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How does the embodied metaphor affect creative thinking?

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ABSTRACT

This study aimed to explore the neural correlates of the embodied metaphor “breaking the rules” and how it affects creativity by using functional near-infrared spectroscopy (fNIRS). To embody the metaphor “breaking the rules,” we created a circumstance in which participants can experience “breaking the walls” through virtual reality (VR) technology. Participants were randomly assigned to three conditions: the “break-wall” condition, where they broke the walls to move forward; the “auto-wall” condition, where the barrier wall opened automatically; and the “no-wall” condition, where no barrier walls appeared. While walking in the virtual scenes, participants were asked to solve a creativity-demanding problem and to wear the fNIRS device to record their neural activities. It was found that participants showed better creative performance in the “break-wall” condition than in the other conditions. Weaker activations were found in the frontopolar cortex, the dorsolateral prefrontal cortex, and the somatosensory association cortex under the “break-wall” condition, which may be associated with rule-breaking behaviors, creative performance, and sense of embodiment. These findings may indicate that physical actions of “breaking the wall” activate the conceptual metaphor of “breaking the rules,” which triggers brain activities related to rule-breaking, thus affecting creative performance.

1. Introduction

You have probably encountered the following scenarios in science fiction: a brain in a nutrient medium or a sophisticated computer with extraordinary and mature cognitive skills. Is this possible? Research on embodied cognitive science has raised doubts. Supporters of embodied cognition emphasize the role of sensory and motor functions in cognition itself, meaning that systems for sensing, acting, and thinking are constitutively interdependent (Barsalou, 1999; Foglia and Wilson, 2013). Along with much evidence, this interactive relationship between the human mind and body has been widely accepted (Thelen et al., 2001; Shapiro, 2010). For instance, one of the most classic studies showed that compared to recalling experiences of being accepted, individuals felt much colder when they recalled experiences of being rejected (Zhong and Leonardelli, 2008). Moreover, participants who held a heavy clipboard judged a problem to be more important compared to those who held a light clipboard (Jostmann et al., 2009). To summarize, our cognition is a collective of our mind and body.

As an important human capacity, creativity is defined as the ability to produce work that is novel and useful (Runco and Jaeger, 2012; Sternberg and Lubart, 1993). In recent years, the study of creativity under the perspective of embodied cognition has drawn more and more attention. Leung et al. (2012) reported that compared to walking in a fixed route, individuals who walked freely performed better on creative tasks. Slepian and Ambady (2012) found that tracing fluid drawing—in other words, fluid arm movements—can facilitate creative cognition. A neuromodulation study showed that using transcranial direct current stimulation (tDCS) to activate the M1 region increased musical improvisation performance, which indicated that the primary motor cortex contributes to musical creativity (Anic et al., 2018).

In addition to sensations and movements, metaphors have also been recognized as another bridge that connects the human mind and body. Higher-order, abstract, mental representations are ultimately grounded in bodily states, and our everyday language is full of metaphors (Lakoff and Johnson, 1980). For instance, in the phrase “rising star,” “rising” implies “progressive and successful; ” in the sentence “I’m very down today,” “down” implies “sad.” Recently, researchers have been more and more interested in the effects of embodied metaphors on creativity. Kim (2015) asked participants to squeeze balls to embody the metaphor “squeeze your head” and found that squeezing a soft, deformable ball can

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enhance divergent thinking, whereas squeezing a hard ball can facilitate convergent thinking. Intriguingly, Leung et al. (2012) found that standing outside a box to embody the metaphor "thinking outside of the box" could enhance participants' creative performance. "Breaking the rules" is another common metaphor. It is an everyday Chinese idiom that is often used to encourage people to solve problems in novel ways, rather than using traditional approaches. Moreover, in both Chinese and English language contexts, the symbolic meanings of "walls" could be rules, traditions, constraints, or even confinements. In this sense, the implication of "breaking the walls" could be equal to "breaking the rules." Wang et al. (2018) used virtual reality (VR) technology to simulate a scenario in which participants could break through walls. It was found that participants showed better creative performance in the break-wall condition than in the no-wall condition. All of these studies have shown that embodying specific metaphors can influence cognitive processes and outcomes, even unconsciously.

Over the past few decades, embodied cognition has become one of the most important and representative research orientations in cognitive research under the rise of the second generation of cognitive science. However, like other burgeoning theories, there are still many unresolved controversies within it. If embodied cognition is "a ghost hovering over the cognitive science laboratory" (Goldman and Vignemout, 2009), then repeatability is "the Sword of Damocles" hanging above the embodied cognition laboratory. Bargh et al. (1996) found that after reading words related to "old age," participants left the lab more slowly than those who read words unrelated to old age, even when the subjects themselves were unaware of this. However, Doyen et al. (2012) completely repeated the experiment and replaced the stopwatch speed measurement in the original experiment with infrared speed measurement and found that there was no significant difference in the walking speed of the subjects. The results of the abovementioned experiment have triggered a large-scale discussion on repeatability indicators in the field of embodied cognitive psychology.

Therefore, research using brain functional imaging technology to reveal the potential neural mechanisms behind embodied cognition is quite necessary. In fact, some studies have demonstrated the beneficial effects of physical activities on the development of brain structures. For instance, Ben-Soussan et al. (2015) reported gray matter volume and fractional anisotropy changes in several brain regions, including the cerebellum after 4-week specific motor training, and these anatomical changes were positively correlated with AUT flexibility scores. However, the neural mechanisms and brain activities by which embodied metaphors affect higher-level cognitive function such as creativity remain unknown.

Under this circumstance, our study aimed to explore the neural correlates of the embodied metaphor "breaking the rules" and how it affects creativity by using a functional near-infrared spectroscopy (fNIRS) device. Unlike fMRI and EEG, fNIRS allows subjects to wear a VR head-mounted display (HMD) and to perform small movements, so we chose it to record the subjects' brain activities. As walls can symbolize rules, laws, and even imprisonment, we used "breaking the walls" to represent "breaking the rules." We exploited VR technology to simulate virtual walls as Wang et al. (2018) did and added a more suitable control condition. Thus, the results in the former study could be replicated and expanded.

