Theory of mind (ToM) is the ability to infer other people's mental states, such as beliefs, intentions, and desires, to predict their behaviors. In this critique, the first study hopes to validate that both ToM and cognitive empathy are mediated in right temporo-parietal junction (rTPJ). The second study explores the hierarchical structure of ToM. Therefore, the objective of both studies is to learn more about where ToM is represented in the brain and its cognitive structure. ToM is interesting because it's closely related to neurodevelopmental disorders, such as autism, and studying ToM allows researchers to understand ToM itself and help people with neurodevelopmental disorders.

In the first study, the researchers conducted transcranial direct current stimulation (tDCS) over the rTPJ. They hypothesized that anodal stimulation would enhance ToM and cognitive empathy, while cathodal stimulation would impair ToM and cognitive empathy. 68 participants were split into three groups: anodal, cathodal, and sham stimulations. Participants were shown 40 cartoon strips that triggered ToM ability, cognitive empathy, or inferences about physical causalities, which acted as a baseline metric. The task was to infer the most likely next cartoon frame given two options. Participants who received cathodal stimulation made correct inferences 80% of the time, while participants who received anodal or sham stimulation made correct inferences 90% of the time.

The tDCS method and between-subject design used in this study were appropriate to demonstrate that ToM and cognitive empathy are mediated by the rTPJ. The researchers confirmed that using tDCS induces cortical excitability and affects participants' inference abilities. By using a between-subject design, the researchers tested the effects of different types of stimulation across participants. However, using a within-subject design would definitively confirm the results, but was not appropriate because participants could become more skilled at inference due to repeated exposure to the same stimulus.

The data did support that cathodal stimulation impairs ToM and cognitive empathy, but did not show that anodal stimulation enhances ToM ability. This does not invalidate that the rTPJ controls ToM and cognitive empathy. The task of inferring others' mental states was too easy for healthy adults; hence performance could not be improved. However there could be alternative explanations of this data. The study did not show how ToM and cognitive empathy are related, just that they are both mediated by the rTPJ. An interesting exercise would be to investigate how impairment of ToM affects cognitive empathy and vice versa. This exercise could show if these two cognitive abilities are dependent on each other or operate independently.

In the second study, the researchers investigated the existence of a hierarchical framework of ToM, hypothesizing that reading the interactive-mind is a more complex process and recruits more energy than reading the single-mind. The electroencephalogram (EEG) method was used to record neural activity from 64 scalp sites of the frontal, central, and parietal regions. The design of the study was to present the 20 participants with 70 four-character Chinese idioms. The idioms either described the physical world, the single-mind, or the interactive-mind. The participants were required to visualize the scene or people's mentality represented by the idiom. The result was that during the 700-800ms epoch, participants on average recruited 2.67 μV to understand the interactive-mind, while participants only used 1.44 μV and 1.9 μV to understand the physical representation and the single-mind, respectively.

The EEG method and Chinese character idiom design were appropriate for this study. This study took advantage of the superior temporal resolution of event-related potential (ERP) to measure neural activity related to the onset of an idiom. Previous studies used fMRI methods, but were limited by fMRI's low temporal resolution. In terms of design, this study used Chinese idioms as consistent visual stimuli to evoke ToM ability. Previous EEG studies used "person cartoons" and "ToM cartoons" with one or more people as stimuli. This might have affected the ERP waveform due to participants having to process different numbers of people.

The data supported that ToM is structured in a hierarchical form. Specifically, in the 500-700ms range, the ERP mean amplitudes over the frontal area for reading the single and interactive mind were much greater than that for physical representation. In the 700-800ms range, the ERP mean amplitude over the frontal-central area for reading the interactive mind was much greater than reading the single mind and physical representation. Participants first distinguished between mental processing (scenery) and non-mental processing (single or interactive mind), then distinguished between understanding the single-mind and the interactive-mind. Due to the controlled design set-up, there are no alternative explanations for the data. Only data from correct trials were included, idioms describing the physical world acted as a baseline, and the experiment was timed with great accuracy to ensure that neural activity corresponded to an idiom.

Both studies converge that rTPJ mediates ToM abilities. In the first study, cathodal stimulation over the rTPJ impaired ToM and cognitive empathy. In the second study, EEG results showed that there was an increased in activation over the rTPJ when participants understood the single and interactive-mind. The hierarchical framework of ToM does not invalidate that rTPJ mediates ToM. Instead these results are complementary, allowing for new questions to emerge, such as how stimulating the brain at certain times could enhance or impair understanding of the single or interactive mind.

These studies have enlightened the field of cognitive neuroscience. The first study provided more data that the rTPJ facilitates ToM and cognitive empathy. The question that remains is how anodal stimulation over certain regions of the brain affects ToM and cognitive empathy. The second study showed that reading the single-mind and the interactive-mind are two different levels of ToM. The question that remains is the neurological reason for the hierarchical structure of ToM. All this work will lead us to better understand social interactions and help individuals with socio-cognitive disabilities.

