inferior frontal gyrus, and bilateral precuneus. A cluster of decreased activation was also observed in the middle cingulate cortex in the DCR+ condition (Fig. 2A; also see Table 1). To explore the behavioral correlation of the changed activations in the DCR+ condition, we defined these clusters as regions of interest (ROIs) and extracted mean beta values of each ROI for each condition for further correlation analysis. Pearson's correlation analysis revealed positive correlations between ΔRT and beta value difference of the two conditions ($Beta_{DCR+}$ *minus* $Beta_{DCR-}$) in the left dACC ($r = 0.49$, $p = .001$), the left SMA ($r = 0.41$, $p = .006$), and the left opercular part of the inferior prefrontal gyrus ($r = 0.41$, $p = .006$). However, no significant correlation was found between $Beta_{DCR+}$ *minus* $Beta_{DCR-}$ and Δaccuracy ($p > .283$) or between $Beta_{DCR+}$ *minus* $Beta_{DCR-}$ and mean confidence ($p > .285$) in these ROIs. These results suggested that the brain activity changes induced by the reactivity effect were associated with changes in decision RTs, but not with variations in Δaccuracy or confidence level.

In the confidence stage, compared with the Digit-selecting condition, the Confidence-rating condition induced greater activity in the right dACC, the right dorsolateral prefrontal cortex, and bilateral primary visual cortex, and lower activity in the right postcentral gyrus, left angular gyrus and bilateral extrastriate visual areas (Fig. 3A, Table 1).

PPI analysis revealed a significantly increased functional connectivity between the left SMA and the right IPL in the DCR+ condition when compared with the DCR− condition (Fig. 2B, Table 1). PPI analysis with other seed regions, including the left dACC, left opercular part of the inferior frontal gyrus, bilateral precuneus, and the middle cingulate cortex, revealed no significant results.

Multiple linear regression analysis with ΔRT as regressor showed that ΔRT was associated with activations in the bilateral dACC (extending to the SMA), right lateral prefrontal cortex, right IPL, right caudate, left precentral gyrus, bilateral anterior insula, and bilateral extrastriate visual areas (Table 1, Fig. 3B). Multiple regression analysis with Δaccuracy as regressor revealed no significant results.

4. Discussion

The present study was motivated to explore the neural substrates underlying the reactivity effect of confidence ratings on decision-making. The behavioral results showed that DCR+ was associated with longer decision RTs and higher decision accuracy than DCR−. The analyses of neuroimaging data revealed significant activation in multiple metacognition-related regions including the left SMA, left dACC, the left opercular part of the inferior frontal gyrus, and bilateral precuneus in the DCR+ condition than in the DCR− condition. Changed beta values ($Beta_{DCR+}$ *minus* $Beta_{DCR-}$) in the left SMA, left dACC and the left opercular part of the inferior frontal gyrus clusters were correlated with ΔRT. PPI analysis revealed increased functional connectivity between the left SMA and the right IPL in the DCR+ condition than the DCR− condition. Moreover, multiple regression showed that the bigger ΔRT was associated with increased activity in bilateral dACC/SMA regions, right IPL, and bilateral anterior insula.