Previous neuroscience studies have revealed that the prefrontal cortex (PFC), as part of the executive control network, plays an essential role in creative cognition processing (Beaty et al., 2015). For instance, a meta-analysis study reviewed 34 functional imaging studies that reported brain activities during creative thinking tasks and found that the PFC was involved in cognitive processes shared by diverse creativity tasks such as the RAT and AUT (Gonen-Yaacovi et al., 2013). Vartanian et al. (2013) found that the activation of the DLPFC was significantly lower in the working memory training group, which might contribute to fluid intelligence and divergent thinking. In addition, creative idea generation (i.e., divergent thinking) is associated with the deactivation of the right temporal-parietal junction (r-TPJ) (Benedek et al., 2014). The r-TPJ is thought to be a core region of the ventral attention network. It is proposed that sustained deactivation of this region indicates an internal attentional state that can help individuals attend to potentially creative ideas generated in the mind, thus benefiting creative idea generation (Berkowitz and Ansari, 2010; Corbetta et al., 2008; Fink et al., 2012).

Since breaking the rules requires individuals to violate rules and inhibit rule-guided behaviors, the underlying neural correlates of these behaviors may also be involved. Previous studies have found that the PFC, especially the frontopolar cortex, plays an important role in mediating abstract integration in analogy (Green et al., 2006), rule learning (Boschin et al., 2015), and adherence to social norms (O'Callaghan et al., 2016; Moll et al., 2007). Moreover, the activation of the r-TPJ is related to a sense of bodily separation and multisensory conflicts (disembodiment), and the deactivation of the r-TPJ is associated with embodiment (Blanke et al., 2005; Papeo et al., 2010). Based on the abovementioned review, the PFC and r-TPJ are not only correlated with creativity but are also correlated with embodiment and rule-breaking behaviors, so we selected these two regions as the regions of interest (ROI) in the present study.

In this study, to explore the neural correlates of the embodied metaphor "breaking the rules" and how it affects creativity, participants were randomly assigned to three conditions: the "break-wall" condition, in which they had to break the walls to move forward in VR; the "auto-wall" condition, where the barrier walls would open automatically when participants were close enough to them; and the "no-wall" condition, where no barrier walls appeared. While walking in the virtual corridor, participants were asked to solve a creativity-demanding task. During the task procedure, the neural activity of the PFC and r-TPJ regions was recorded using fNIRS. Participants' openness, emotional state, ideation in daily life, personal need for structure, self-rated enjoyment, and difficulty of the experimental tasks were measured using scales to test whether the observed effects of embodied metaphor on creative performance were independent from these factors.

Three hypotheses were raised: (1) better creative performance would be observed in the "break-wall" condition; (2) no difference in creative performance would be observed between the "auto-wall" and "no-wall" conditions; (3) deactivation of the frontopolar area, DLPFC and the r-TPJ would be observed in the "break-wall" condition, given that the deactivation of these three brain regions were found to be associated with rule-breaking behavior, creativity improvement and embodiment (Benedek et al., 2014; Blanke et al., 2005; Buckholtz et al., 2015; Crescentini et al., 2011).

2. Methods

2.1. Participants and design

Ninety undergraduates (67 females; age: 21.55 ± 1.98 years) were recruited for the study through school-wide online advertising. All participants were right-handed, with normal or corrected-to-normal visual acuity. Before the experiment, each participant signed an informed consent form. Participants were paid ¥ 30 for their time and effort. The study procedure was approved by the University Committee on Human Research Protection (UCHRP) of East China Normal University.

The experiment used a between-subject design (Condition: break-wall; auto-wall vs. no-wall). Participants were randomly assigned into three conditions. There were 34, 29, and 27 participants in the "auto-wall," "break-wall," and "no-wall" groups, respectively.

2.2. Virtual environment

In the VR scene, a zigzagging, one-way, fixed-route corridor that consisted of 11 small corridors with 10 turns (five left and five right) was constructed. A first-person view setting was adopted. Given that a pure white wall in VR can easily cause dizziness, especially when the participants are turning around a corner, we placed some pictures on the white wall at the corner of each corridor. The painting in the first corridor was a colorful painting of trees, while the others were white translucent paintings of trees. All the pictures presented in the corridors were exactly the same in all conditions. Participants could move forward and turn their direction by clicking the button on the handle's touchpad, without actual bodily movement. In the "break-wall" condition, a barrier wall would appear in the middle of each small corridor. Participants needed to break the wall by continuously pressing the forward button on the touchpad. In the "auto-wall" condition, the barrier wall would open automatically when participants were close enough to it. In the "no-break" condition, participants encountered no barriers (walls) (see Fig. 1A). The hand movements in the three conditions were almost the same.

When participants were 1 m away from the barrier wall (before and after moving through it, respectively), two marks (Mark1 and Mark2) would be automatically recorded. There were 11 mark-pairs corresponding to 11 small corridors in total. The average interval between Mark1 and Mark2 was 6 s. For further analysis, the mark-pairs were used to divide the time walking along each corridor into three periods: 6 s before Mark1 was defined as "before"; 6 s after Mark2 was defined as "after"; and the period between Mark1 and Mark2 was defined as "while" (Fig. 1C). Once the VR program started, the spatial coordinates of the participants' position in the virtual route were automatically recorded at a refreshing rate of 1 Hz.

2.3. Experimental tasks and procedure

The alternative uses task (AUT; Guilford, 1967) was used to assess creative performance in this study. Participants were required to generate as many unusual and original uses as possible for a common object (*broom* in this study) in the AU task.

Upon arrival, participants were asked to complete several pre-tests (see details below) and to wear the fNIRS device, followed by a VR helmet. The experimental procedure consisted of a 1-min practice block, 1-min resting-state block, and unlimited task block. Participants familiarized themselves with the VR scene and the operation of the handle in the practice block. During the 1-min resting-state session, participants were required to remain as still as possible with their eyes closed and their mind in a relaxed state. This session served as the baseline. Next, the instruction of the AUT was introduced as follows: "During the walking process, please report as many alternative uses for brooms as possible. Try your best to produce ideas that would be thought of by no one else (Fink et al., 2009). Once ideas are generated, please report them aloud. Your ideas will be recorded by a recording pen." In the task block, participants were required to stand up and report the generated ideas orally while walking in the VR scene. Once an idea was reported, the experimenter hit the space bar to mark the time point (recorded as Mark3). All ideas were recorded using a digital recording pen and were transcribed for further analysis. Once they completed the prescribed routes, the task would be terminated, and the elapsed time (started from walking) was recorded. Immediately after the task, participants were required to complete the post-tests.