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Using tDCS to Explore the Role of the Right Temporo-Parietal Junction in Theory of Mind and Cognitive Empathy

*Xiaoqin Mai[1], Wenli Zhang[1], Xinmu Hu[1], Zhen Zhen[2], Zhenhua Xu[1], Jing Zhang[1] and Chao Liu[2]**

[1] Department of Psychology, Renmin University of China, Beijing, China, [2] State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, China

The right temporo-parietal junction (rTPJ) is thought to be closely related to theory of mind (ToM) and cognitive empathy. In the present study, we investigated whether these socio-cognitive abilities could be modulated with non-invasive transcranial direct current stimulation (tDCS) of the rTPJ. Participants received anodal (excitatory), cathodal (inhibitory), or sham stimulation before performing a social cognitive task which included inferring other's intention (the ToM condition) and inferring other's emotion (the cognitive empathy condition). Our results showed that the accuracy of both ToM and cognitive empathy decreased after receiving the cathodal stimulation, suggesting that altering the cortical excitability in the rTPJ could influence human's socio-cognitive abilities. The results of this study emphasize the critical role of the rTPJ in ToM and cognitive empathy and demonstrate that these socio-cognitive abilities could be modulated by the tDCS.

Keywords: social cognition, theory of mind, cognitive empathy, temporo-parietal junction (TPJ), transcranial direct current stimulation (tDCS)

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****Correspondence:***
Chao Liu
liuchao@bnu.edu.cn

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INTRODUCTION

Successful human social interaction mostly depends on the understanding of others' mental states, which are built on the social abilities such as theory of mind (ToM) and cognitive empathy. ToM is the central function of human social cognition, referring to the ability to attribute other's mental states, such as beliefs and intentions (Frith and Frith, 1999). It can help us understand observable actions by inferring agents' mental representations. Affective empathy is the ability to share the emotional experience of others ("I feel what you feel"). It is different from cognitive empathy which is the capacity to understand other's perspective or mental states (Preston and de Waal, 2002; Shamay-Tsoory et al., 2009; Schnell et al., 2011). Cognitive empathy emphasizes inferring other's affective mental state ("I understand what you feel") but not necessarily sharing this feeling (de Waal, 2008). Many researchers believe that cognitive empathy is related to ToM (Eslinger, 1998; Shamay-Tsoory et al., 2003). Walter (2012) proposes that cognitive empathy is the emotional part of ToM. Blair (2005) even equates cognitive empathy with ToM. Since ToM and cognitive empathy have an overlap in concept, they might recruit common brain regions.

Functional magnetic resonance imaging (fMRI) studies have demonstrated the involvement of temporo-parietal junction (TPJ) in the attribution of mental states (Vogeley et al., 2001; Saxe and Kanwisher, 2003; Saxe and Wexler, 2005; Spengler et al., 2009; Schurz and Perner, 2015). For example, Saxe and Kanwisher (2003) used false belief tasks and found the greater activity in the

TPJ when participants read stories about a person's belief than the stories describing a physical process, such as melting or rusting, suggesting the important role of the TPJ in understanding other's mental states. Some studies also suggests that the TPJ is involved in cognitive empathy (Rankin et al., 2005; Shamay-Tsoory et al., 2005; Vollm et al., 2006). Vollm et al. (2006) designed an experimental paradigm to directly compare the neural correlates of ToM and cognitive empathy using fMRI, in which participants were asked to make inferences about the emotional or the intentional states of the protagonists in a visual cartoon task. The results showed that both ToM and cognitive empathy activated the TPJ, medial prefrontal cortex, and temporal poles, though they also recruited other distinct brain regions. They concluded that the overlapping network of ToM and cognitive empathy is related to inferring others' internal states. Using the same cartoon task, Atique et al. (2011) also found that both ToM and cognitive empathy (in their paper, they use the term "intention mentalizing" and "emotion mentalizing", respectively) activated the TPJ, though different subregions. These findings suggest that ToM and cognitive empathy are closely related and the TPJ is engaged in both of them.

In recent years, non-invasive brain stimulation techniques, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), have been used to explore the role of the TPJ, especially the right TPJ (rTPJ), in social cognition. Costa et al. (2008) reported that the application of repetitive TMS over the rTPJ significantly worsened accuracy and response times (RTs) in both false belief and faux-pas written story tasks, confirming the important role of the rTPJ in ToM performance. Some studies have also found that applying the TMS over the rTPJ disrupted the capacity to use mental states in moral decision making (Young et al., 2010; Jeurissen et al., 2014). Moreover, Young et al. (2010) revealed that using TMS over the rTPJ led participants rely less on the actor's mental states when making moral judgments.