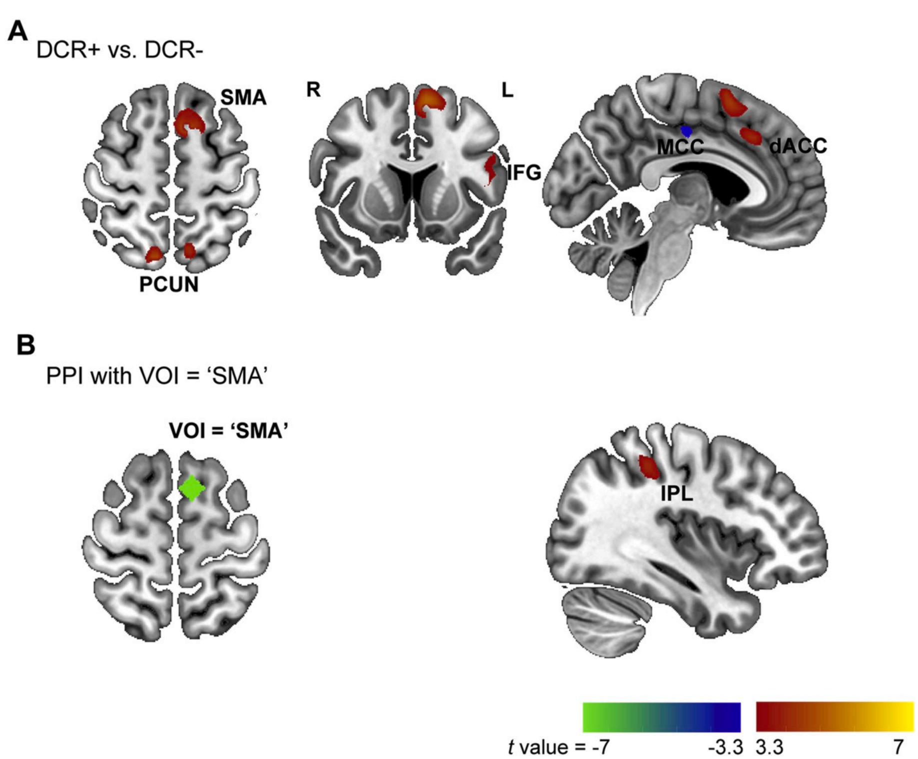

Fig. 2. (A) fMRI comparisons of decisions with and without confidence ratings. Significant activation during the decision stage was found in the left SMA, the left opercular part of inferior frontal gyrus, the left dACC, and bilateral precuneus, and a cluster of decreased activation in the middle cingulate cortex were observed in the DCR+ relative to the DCR− condition. (B) Results of PPI analysis. When using the left SMA as VOI increased functional connection between the seed region and right IPL was found in the DCR+ condition. Threshold set at voxel-level $p < .001$ cluster-wise AlphaSim corrected. The color bar represents the voxel-level t values. Abbreviations: SMA, supplementary motor area; IFG, the opercular part of inferior frontal gyrus; dACC, dorsal anterior cingulate cortex; PCUN, precuneus; MCC, middle cingulate cortex; VOI, volume of interest; IPL, inferior parietal lobe; R, right; L, left. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