2.4. Pre- and post-experimental tests

Prior to the experiment, participants completed the personal need for structure scale (PNS) (Thompson et al., 2001; α = 0.80 in the current study), the openness subscale of NEO-PI-R (Costa and McCrae, 1992; α = 0.82 in the current study), and the Runco Ideational Behavior Scale (RIBS) (O'Neal et al., 2015; Paek et al., 2016; Runco et al., 2016; α = 0.90 in the current study). The Self-Assessment Manikin (SAM; Bradley et al., 1994) was also completed to rate the valence and arousal of participants' emotional states.

After the experiment, participants rated the difficulty of the task, feelings of depletion, enjoyment of the task, difficulty controlling themselves in VR, and feeling of embodiment (explained by "How much did you feel immersed in the scene?") on scales ranging from 1 ("not at all") to 7 ("very much"), and they were required to rate their emotional states using the SAM again.

Because one participant from the "no-wall" condition did not complete the pre- and post-tests, this participant was excluded from further pre- or post-tests analyses.

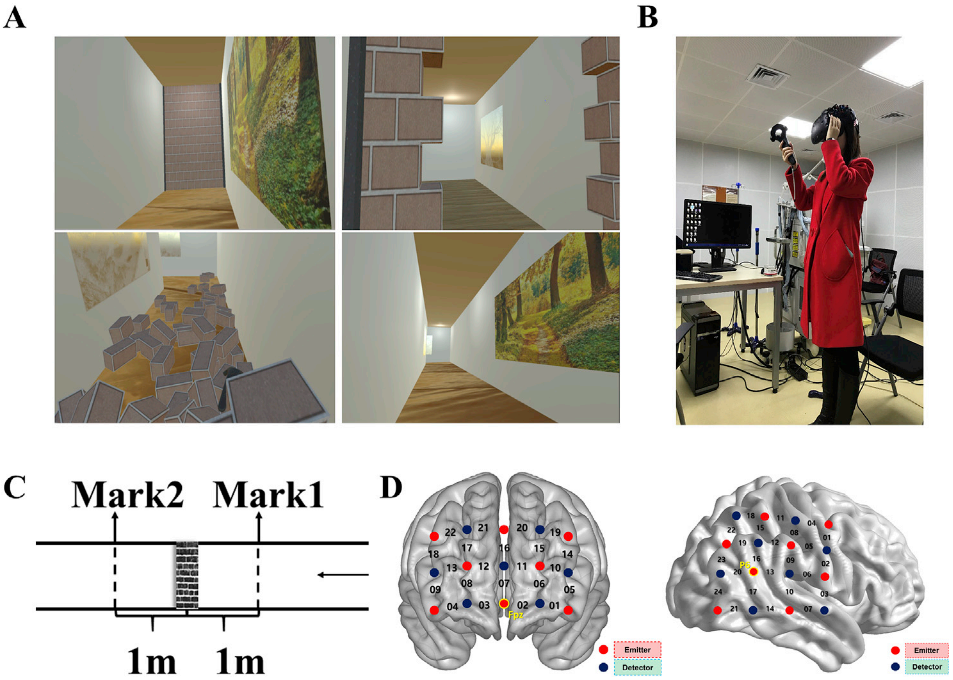

Fig. 1. (A) The scene participants saw in the "break-wall," "auto-wall," and "no-wall" conditions; (B) One participant was performing the task; (C) The position of one mark-pairs; (D) The optode probe sets placed on the PFC and the r-TPJ.

2.5. Assessment of performance on AUT problems

Participants' performance on AUT problems was measured through scores of fluency, originality, and flexibility (Guilford, 1967; Runco, 1991). Fluency scores were the total number of ideas reported. Specifically, each generated response was scored as a point. Originality scores were calculated based on statistically infrequent responses. To this end, the ideas that all participants generated were collected into a comprehensive lexicon. Synonyms were identified and ideas collapsed accordingly. If a response was statistically infrequent (i.e., if 5% or fewer participants in the sample gave the response), then it was scored as "1." All other responses were scored as "0," regardless of the frequency of their appearance. Flexibility scores were coded as the number of categories of generated responses (categories included, e.g., toys, weapons, and props). Following this scoring procedure, two trained raters independently assessed originality and flexibility for each participant. The inter-rater agreements (originality ICCs = 0.93; flexibility ICCs = 0.91) of two raters were satisfactory. The final originality and flexibility scores of each participant were computed by averaging the two raters' ratings.

2.6. fNIRS data acquisition and analysis

A NIRS system (ETG-7100, Hitachi Medical Corporation, Japan) was used to continuously record the oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentrations of each participant. Based on the abovementioned studies suggesting the involvement of the PFC and r-TPJ regions in creativity and embodied cognition, two optode probe sets were placed over each participant's PFC (3*5 optode probe set, 22 measurement channels) and r-TPJ regions (4*4 optode probe set, 24 measurement channels). The registration of probe sets was based on the 10–20 system for electroencephalography (Fig. 1D).

Our study mainly focused on the HbO signal, considering the higher sensitivity to changes in cerebral blood flow when compared to the HbR signal (Cui et al., 2012; Hoshi, 2007; Jiang et al., 2012). The data were preprocessed with hrf low-pass filtering and DCT-based detrending algorithm in NIRS_SPM. Neural activation during the three periods (i.e., "before-breaking," "while-breaking," "after-breaking") was estimated using the General Linear Model (GLM). A series of beta (β) values were obtained as the regression coefficient from all channels under the three periods in the different conditions. The beta value indicated the variation of neural activation. After this, the beta increment was calculated using the equation: $\beta_{\text{increment}} = (\beta_{\text{task}} - \beta_{baseline})/\beta_{baseline}$. Eventually, the beta increment was entered into further analysis.