More recently, using tDCS, several studies reported that the application of anodal or cathodal stimulation over the rTPJ could modulate the belief attribution (Sellaro et al., 2015; Sowden et al., 2015; Ye et al., 2015). Sellaro et al. (2015) found that participants who received anodal stimulation assigned less blame to accidental harms compared to participants who received cathodal or sham stimulation, emphasizing the role of rTPJ in mediating the belief attribution for moral judgements. Ye et al. (2015) reported that inhibiting the rTPJ of typical adults with cathodal stimulation decreased the role of beliefs in moral judgments and increased the dependence on the action's outcomes when making moral judgment.

However, Santiesteban et al. (2012) did not find the effects of anodal or cathodal stimulation of the rTPJ when participants were asked to make mental judgments about themselves or others (ToM), though they did observe that anodal stimulation of the rTPJ improved the on-line control of self and other representations in the imitation and perspective-taking tasks which involve low-level sociocognitive processes. In their latest study (Santiesteban et al., 2015), they applied anodal stimulation over the rTPJ or left TPJ (lTPJ) and observed the bilateral TPJ involvement in the perspective-taking and imitation inhibition, while they still found no effect on the ToM task in which participants watched a movie and were asked to infer the mental state of characters. The possible reason for no tDCS effects on ToM in their studies might be that the ToM tasks they used are insensitive to the performance variation induced by stimulation in typical adults (Santiesteban et al., 2015).

The present study aimed to use the non-invasive tDCS to examine whether both ToM and cognitive empathy depends causally on the neural activity in the rTPJ that has previously identified through fMRI (Vollm et al., 2006; Atique et al., 2011). Therefore, in the present study, we used the cartoon task derived from Vollm et al. (2006) to validate the crucial role of rTPJ in the these sociocognitive abilities through elevating or inhibiting the cortical excitability. Many fMRI studies of ToM reported the activity in the rTPJ or bilateral TPJ, while a few studies reported the unilateral activation of the left TPJ (see meta-analysis by Van Overwalle, 2009). In addition, most previous TMS and tDCS studies of ToM stimulate the rTPJ (e.g., Costa et al., 2008; Santiesteban et al., 2012). In order to make our study comparable to previous studies, we focused on the rTPJ instead of lTPJ. Based on the previous studies, we hypothesized that anodal stimulation could enhance the abilities of ToM and cognitive empathy, while the cathodal could have the opposite effect. As to our knowledge, this is the first study to explore whether both ToM and cognitive empathy could be modulated by the tDCS of the rTPJ.

There are several reasons for why we are interested in ToM in adults. First, although the ToM ability is already fully developed at the age of 4–5 years, its specific neural mechanisms remain unclear. Second, the ToM ability is closely correlated with neurodevelopmental disorders, such as autism. Third, some socio-cognitive abilities, such as moral judgment, and lie detection, also rely on ToM (Sellaro et al., 2015; Sowden et al., 2015; Ye et al., 2015; Young et al., 2010). Therefore, investigating ToM in adults could help us understand not only ToM itself but also neural models of other socio-cognitive abilities, as well as help individuals with neurodevelopmental disorders.

MATERIALS AND METHODS

Participants

Sixty-eight right-handed adults (mean age 22.8 ± 2.6 years, 35 females) participated in the study. They were randomly assigned to three groups: the anodal ($n = 21$), the cathodal ($n = 23$), or the control "sham" ($n = 24$). Two additional participants, one in the anodal group and another in the cathodal group, withdrew from the study because they reported to be afraid of receiving the tDCS. None of the participants reported a history of neurological or psychiatric disorders. All participants were paid for their participation and gave their informed consent. The study was approved by the Institutional Review Board of Department of Psychology at Renmin University of China.

tDCS Protocol

Transcranial direct current stimulation was administered through a specially battery-driven constant current stimulator

(DC-Stimulator Plus, NeuroConn GmbH, Germany). The stimulation was induced through a saline-soaked pair of surface sponge electrodes (35 cm^2 in size). To stimulate the rTPJ, the anodal or cathodal electrode was placed between CP6 and C6 according to the international 10–20 EEG system and previous fMRI studies (Jurcak et al., 2007) (see **Figure 1**). This area covers the MNI coordinates [54, −59, 22] of the rTPJ reported in previous fMRI studies (Young et al., 2007; Young and Saxe, 2009). The reference electrode was placed over the left cheek.

As in previous studies, to assure the target cortex to be activated completely (Jurcak et al., 2007; Cerruti and Schlaug, 2009), a relatively weak current (1.5 mA) was constantly delivered for 20 min. For the sham group, although the electrode was placed over the rTPJ for 20 min, the stimulation only lasted for 15 s. At the onset of each condition (anodal, cathodal, or sham), the fade in and fade out time were both 15 s (Cerruti and Schlaug, 2009; Holland et al., 2011; Keeser et al., 2011). Participants felt the current as itching sensation at the beginning of the stimulation.