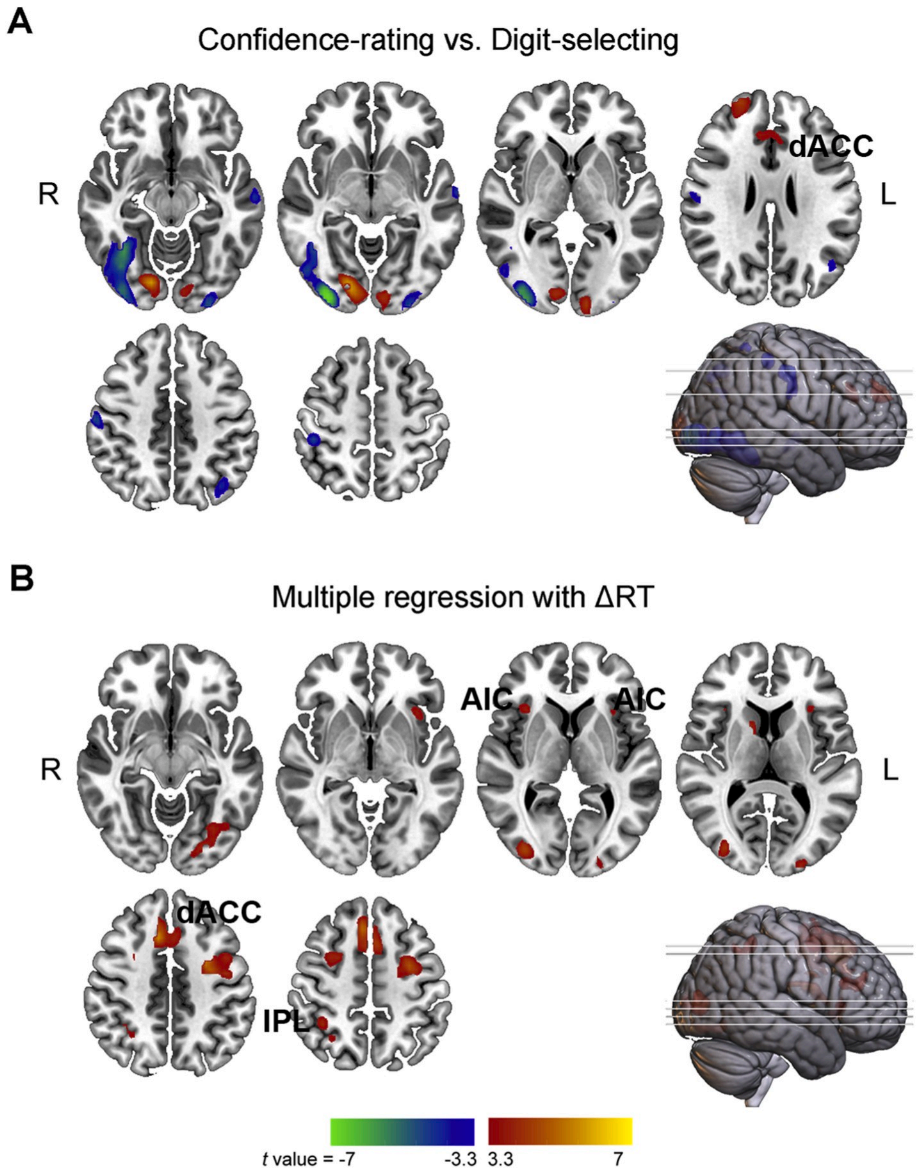

Fig. 3. (A) fMRI comparisons of the Confidence-rating condition and the Digit-selecting condition in the confidence stage. When **c**ompared with the Digit-selecting condition, the Confidence-rating condition showed increased activation in the right dorsolateral prefrontal cortex, right dACC, and bilateral primary visual cortex; and decrease activations in the right postcentral gyrus, left angular gyrus and bilateral extrastriate visual areas. (B) Results of multiple regression analysis with ΔRT as the independent variable. The ΔRT significantly predicted the activity of multiple metacognition-related regions including the bilateral dACC/SMA, right lateral prefrontal cortex, right IPL, and bilateral anterior insula. Threshold set at voxel-level $p < .001$ cluster-wise AlphaSim corrected. The color bar represents the voxel-level t values. Abbreviations: dACC, dorsal anterior cingulate cortex; AIC, anterior insula; IPL, inferior parietal lobe; R, right; L, left. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Our results demonstrated that providing confidence ratings could affect decision-making by showing that: 1) confidence increased monotonically as decision accuracy increases, and 2) decision RTs decreased as confidence increases. These results were consistent with the findings of Petrusic and Baranski (2003), suggested dynamic interaction between decision-making and confidence. Moreover, our results provided clear evidence of a reactivity effect of confidence ratings on perceptual decision-making. The findings that providing confidence ratings resulted in longer decision RTs and higher decision accuracy were in line with what previous behavioral studies documented (Double and Birney, 2017; Mitchum et al., 2016; Petrusic and Baranski, 2003; Schoenherr et al., 2005). Our results expand previous findings by showing that the reactivity effect is mainly derived from increased discriminability but not changes in decision criterion; and the reactivity effect cannot be accounted for by different speed-accuracy tradeoffs between the two conditions, as we found no significant association between accuracy and RTs or between Δaccuracy and ΔRTs.