3. Results

3.1. Performance on AUT problems in different conditions

A one-way ANOVA with Condition (i.e., break-wall; auto-wall vs. no-wall) as the between-subject factor was performed on AUT originality. Results demonstrated a significant main effect of Condition on AUT originality, $F\,(2, 86) = 6.186$, $p = .003 < 0.05$, $\eta_p^2 = 0.126$. Post-hoc tests revealed that participants in the "break-wall" condition showed higher originality ($M = 4.83$, $\mathrm{SD} = 2.52$) than those in the "auto-wall" ($M = 3.18$, $\mathrm{SD} = 2.34$) and "no-wall" conditions ($M = 2.69$, $\mathrm{SD} = 2.32$). Similarly, two one-way ANOVAs using Condition as the between-subject factor were performed on AUT fluency and AUT flexibility, respectively. Results revealed a significant main effect of Condition on AUT fluency, $F\,(2, 86) = 5.237$, $p = .007 < 0.05$, $\eta_p^2 = 0.109$, and AUT flexibility, $F\,(2, 86) = 10.01$, $p < .001$, $\eta_p^2 = 0.189$. Post-hoc tests revealed higher fluency and flexibility in the "break-wall" condition (fluency: $M = 10.59$, $\mathrm{SD} = 3.78$; flexibility: $M = 6.17$, $\mathrm{SD} = 1.73$) than in the "auto-wall" condition (fluency: $M = 8.59$, $\mathrm{SD} = 3.74$; flexibility: $M = 4.94$, $\mathrm{SD} = 1.82$) and "no-wall" condition (fluency: $M = 7.19$, $\mathrm{SD} = 4.29$; flexibility: $M = 3.96$, $\mathrm{SD} = 1.97$) (Fig. 2A).

When scores on the RIBS, openness, and PNS were entered into the above ANOVA models as covariates, the main effects of Condition on originality ($p = .006 < 0.05$, $\eta_p^2 = 0.12$), fluency ($p = .014 < 0.05$, $\eta_p^2 = 0.10$), and flexibility ($p = .000 < 0.05$, $\eta_p^2 = 0.18$) remained significant.

Similar one-way ANOVAs using Condition as the between-subject factor were performed on the valence and arousal of emotional state, difficulty of the task, sense of control, embodiment, enjoyableness, time durations of reporting, and scores on the RIBS, openness, and PNS, respectively. No significant effect was observed (see Table 1).

3.2. Answer distribution map in three conditions

Given that some subjects' marks were lost due to machine malfunctions, data from these subjects were excluded from the analysis of the

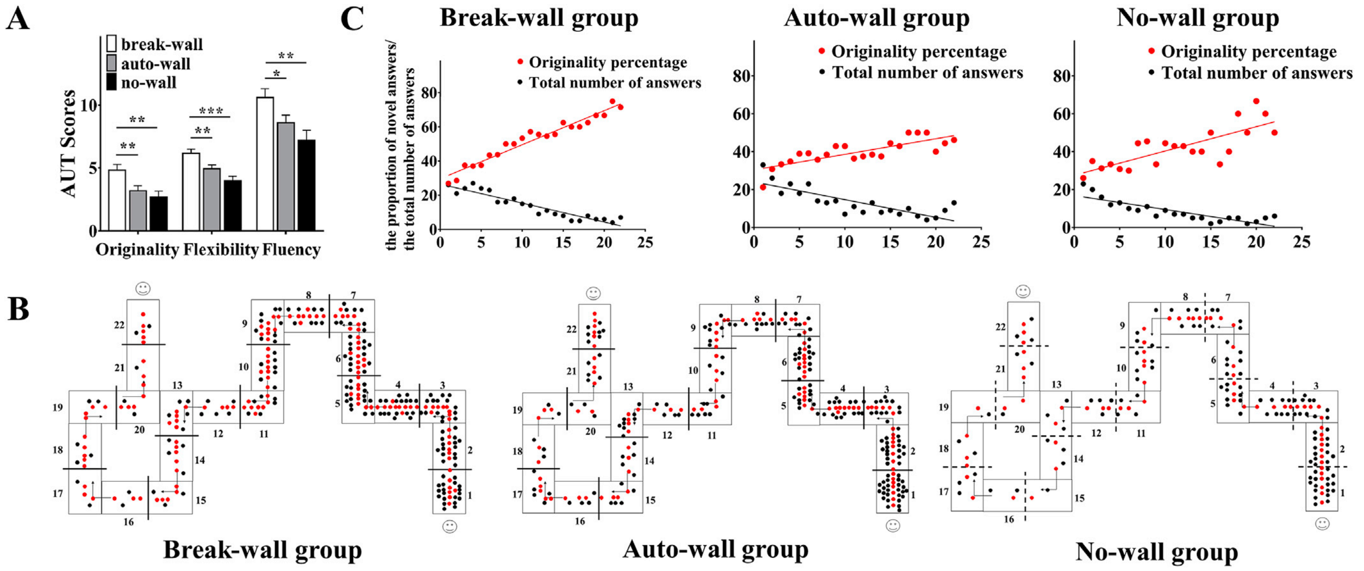

Fig. 2. (A) The effects of Conditions on creative performance. Error bars indicate standard errors of the mean, *$p < 0.05$, **$p < 0.01$; (B) Answer distribution map in the three conditions. The 11 corridors were divided into 22 sections by a line in the middle of each corridor. Subjects advanced in order from 1 to 22; (C) Linear regression predicting the total number of answers and the proportion of novel answers from the number of corridor sections.

Table 1
The descriptive and inferential statistics of the covariates in three conditions.

Variable	Break-wall[a]		Auto-wall[b]		No-wall[c]		F	p
	M	SD	M	SD	M	SD		
Valence	6.45	1.22	6.24	1.28	6.76	1.14	1.28	0.28
Arousal	5.21	1.42	4.71	1.62	5.32	1.71	1.26	0.29
Difficulty	2.90	1.40	3.76	1.68	3.52	1.72	2.29	0.11
Sense of controlling	4.59	1.50	4.38	1.68	4.32	1.71	0.19	0.82
Sense of embodiment	3.31	1.26	3.06	1.47	3.40	1.39	0.48	0.62
Enjoyableness	3.76	1.55	3.15	1.48	3.36	1.16	1.42	0.25
RIBS	64.45	12.22	64.56	12.18	59.08	11.08	1.86	0.16
Openness	34.03	6.38	33.68	7.16	33.31	6.49	0.08	0.93
PNS	46.17	4.74	48.12	5.69	45.73	5.05	1.78	0.17
Time (s)	286.14	43.50	278.62	33.80	278.31	35.72	0.39	0.68

[a] N = 29.
[b] N = 34.
[c] N = 26. RIBS means the Runco Ideational Behavior Scale; PNS means the personal need for structure scale; Time means the time spent on the task.

answer distribution map. Specifically, 4, 2, 2 participants were deleted from the "auto-wall" group, "break-wall" group and "no-wall" group, respectively. Eventually, data from 30 participants in the "auto-wall" group, 27 participants in the "break-wall" group, and 25 participants in the "no-wall" group were entered into the following analyses.