Experimental Procedure

All participants filled in the Interpersonal Reactivity Index (IRI) questionnaire (Davis, 1980) to assess empathy before receiving the stimulation. The IRI is a self-report questionnaire that includes four subscales, perspective- taking, fantasy, empathic concern, and personal distress. Each subscale is comprised of seven questions, which constitutes the total 28 items. The perspective- taking and fantasy subscales are two cognitive scales, while the empathic concern and personal distress subscales are two affective scales (Davis, 1983). We focused our analysis on the perspective- taking and fantasy subscales, because we only interested in cognitive empathy. The perspective- taking scale measures the tendency to accept spontaneously others' point of view (e.g., "I sometimes try to understand my friends better by imagining how things looks from their perspective"); while the fantasy scale measures the tendency to transfer oneself into fictional situations (e.g., "When I am reading an interesting story or novel I imagine how I would feel if the events in the story were happening to me"). Responses are on a 5-point Likert scale ranging from 0 (does not describe me well) to 4 (describe me very well). The Cronbach's alpha was 0.81 for the perspective-taking scale and 0.79 for the fantasy scales.

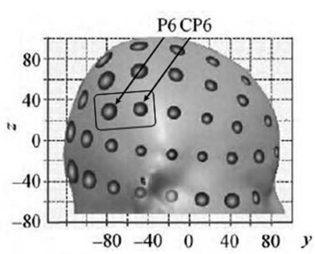

FIGURE 1 | The location of the anodal or cathodal electrode was placed in the MNI coordinates (adapted from Jurcak et al., 2007).

After the stimulation, participant performed the task derived from Vollm et al. (2006) on the computer. The task consists of four conditions: ToM, Cognitive empathy, Physical 1, and Physical 2. The Physical 1 and Physical 2 are the control of the ToM and Cognitive empathy, respectively. **Figure 2** shows examples of stimuli from each condition. In the ToM and Cognitive empathy conditions, participants were asked to infer the character's intention or emotion, respectively. In the other two conditions, they had to make inferences based on physical causalities. The stories of ToM and Physical 1 described one character only while Cognitive empathy and Physical 2 described two characters.

A total of 40 comic strips each depicting a short story were presented in eight blocks, with each block comprising of five comic strips belonging to the same condition. Thus each condition was showed twice and each strip was showed only once. The sequence of blocks and comic strips in each block were counterbalanced.

Each block began with an introductory question for 6 s which indicated the required type of inference (ToM condition: "What will the main character do next?"; Cognitive empathy condition: "What will make the main character feel better?"; Physical 1 and Physical 2 conditions: "What is most likely to happen next?"). Each strip cartoon was presented for 6 s, and then another two cartoons showing the possible outcome were imposed on the bottom of the screen for 4.5 s. Participants were required to make a choice between the two possible outcomes of the stories by pressing the button as soon as possible. Accuracy and RTs were recorded for all cartoons. A score of one referred to a correct answer while a score of 0 was assigned to be wrong.

Data Analysis

Analyses were done with SPSS statistical software (version 22, Chicago, IL, USA). Accuracy and RTs in each condition (ToM, Cognitive empathy, Physical 1, and Physical 2) were analyzed using one-way analysis of variance (ANOVA) with Group as a between-subjects factor (i.e., anodal, sham, and cathodal). Further *Post hoc* analyses were conducted using the Tukey's honestly significant difference (HSD) test when appropriate.

RESULTS

IRI score

The scores for the perspective-taking and fantasy subscales which measure cognitive empathy were analyzed using a one-way ANOVA with Group as a between-subjects factor (i.e., anodal, sham, and cathodal). No significant differences were found for scores of both perspective-taking (mean $\pm$ SD, 17.9 $\pm$ 3.2, 17.9 $\pm$ 3.1, and 18.8 $\pm$ 4.5) and fantasy (15.2 $\pm$ 5.0, 15.4 $\pm$ 5.8, and 14.0 $\pm$ 6.4) among the Anodal, Cathodal, and Sham groups before stimulation, indicating that there were no group differences in cognitive empathy before receiving the tDCS.

Accuracy

Figure 3 shows accuracy in four conditions for three stimulation groups. In the ToM condition, there was a reliable main effect