More importantly, this study found that a metacognition-related network involved in the neural mechanisms of the reactivity effect. When compared with the DCR− condition, the DCR+ condition induced increased activation in the left SMA, left dACC, left opercular part of the inferior frontal gyrus, and bilateral precuneus. The dACC was also activated in the Confidence-rating condition when compared with the Digit-selecting condition during the confidence stage. Moreover, our PPI analysis revealed increased functional connectivity between the left SMA and right IPL in the DCR+ condition than the DCR− condition. The dACC and SMA are among the central of the cingulo-opercular network that suggested to encode generic signal of post decisional confidence level, monitoring conflict and detecting errors across different tasks (Chen et al., 2013; Fleck et al., 2005; Fleming et al., 2012; Hebart et al., 2014; Heereman et al., 2015; Hilgenstock et al., 2014; Morales et al., 2018). The dACC is thought to be a cognitive control hub of the brain, which serves to specify the currently optimal allocation of control by determining the overall expected value of control, thereby licensing the associated cognitive effort (Shenhav et al., 2016). From this point of view, dACC may serve as a trigger point of the reactivity effect, which detects the salient cues and induces enhanced monitoring of ongoing cognitive processing. The SMA is a hub of action control that involved in reprogramming the motor response as well as inhibiting prepotent motor responses under conflict (Mars et al., 2009). The activity of SMA and ACC regions hence could reflect the detection of the salient cues in the reactivity effect. The IPL is a hub of the frontoparietal attention network (Ptak, 2012), that serves to maintain attention and responding to salient events (Singh-Curry and Husain, 2009). This region also implicated in self-reference processing, i.e. the represent and process of relating information to the self (Uddin et al., 2006). The increased SMA-IPL functional connectivity in the DCR+ condition could indicate a process from salience detection to the internal representation of metacognitive uncertainty. The opercular part of the inferior frontal gyrus is also a part of the cingulo-opercular network that implicated in metacognitive evaluation (Fleming et al., 2012; Morales et al., 2018). The opercular part of the inferior frontal gyrus is functionally connected with the anterior cingulate cortex and the lateral part of the orbitofrontal cortex and is involved in representing and learning about the reinforcers that elicit emotions and conscious feelings (Du et al., 2020; Kringelbach, 2005). The precuneus has been implicated in visual perceptual metacognitive processing in several previous studies (Fleming et al., 2010; McCurdy et al., 2013; Morales et al., 2018). Furthermore, the precuneus also involved in self-reference processing and have functional connectivity toward dorsal and ventral attention networks, these regions thus could also contribute in the attention shifting processing in the reactivity effect (Cavanna and Trimble, 2006; Liu et al., 2019; Schmidt et al., 2017). Together, our results suggested that the metacognition-related regions, especially the cingulo-opercular network centered at the dACC/SMA regions, may be underlying the reactivity effect of confidence ratings on perceptual decision-making. Activations in these regions could contribute to the detection of salient cues and the shift of attention toward an internal representation of metacognitive uncertainty. The involvement of these metacognition-related regions in the reactivity effect also supports the idea that the reactivity effect is a result of changed metacognitive monitoring that induced by prompted confidence ratings (Double and Birney, 2019a).

In the current study, the involvement of the metacognition-related regions was associated with the increased decision RTs but not the enhanced accuracy in the DCR+ condition. Firstly, the beta values of dACC, SMA, and the opercular part of the inferior frontal gyrus were positively correlated with ΔRTs but not with Δaccuracy. Secondly, multiple regression showed that prolonged ΔRTs were associated with activity in multiple metacognition-related regions, including the dACC/SMA, bilateral anterior insula, lateral prefrontal cortex, and IPL. These regions were all implicated in retrospective confidence evaluations in previous studies (Chen et al., 2013; Fleming et al., 2012; Hilgenstock et al., 2014; Lemaitre et al., 2018; Qiu et al., 2018; Rouault et al., 2018). On the contrary, multiple regression analysis with Δaccuracy as regressor revealed no significant results. These results suggest that the involvement of metacognition-related regions could account for the slower decision in the DCR+ condition, but not directly related to the performance changes. The increased RTs in the DCR+ condition could be understood by assuming a postdecisional processing of confidence judgments in the DCR+ condition. According to the Two-Stage Dynamic Signal Detection (2DSD) model of decision-making, after a choice was made, the confidence is derived from a second stage of evidence accumulation that builds on the evidence accumulated during the choice stage (Pleskac and Busemeyer, 2010). The prolonged decision RTs in the DCR+ condition hence might be consumed by this postdecisional processing (Petrusic and Baranski, 2003; Pleskac and Busemeyer, 2010; Schoenherr et al., 2010). And base on our discussion above, we suspect that, in our task setting, this postdecisional processing could including the detection of salient cues and the internal representation of metacognitive uncertainty.