In each condition, the answers of all subjects were plotted on the corridor plan based on Mark3 and the spatial coordinates recorded while participants walking in the virtual corridor (see Fig. 2B). Each point symbolizes one idea given by a participant. The red dots symbolize novel answers that scored one point in the AUT originality, and the black dots symbolize normal answers that scored zero points. To improve the readability and aesthetics of Fig. 2, the x-coordinate/y-coordinate of each answer point was aligned in the vertical/horizontal corridor. However, the walking distance of each corridor remained unchanged. Specifically, in the vertical corridor, the y-coordinate of the answer point was retained, while the x-coordinate was modified to be aligned with other points. The x-coordinate of the answer point in the horizontal corridor was retained, while the y-coordinate was modified to be aligned with the others.

Intuitively, the "break-wall" group had a denser distribution of answer points. In order to further analyze the location data, we set the number of corridor sections as an independent variable to observe its influence on the number of answers and the proportion of novel answers in each section (see Fig. 2C). In all three conditions, as the number of corridors increased, the proportion of novel answers increased. In the "break-wall" condition, the proportion of novel answers was primarily a linear function of the corridor sections ($\beta = 1.992$, $p < .001$, $R^2 = 0.947$). The same positive linear relationships were found in the "auto-wall" ($\beta = 0.822$, $p < .001$, $R^2 = 0.628$) and "no-wall" conditions ($\beta = 1.282$, $p < .001$, $R^2 = 0.607$). These results indicated that although the proportion of novel answers increased with distance (time), "breaking the walls" made participants generate novel ideas more rapidly. When focusing instead on the number of answers in each section, we found this correlation reversed. As the number of corridors increased, the number of answers decreased in the "break-wall" ($\beta = -1.11$, $p < .001$, $R^2 = 0.883$), "auto-wall" ($\beta = -0.934$, $p < .001$, $R^2 = 0.654$), and "no-wall" ($\beta = -0.737$, $p < .001$, $R^2 = 0.726$) conditions. This finding indicated that the quantity (fluency) of responses decreased over time, while the quality (originality) of responses increased over time, which is consistent with the serial order effect in divergent thinking (Johns et al., 2001; Wang et al., 2017).

3.3. Effects of conditions on beta increment within the PFC

A series of one-way ANOVAs with Condition (i.e., break-wall; auto-wall vs. no-wall) as the between-subject factor were conducted on the beta increment of all channels in the PFC during the three periods, respectively. After FDR correction ($p < .05$), the results revealed a significant effect of Condition on the beta increments at the following CHs: CH2, CH11, CH12, and CH15 (see Fig. 3A). The post-hoc tests (Bonferroni corrected) showed a consistent pattern in CH2 and CH11 (BA10: Frontopolar area), where the beta increment was significantly lower in the "break-wall" condition during the "while breaking" period than in the "auto-wall" (CH2: $p = .027$; CH11: $p = .036$) and "no-wall" conditions (CH2: $p = .043$; CH11: $p = .028$) (Fig. 3B and C). The post-hoc tests (Bonferroni corrected) also showed that the beta increment at CH12 (BA11: Frontopolar area) was significantly lower in the "break-wall" condition than in the "no-wall" condition ($p = .043$) during the "while breaking" period (Fig. 3D). During the "after breaking" period, the post-hoc tests showed that the beta increment at CH15 (BA46/BA9: DLPFC) was marginally significantly lower in the "break-wall" condition than in the "auto-wall" condition ($p = .056$) (Fig. 3E). Interestingly, Pearson correlation analysis showed that the beta increment at CH11 in the "auto-wall" condition was significantly negatively correlated with AUT flexibility ($r = -0.485$, $p = .019$) and AUT fluency ($r = -0.548$, $p = .007$) during the "while breaking" period (Fig. 3F and G), and it showed that the beta increment at CH15 in the "auto-wall" condition was significantly negatively correlated with AUT fluency ($r = -0.440$, $p = .035$) (Fig. 3H).

A series of one-way repeated measures ANOVAs with Period (i.e., "before-breaking," "while-breaking," "after-breaking") as the within-subject factor were conducted on the beta increment of all channels in the PFC under the break-wall condition. No significant difference was found (see Table S1 in the supplementary materials).

3.4. Effects of conditions on beta increment within the r-TPJ

A series of one-way ANOVAs with Condition (i.e., break-wall; auto-wall vs. no-wall) as the between-subject factor were conducted on the beta increment of all channels in the r-TPJ during the three periods, respectively. After FDR correction ($p < .05$), a significant, main effect of Condition on the beta increments was observed at CH10, CH21, and CH22 (Fig. 4A). The post-hoc tests (Bonferroni corrected) showed a consistent pattern in CH10 (BA22: Superior Temporal Gyrus) and CH21 (BA19: V3), where the beta increment was significantly lower in the "no-wall" condition during both before and after breaking periods than in the "break-wall" (before: CH10: $p = .030$, CH21: $p = .019$; after: CH10: $p = .031$, CH21: $p = .013$) and "auto-wall" conditions (before: CH10: $p = .026$, CH21: $p = .001$; after: CH10: $p = .041$, CH21: $p = .001$) (see Fig. 4B and C). The post-hoc tests (Bonferroni corrected) also showed that the beta increment at CH22 (BA7: Somatosensory Association Cortex) was significantly lower in the "break-wall" condition than in the "auto-wall" condition ($p = .036$) during the "while breaking" period (see Fig. 4D), and Pearson correlation analysis showed that the beta increment at CH22 in the "auto-wall" condition was significantly negatively correlated with AUT fluency ($r = -0.519$, $p = .020$) (Fig. 4E).