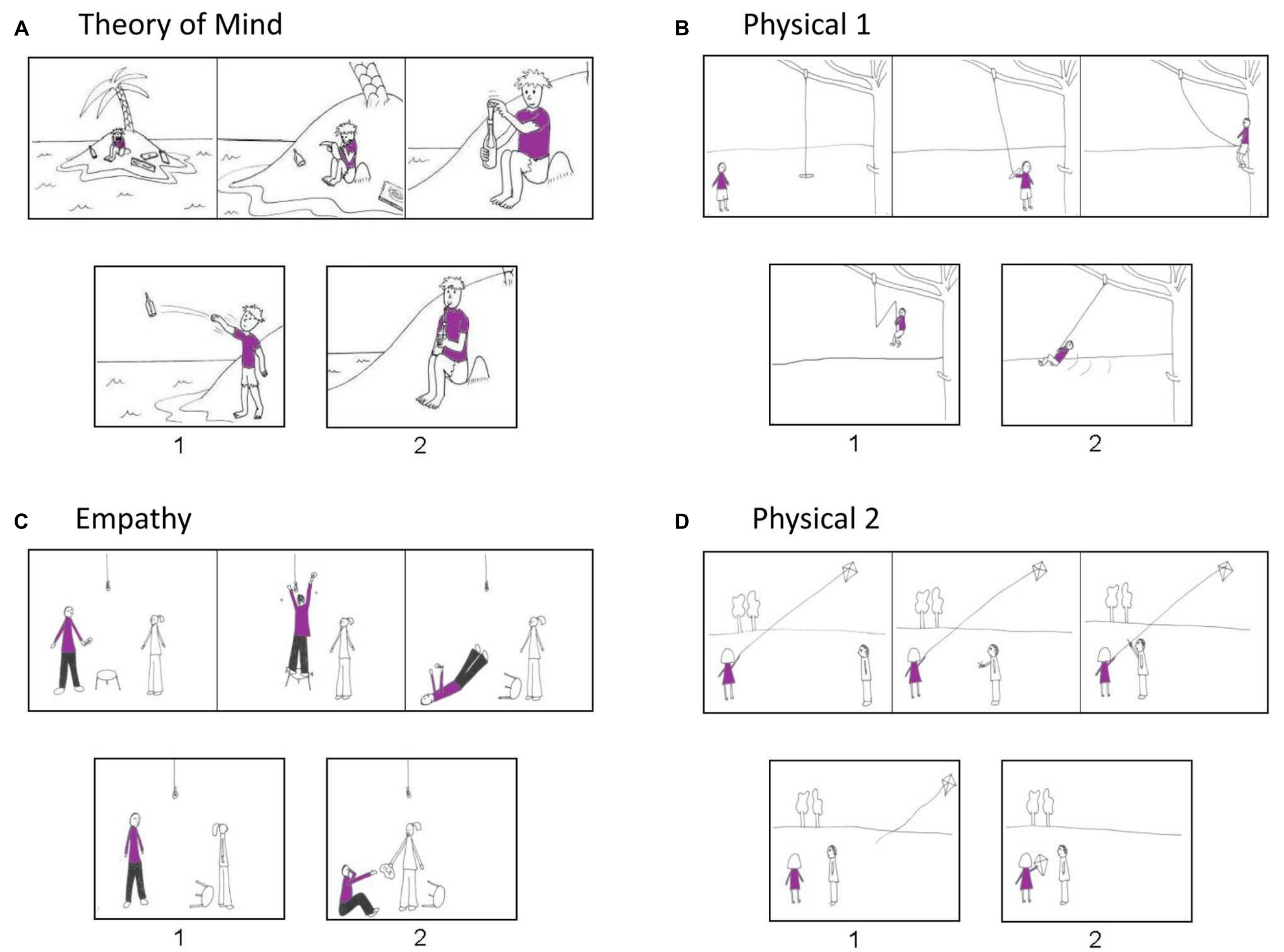

FIGURE 2 | Examples of stimuli from four conditions. The correct answers in **(A)** Theory of mind (ToM), **(B)** Physical 1, **(C)** Empathy, and **(D)** Physical 2 stories are picture 1, picture 2, picture 2, and picture 1, respectively (derived from Vollm et al., 2006).

of Group, $F(2,65) = 3.76$, $p = 0.028$. *Post hoc* analyses revealed that the difference between Cathodal and Sham groups reached significance ($p = 0.040$) but no differences were found between Anodal and Shame groups ($p = 0.980$) and between Anodal and Cathodal groups ($p = 0.075$), indicating that compared with the the Sham group, participants in the Cathodal group were less accurate in inferring the character's intention. In the Physical 1 condition which is the control of the ToM condition, no differences were found between stimulation groups.

In the cognitive empathy condition, there was aslo a reliable main effect of Group, $F(2,65) = 3.35$, $p = 0.041$. *Post hoc* analyses showed that the difference between Cathodal and Sham groups reached significance ($p = 0.035$) but no differences were found between Anodal and Shame groups ($p = 0.236$) and between Anodal and Cathodal groups ($p = 0.685$), indicating that compared with the Sham group, participants were less accurate in inferring the character's emotion after receiving the cathodal stimulation. In the Physical 2 conditions which is the control of the cognitive empathy condition, no differences were found between stimulation groups.

Response Times

Response times were recorded for all 40 trials and the trials failing to respond within 4.5 s were excluded from the analsyis. **Table 1** shows RTs in four conditions for three stimulation groups. For each condition, the one-way ANOVA did not found any siginficant between-group effects, indicating that the tDCS over the rTPJ did not significantly affect RTs.