The mechanism underlying the reactivity effect of accuracy changes, however, appears more complicated. Indeed, previous studies of the reactivity effect suggest that eliciting metacognitive judgments could even induce poorer performance in some cases, e.g. among older individuals (Double and Birney, 2018) or participants with low preexisting self-confidence (Double and Birney, 2017). These findings suggest the reactivity effect on performance may involve factors outside metacognition, such as task characteristics, goal, and prospective self-confidence (for reviews see Double and Birney, 2019a and Double et al., 2018). The absence of a linear correlation between Δaccuracy and fMRI signals of the metacognition-related regions also implies the existence of intermediate variables.

This study has several limitations. Firstly, the current study has not separated the decision stage and confidence stage via a random jitter, which could diminish the power to detect differences during the confidence stage. Secondly, the observed reactivity effects may be divergent in tasks of different cognitive domains (e.g. memory and reasoning) or tasks using different self-report approaches (e.g. JOLs) (for a recent review on this topic, see Rouault et al., 2018). It is thus important for future studies to examine the reactivity effect in other cognitive domains to gain more specific conclusions. Thirdly, the direction and magnitude of the reactivity effect appear to depend on the salient cues (e.g. Fox et al., 2011; Double and Birney, 2019b). For example, Double and Birney (2019b) suggested that reactivity may be a specific response to the wording of confidence rating. Further study is needed to examine if the activation of metacognition-related regions also occurs when different cues are salient. Finally, further research is needed to clarify whether (and if so, how) individual differences in metacognitive ability (e.g., Fleming et al., 2010) will affect the reactivity effect. If the reactivity effect reflects the impact of metacognitive monitoring on online cognitive processing, intuitively, individuals with better metacognitive ability would have a bigger reactivity effect.

5. Conclusion

This study found that provide confidence ratings significantly changed online decision-making while activating multiple metacognition-related regions. The activity of metacognition-related regions may be a crucial part of the neural mechanisms underlying the reactivity effect of confidence ratings on perceptual decision-making.

Declaration of competing interest

The authors report no conflicts of interest.

CRediT authorship contribution statement

Wei Lei: Writing - original draft, Formal analysis, Visualization. **Jing Chen:** Writing - original draft, Conceptualization, Data curation, Methodology. **Chunliang Yang:** Writing - review & editing. **Yiqun Guo:** Data curation, Investigation. **Pan Feng:** Data curation, Software. **Tingyong Feng:** Project administration, Resources, Writing - review & editing. **Hong Li:** Supervision, Funding acquisition, Writing - review & editing.

Acknowledgments

This work was supported by the Natural Science Foundation of China (81701322; 31800959; and 31571128); Humanity and Social Science Youth Foundation of Ministry of Education of China (17YJC190009; 17YJC190001); Shenzhen Peacock Plan, China (KQTD2015033016104926); Shenzhen Basic Research Layout Project, China (JCYJ20150729104249783); the joint project of Southwest Medical University & Affiliated Hospital of Southwest Medical University, China (2015-QB-003); Luzhou Science and Technology Bureau Project, China (2017-S-40(7/18); 2018LZXNYD-ZK03); Sichuan Education Department, China (18ZA0534).

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