A series of one-way repeated measures ANOVAs with Period as the

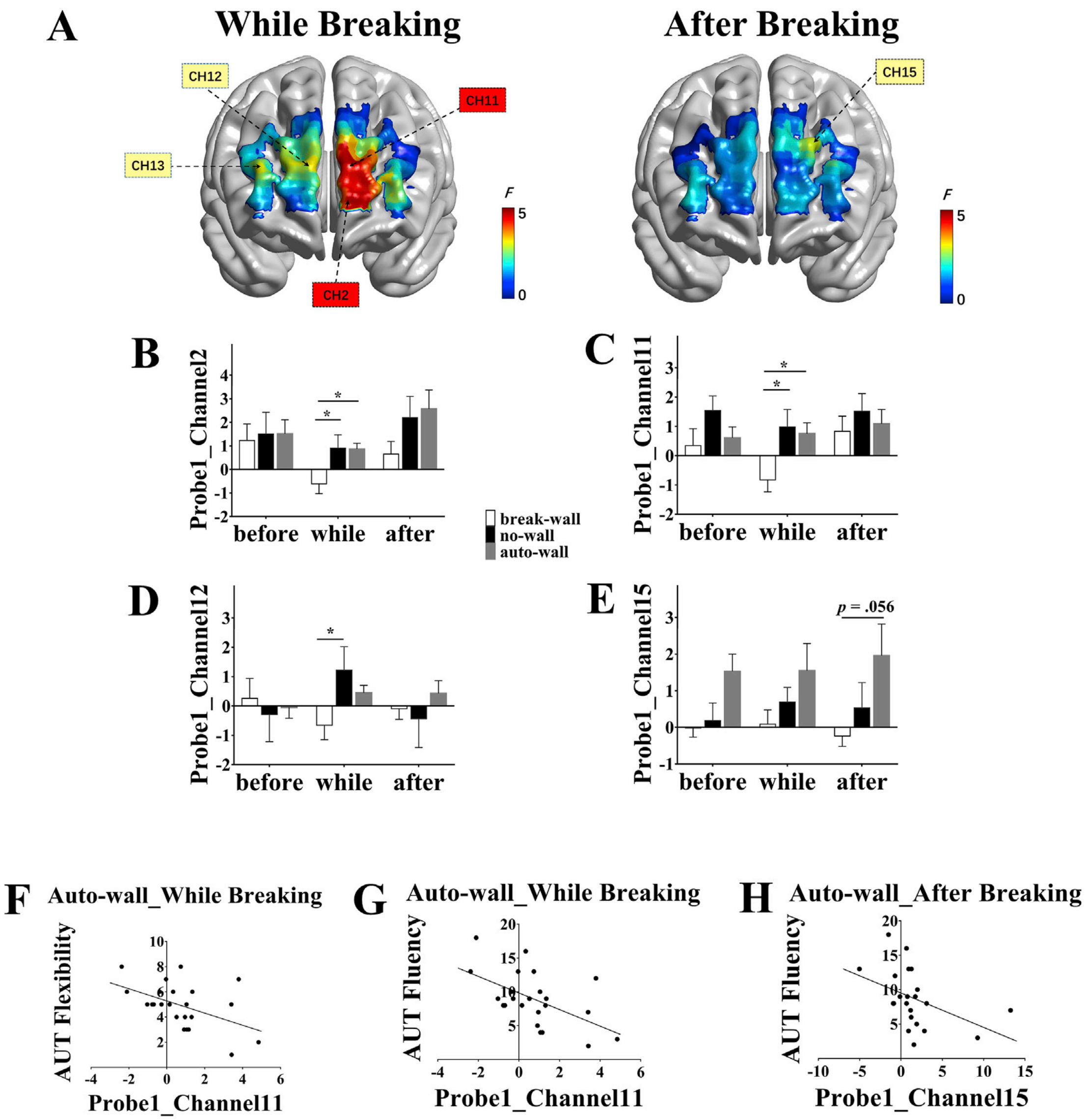

Fig. 3. (A) One-way ANOVA F-maps under different periods, with Condition as the between-subject factor. The F-maps were generated using a spatial interpolation linear method. The coordinates and F values of the maps were converted into *.img files using xjView and then rendered over the 3D brain model using BrainNet Viewer (Xia et al., 2013). (B) (C) (D) (E) The beta increments in the Frontopolar area and the dorsolateral prefrontal cortex (DLPFC); (F) (G) AUT flexibility and AUT fluency were negatively correlated with beta increment in CH11 during the "while breaking" period under the "auto-wall" condition. (H) AUT fluency was negatively correlated with beta increment in CH15 during the "after breaking" period under the "auto-wall" condition. Error bars indicate standard errors of the mean, $*p < 0.05$, $**p < 0.01$.

within-subject factor were conducted on the beta increment of all channels in the r-TPJ under the break-wall condition. The post-hoc tests showed no significant difference (see Table S2 in the supplementary materials).

4. Discussion

In this study, we explored whether the embodiment of the metaphor "breaking the rules" could affect creative performance and revealed the underlying neural correlates using the fNIRS device. As far as we know, this is the first study to image the brain function of subjects when they are performing embodied metaphors and creative tasks. The behavioral results showed that fluency, originality, and flexibility scores on the AUT were significantly higher in the "break-wall" condition when compared with the auto-wall and no-wall conditions. The fNIRS results showed that the frontopolar areas (PFC–CH2; PFC-CH11) were less activated in the "break-wall" condition than in the "auto-wall" and "no-wall" conditions during the "while breaking" period, and the beta increment at the DLPFC (PFC–CH15) was marginally significantly lower in the "break-wall" condition than in the "auto-wall" condition ($p = .056$) during the "after breaking" period. Moreover, we found that the beta increment at the somatosensory association cortex (r-TPJ-CH22) was significantly lower in the "break-wall" condition than in the "auto-wall" condition during the "while breaking" period.