DISCUSSION

The present study assessed the potential effect of the tDCS of the rTPJ on ToM and cognitive empathy. Our findings indicate that the accuracy of both ToM and cognitive empathy decreased after receiving the cathodal stimulation, suggesting that altering the cortical excitability in the rTPJ could influence human's socio-cognitive abilities. More specifically, the inhibition of cortical excitability by the tDCS in the rTPJ could impair human's ability in inferring others' mental states or emotional states. Therefore, the results of this study

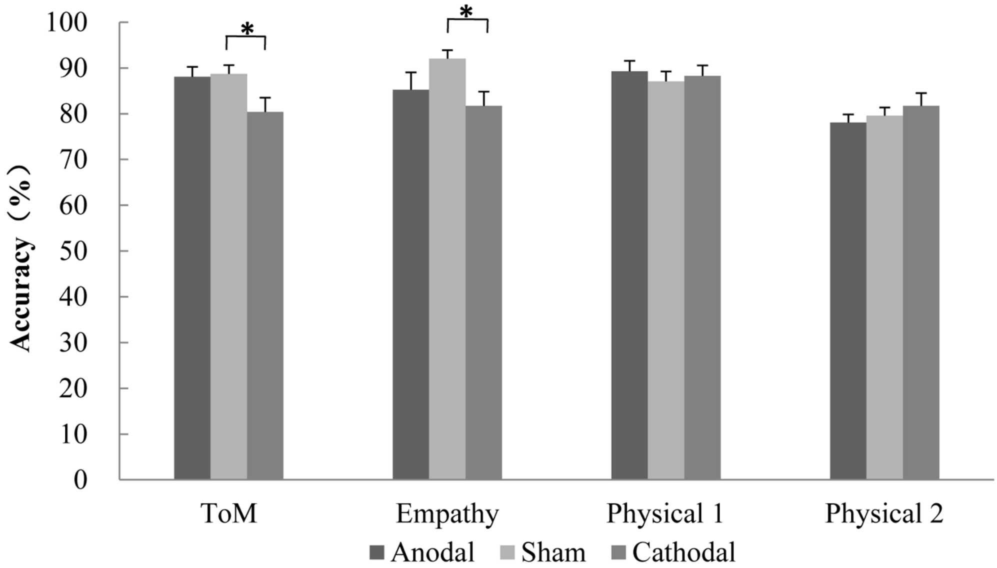

FIGURE 3 | Mean accuracy in each task condition for three stimulation groups. Error bars indicate SEM (standard error of the mean). $^*P < 0.05$.

emphasize the critical role of the rTPJ in ToM and cognitive empathy.

The results of the present study are in line with the findings of previous fMRI studies in which they have found that the rTPJ is closely related to both ToM and cognitive empathy (Vogeley et al., 2001; Saxe and Kanwisher, 2003; Vollm et al., 2006; Spengler et al., 2009; Atique et al., 2011). They are also consistent with the TMS study by Costa et al. (2008) in which they reported that the application of the rTMS over the rTPJ could worsen ToM performances, as well as the tDCS study of Ye et al. (2015) in which they observed that the inhibition of the rTPJ with cathodal stimulation decreased the role of beliefs in moral judgments. Together with previous studies, our findings suggest that ToM and cognitive empathy could be related to the neural activity in the rTPJ.

However, Santiesteban et al. (2012) did not observe the inhibition effect of cathodal stimulation in the rTPJ on ToM. One likely reason of the discrepancy is that the reaction time, which is the only behavioral measure of the ToM test in their study, might not be a sensitive behavioral index of ToM performance. In our study, both accuracy and reaction times were measured in the ToM task and the cathodal-inhibition effects were shown only in accuracy data but not reaction times. In both studies of Santiesteban et al. (2012) and ours, participants' reaction times are more than 2000 ms. Such slow reaction times might be insensitive to measuring the variation of the ToM ability. More recently, Santiesteban et al. (2015) further examined the bilateral TPJ involvement in ToM using tDCS and accuracy was measured in the ToM task. Unfortunately, they only applied anodal stimulation but did not use cathodal stimulation and thus the effect of cathodal stimulation of TPJ on ToM is unknown in their study.

In addition, we did not validate our hypothesis that anodal stimulation might enhance the performance of ToM and cognitive empathy. Santiesteban et al. (2012, 2015) did not find any reliable effect of anodal stimulation of the rTPJ on ToM either. The possible explanation is that the tasks in their studies and ours are so easy for healthy adults that their performances (accuracy and RTs) of the ToM and cognitive empathy were already good enough when without any stimulation and thus could not be improved with anodal stimulation. This interpretation should be tested in the future studies by investigating individuals with ToM impairment, such as people with autism spectrum disorders and schizophrenia.