Specifically, significantly higher creative performance was observed in the "break-wall" condition compared with that in the "auto-wall" and "no-wall" conditions, and the effect sizes of the effect of Condition on fluency, originality, and flexibility were all medium, which is consistent with our previous study (Wang et al., 2018). These results provided reproducible evidence for embodied cognition and revealed the effects of embodied metaphors on creative cognition. In the current study, however, we added a more suitable control condition in which the same barrier walls existed (i.e., "auto-wall" condition). This strategy allowed us to assess the behavioral and neural effects of the "breaking the wall"

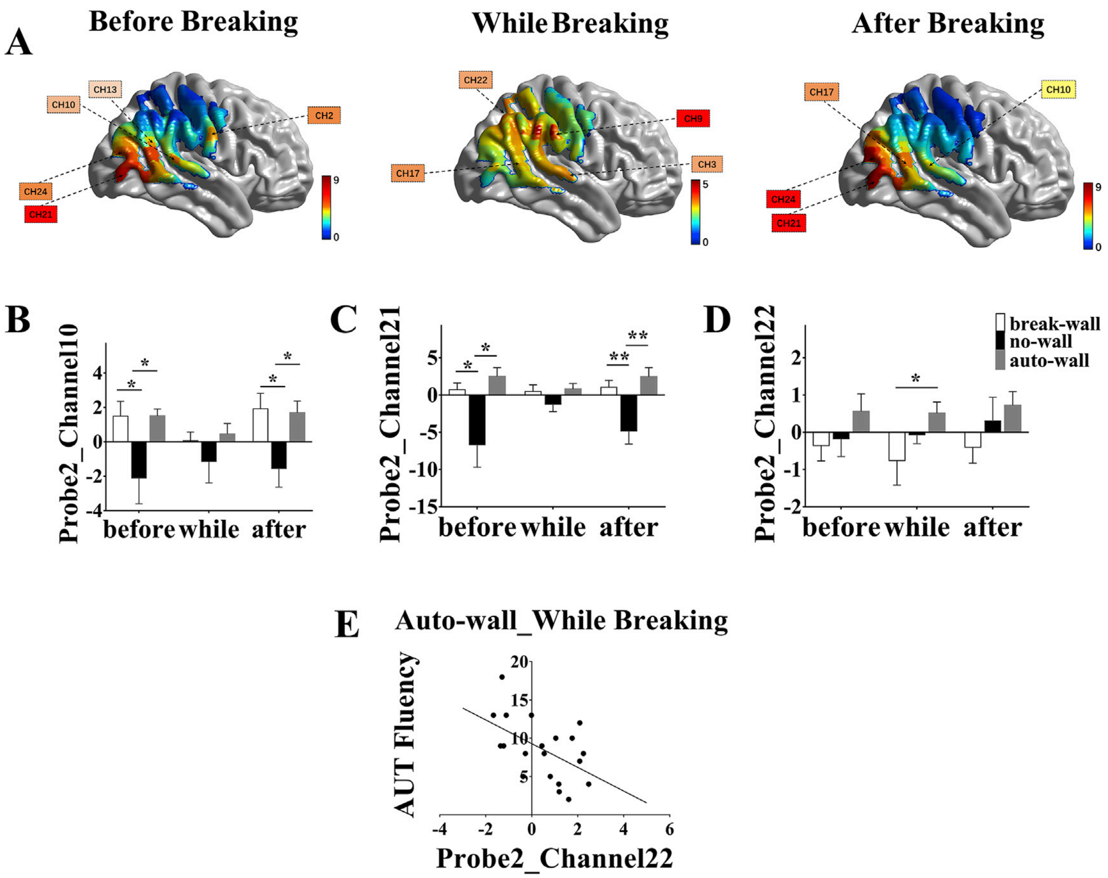

Fig. 4. (A) One-way ANOVA F-maps under different periods, with Condition as the between-subject factor. (B) (C) (D) The beta increments in r-TPJ CH10, CH21, and CH22. (E) The correlation between AUT fluency and beta increment in CH22 during the "while breaking" period. Error bars indicate standard errors of the mean, $*p < 0.05$, $**p < 0.01$.

metaphor while removing confounding factors, such as differences in visual stimulation. Moreover, participants passed through the barrier walls in both the "break-wall" and "auto-wall" conditions, but in different manners. Rather than being broken, in the "auto-wall" condition, barrier walls would automatically open when the participants were close enough to them. Moreover, one-way ANOVA using Condition as the between-subject factor on the RIBS scores showed no significant effect. This may indicate that the basal creative performance is equal across groups, and the group differences observed in the study were not induced by basal creativity potential (see Table 1). However, it also should be noted that the RIBS is not an equal creativity assessment when compared to the AUT used in the study, namely creativity tests and questionnaires are not equivalent. Accordingly, it would be better to use a preliminary AUT rather than RIBS before the experiment to assess the basal creative performance of participants in the future studies.

Previous studies have shown that the activation of the frontopolar area is related to rule generation and rule compliance (Bunge, 2004; Crescentini et al., 2011). For instance, Crescentini et al. (2011) asked participants to watch a series of images of cards, each consisting of a set of circles numbered in a sequence with one colored blue, and participants had to predict the position of the blue circle on the next card. Researchers categorized participants' responses in a series of phases—either rule acquisition (responses given up to and including rule discovery) or rule following (correct responses after rule acquisition)—and found that the frontopolar cortex was active throughout both the rule acquisition and rule following phases before a rule became familiar. During the "while breaking" period, participants bodily experienced the event of "breaking the walls," and the "rules" disappeared as participants broke the walls. During this period, participants might be more involved in perceiving and breaking rules than performing the creativity task. Therefore, during the "while breaking" period, the "break-wall" group showed neural deactivation in the frontopolar area. Previous studies have also found that rule-breaking behavior might be related to the deactivation of the DLPFC, and deactivating the DLPFC using transcranial magnetic stimulation can reduce individual punishment for social norm violations (Buckholtz et al., 2015; Raine and Yang, 2006). Accordingly, the deactivation of the DLPFC observed in the "break-wall" group during the "after breaking" period may reflect the experience of breaking the rules. Moreover, it has been demonstrated that the deactivation of the DLPFC can facilitate the cognitive process of creativity by allowing unfiltered, unconscious, or random thoughts and sensations to emerge (Limb and Braun, 2008; Vartanian et al., 2013). For instance, Limb and Braun (2008) observed a decreased activation of the DLPFC during improvisation in professional jazz pianists. Hence, the deactivation of the DLPFC induced by "breaking the walls" eventually contributed to individual creative performance. Intriguingly, Pearson correlation analysis showed that the beta increment at PFC-CH11 (the frontopolar cortex) in the "auto-wall" condition was significantly negatively correlated with AUT flexibility and AUT fluency during the "while breaking" period. It also showed that the beta increment at PFC-CH15 (DLPFC) in the "auto-wall" condition was significantly negatively correlated with AUT fluency. These findings may in part mirror our explanations that the physical actions of breaking walls activated the conceptual metaphor of breaking rules, which triggered brain activities related to rule breaking, thus affecting creative performance, and such improvement was also reflected in the corresponding changes in neural activities.