In the present study, we used a between-subject design and found that tDCS of the rTPJ had effects on ToM and cognive empathy. It should ackownlege that our argument that stimulation makes a differece would be stronger if we use a within-subject design. However, the task we used in the present study is not appropriate for the within-subject design. For the within-subject design, there should be two tests, one before stimulation and another after stimulatoin. But there was only 10 trials in each condition in our task and there would not be enough trials for each test if we split 10 trials into two tests, i.e., pre-stimulation and after-stimulation tests. In addition, there might be learning and priming effects if the task is repeated after stimulation.

TABLE 1 | Response times (ms) in each task condition for three stimulation groups (M ± SD).

	ToM	Empathy	Physical 1	Physical 2
Anodal	2161 ± 363	2197 ± 446	2162 ± 459	2286 ± 418
Sham	2098 ± 374	2178 ± 386	2180 ± 452	2375 ± 403
Cathodal	2085 ± 433	2177 ± 400	2137 ± 585	2273 ± 586

It has to be acknowledged that there are several limitations of the present study. First, the findings are based on one study in which the experimental materials and task came from the study of Vollm et al. (2006). However, some evidence shows that brain areas related to ToM differ for different tasks and stimuli (see the review by Schurz and Perner, 2015). Therefore, our results may not be generalizable to other ToM tasks with different stimuli. Moreover, the task might be too easy for healthy adults to validate the enhancement of anodal stimulation on ToM and cognitive empathy. Third, although previous studies have confirmed that the tDCS could induce excitability changes of the cortex (Jaberzadeh and Zoghi, 2013), we must admit that the tDCS does not have the spatial specificity and thus it is impossible to distinguish different functions of subdivisions of the TPJ. Also, different brain areas might be involved in the different types of ToM tasks (see the review by Schurz and Perner, 2015). Therefore, in the future studies, more tasks should be tried and the role of the different subregions of the TPJ should be explored through combining other neuroimaging techniques. Despite these limitations, the findings of this study still could help us understand the relationship between the rTPJ and some socio-cognitive abilities, such as ToM and cognitive empathy, and also highlight the potential contribution of the tDCS to the field of social cognition.

The tDCS technique is mainly used in clinical treatment and rehabilitation (Nair et al., 2011; Schlaug et al., 2011), while the results of the present study also show the significant value of this technology in the normal group. Some other socio-cognitive abilities also rely on ToM, such as moral judgment and lie detection (Sellaro et al., 2015; Sowden et al., 2015; Ye et al., 2015). Therefore, investigating the neural mechanisms of ToM in adults could help us understand not only ToM itself but also other socio-cognitive abilities. In addition, depression, anti-social personality disorder and stroke patients have been characterized by local changes in the brain structure and function (Grefkes and Fink, 2011; Palazidou, 2012) and thus most of them may have problems in understanding others' intentions and emotion. The tDCS, as a non-invasive stimulation, has a wide application prospect in the improvement of such disabled patients. Future studies should also address how such clinical diseases can be modulated by the tDCS.

As far as we know, this is the first study to explore tDCS effects on both ToM and cognitive empathy by controlling the cerebral cortex excitability of the rTPJ. Future research can continuously investigate the anodal effect of tDCS over the rTPJ on ToM and cognitive empathy or apply tDCS over the left temporal area, the frontal area, and other brain areas related to social cognitive processing.

AUTHOR CONTRIBUTIONS

XM, CL, and WZ designed the study. WZ, ZZ, and ZX performed data collection and analysis. XM, WZ, XH, CL, and JZ wrote the paper. All authors approved the final version of the paper for submission.

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REFERENCES

Atique, B., Erb, M., Gharabaghi, A., Grodd, W., and Anders, S. (2011). Task-specific activity and connectivity within the mentalizing network during emotion and intention mentalizing. *Neuroimage* 55, 1899–1911. doi: 10.1016/j.neuroimage.2010.12.036

Blair, R. J. R. (2005). Responding to the emotions of others: dissociating forms of empathy through the study of typical and psychiatric populations. *Conscious. Cogn.* 14, 698–718. doi: 10.1016/j.concog.2005.06.004

Cerruti, C., and Schlaug, G. (2009). Anodal transcranial direct current stimulation of the prefrontal cortex enhances complex verbal associative thought. *J. Cogn. Neurosci.* 21, 1980–1987. doi: 10.1162/jocn.2008.21143

Costa, A., Torriero, S., Oliveri, M., and Caltagirone, C. (2008). Prefrontal and temporo-parietal involvement in taking others' perspective: TMS evidence. *Behav. Neurol.* 19, 71–74. doi: 10.1155/2008/694632

Davis, M. H. (1980). A multidimensional approach to individual differences in empathy. *JSAS Catalog Sel. Doc. Psychol.* 10, 85.