In addition, we observed that the somatosensory association cortex (r-TPJ-CH22) was less activated in the "break-wall" condition than in the "auto-wall" condition during the "while breaking" period (Fig. 4). Previous studies have shown that the r-TPJ was involved in body ownership and embodiment (Donaldson et al., 2015; Lopez et al., 2008). For instance, the "out-of-body experience" is a disembodied, illusory, visual experience during which the subject experiences the impression of seeing a second own body in extra-personal space (Blanke and Mohr, 2005). Blanke et al., 2002 found that using focal electrical stimulation to activate the r-TPJ in a patient who was undergoing evaluation for epilepsy treatment could repeatedly induce "out-of-body experiences." Researchers also found that when healthy individuals were imagining the experience of "out-of-body," activation of the r-TPJ was observed (Blanke et al., 2005). Moreover, using transcranial magnetic stimulation (TMS) to deactivate the r-TPJ can impair these imaginings (Blanke et al., 2005). These studies might indicate that the activation of the r-TPJ is related to a sense of bodily separation (disembodiment), and deactivation is associated with embodiment. In our study, the "break-wall" group represented an embodied metaphor, which might enhance the feeling of embodiment and then lead to deactivation of the r-TPJ, which is consistent with previous studies. Since it is proposed that sustained deactivation of this region indicates an internal attentional state that can help individuals attend to potentially creative ideas generated in the mind—thus benefiting creative idea generation (Berkowitz and Ansari, 2010; Corbetta et al., 2008; Fink et al., 2012)—deactivation of the r-TPJ might contribute to better creative performance in the "break-wall" condition. Berkowitz and Ansari (2010) found that during melodic improvisation, the r-TPJ of musicians deactivated, whereas no change in this region was observed for ordinary people. Other researchers also found that stimulating individuals with common ideas can contribute to creative idea generation and is associated with deactivation of the r-TPJ (Fink et al., 2012). In our study, we found better creative performance and deactivation of the r-TPJ in the "break-wall" group, and the beta increment at r-TPJ-CH22 in the "auto-wall" condition was significantly negatively correlated with AUT fluency, which is consistent with previous studies.

Moreover, during both the before and after breaking periods, we found a consistent pattern in r-TPJ-CH10 (BA22: Superior Temporal Gyrus) and r-TPJ-CH21 (BA19 Visual areas, V3), where the beta increment was significantly lower in the "no-wall" condition than in the "break-wall" and "auto-wall" conditions (Fig. 4). It has been demonstrated that activity in the superior temporal gyrus was associated with semantic processing and language association, which play important roles in divergent thinking (Henke et al., 2003). Since there was no brick wall in the "no-wall" group when compared to other groups, it lacked not only visual stimulation but also semantic processing of "walls" and "rules." Therefore, the beta increments in the superior temporal gyrus and visual areas were significantly lower in the "no-wall" condition than in the other conditions. Meanwhile, no difference was observed among the three groups during the period of "while-breaking," possibly because the walls in the three conditions were nonexistent, and participants might focus on passing through the corridors.

Further, it is worth discussing that in some cases, differences were found between the "break-wall" and both the "auto-wall" and "no-wall" conditions, and in other cases, the effect was only present in comparison to one of the two control groups. In PFC-CH15 and r-TPJ-CH22, a significantly lower beta increment was only observed in the "break-wall" group when compared to the "auto-wall" group. As mentioned above, the "no-wall" group lacked visual stimulation and semantic association when compared to the other two groups. Moreover, the only difference between the "break-wall" group and "auto-wall" group was the way in which the brick wall disappeared. In this case, the lower beta increment at PFC-CH15 and r-TPJ-CH22 in the "break-wall" group when compared to the "auto-wall" group, rather than the "no-wall" group, indicates the specific effect of "breaking the walls" on individual creative performance. In other words, the "auto-wall" group is a more appropriate control condition for the "break-wall" group when compared to the "no-wall" group. In addition, although no significant difference was observed, there was still a tendency for the "break-wall" group to show a lower beta increment than the "no-wall" group in both PFC-CH15 and r-TPJ-CH22.

Furthermore, it is worth mentioning that this is the first study using VR and fNIRS to explore the effects of embodied metaphor on creativity. VR is a medium that is able to induce the experience of "presence" in a computer-generated world Zhou et al., 2019, and thus it can be used to simulate the experience of "breaking the walls," which is almost impossible to manipulate in the real world due to the danger. By designing targeted virtual environments to alter the experience of the body, VR can be defined as an "embodied technology'' for its possibility to modify the embodiment experience of its users (Riva et al., 2019). Meanwhile, fNIRS offers high freedom in recording participants' brain activities in various scenes. Taken together, our study is a preliminary attempt to explore the neural correlates of the embodied metaphor "breaking the rules" and how it affects creativity. Findings of the current study may provide a promising direction for future research in this field, which is combining VR technology and fNIRS to investigate embodied cognition.

There were still several limitations in the current study. Primarily, it should be noted that due to the low spatial resolution of fNIRS, only neural activities in the cerebral cortex can be recorded during the scanning, which leaves neural activities under the cerebral cortex unexplored. Although devices such as fMRI can provide higher spatial resolution, as already explained in the introduction, we suggest that fNIRS is more appropriate for this study. In addition, we only focused on the PFC and r-TPJ areas in this study. Future research in this field can expand the coverage of the fNIRS optode probe sets so that the underlying neural correlates of the embodied metaphor can be fully explored. Moreover, individuals who are familiar with this metaphor might be more susceptible to the "breaking the walls" metaphor, whereas others might be less susceptible to the metaphor. Hence, the impact of individual familiarity with the metaphor on the effect of the "breaking the rules" metaphor should be explored in future studies. Furthermore, considering that it is quite exhausting for individuals to wear both fNIRS devices and VR head-mounted display for a long time, only one AUT problem was used in the study. However, previous studies have reported poor inter-objective reliability of the AUT task and using several objects in a study was recommended (Barbot, 2019; Reiter-Palmon et al., 2019). Hence, more objects should be used for the AUT in future studies.

Conflicts of interest

The authors have nothing to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2019.116114.

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