Davis, M. H. (1983). Measuring individual differences in empathy-evidence for a multidimensional approach. *J. Pers. Soc. Psychol.* 44, 113–126. doi: 10.1037/0022-3514.44.1.113

de Waal, F. B. M. (2008). Putting the altruism back into altruism: the evolution of empathy. *Annu. Rev. Psychol.* 59, 279–300. doi: 10.1146/annurev.psych.59.103006.093625

Eslinger, P. J. (1998). Neurological and neuropsychological bases of empathy. *Eur. Neurol.* 39, 193–199. doi: 10.1159/000007933

Frith, C. D., and Frith, U. (1999). Cognitive psychology – Interacting minds – A biological basis. *Science* 286, 1692–1695. doi: 10.1126/science.286.5445.1692

Grefkes, C., and Fink, G. R. (2011). Reorganization of cerebral networks after stroke: new insights from neuroimaging with connectivity approaches. *Brain* 134, 1264–1276. doi: 10.1093/brain/awr033

Holland, R., Leff, A. P., Josephs, O., Galea, J. M., Desikan, M., Price, C. J., et al. (2011). Speech facilitation by left inferior frontal cortex stimulation. *Curr. Biol.* 21, 1403–1407. doi: 10.1016/j.cub.2011.07.021

Jaberzadeh, S., and Zoghi, M. (2013). Non-invasive brain stimulation for enhancement of corticospinal excitability and motor performance. *Basic Clin. Neurosci.* 4, 257–265.

Jeurissen, D., Sack, A. T., Roebroeck, A., Russ, B. E., and Pascual-Leone, A. (2014). TMS affects moral judgment, showing the role of DLPFC and TPJ in cognitive and emotional processing. *Front. Neurosci.* 8:18. doi: 10.3389/fnins.2014.00018

Jurcak, V., Tsuzuki, D., and Dan, I. (2007). 10/20, 10/10, and 10/5 systems revisited: their validity as relative head-surface-based positioning systems. *Neuroimage* 34, 1600–1611. doi: 10.1016/j.neuroimage.2006.09.024

Keeser, D., Meindl, T., Bor, J., Palm, U., Pogarell, O., Mulert, C., et al. (2011). Prefrontal transcranial direct current stimulation changes connectivity of resting-state networks during fMRI. *J. Neurosci.* 31, 15284–15293. doi: 10.1523/JNEUROSCI.0542-11.2011

Nair, D. G., Renga, V., Lindenberg, R., Zhu, L., and Schlaug, G. (2011). Optimizing recovery potential through simultaneous occupational therapy and non-invasive brain-stimulation using tDCS. *Restor. Neurol. Neurosci.* 29, 411–420. doi: 10.3233/RNN-2011-0612

Palazidou, E. (2012). The neurobiology of depression. *Br. Med. Bull.* 101, 127–145. doi: 10.1093/bmb/lds004

Preston, S. D., and de Waal, F. B. M. (2002). Empathy: its ultimate and proximate bases. *Behav. Brain Sci.* 25, 1–72.

Rankin, K. P., Kramer, J. H., and Miller, B. L. (2005). Patterns of cognitive and emotional empathy in frontotemporal lobar degeneration. *Cogn. Behav. Neurol.* 18, 28–36. doi: 10.1097/01.wnn.0000152225.05377.ab

Santiesteban, I., Banissy, M. J., Catmur, C., and Bird, G. (2012). Enhancing social ability by stimulating right temporoparietal junction. *Curr. Biol.* 22, 2274–2277. doi: 10.1016/j.cub.2012.10.018

Santiesteban, I., Banissy, M. J., Catmur, C., and Bird, G. (2015). Functional lateralization of temporoparietal junction – imitation inhibition, visual perspective-taking and theory of mind. *Eur. J. Neurosci.* 42, 2527–2533. doi: 10.1111/ejn.13036

Saxe, R., and Kanwisher, N. (2003). People thinking about thinking people: the role of the temporo-parietal junction in "theory of mind". *Neuroimage* 19, 1835–1842. doi: 10.1016/S1053-8119(03)00230-1

Saxe, R., and Wexler, A. (2005). Making sense of another mind: the role of the right temporo-parietal junction. *Neuropsychologia* 43, 1391–1399. doi: 10.1016/j.neuropsychologia.2005.02.013

Schlaug, G., Marchina, S., and Wan, C. Y. (2011). The use of non-invasive brain stimulation techniques to facilitate recovery from post-stroke aphasia. *Neuropsychol. Rev.* 21, 288–301. doi: 10.1007/s11065-011-9181-y

Schnell, K., Bluschke, S., Konradt, B., and Walter, H. (2011). Functional relations of empathy and mentalizing: an fMRI study on the neural basis of cognitive empathy. *Neuroimage* 54, 1743–1754. doi: 10.1016/j.neuroimage.2010.08.024

Schurz, M., and Perner, J. (2015). An evaluation of neurocognitive models of theory of mind. *Front. Psychol.* 6:1610. doi: 10.3389/fpsyg.2015.01610

Sellaro, R., Guroglu, B., Nitsche, M. A., van den Wildenberg, W. P. M., Massaro, V., Durieux, J., et al. (2015). Increasing the role of belief information in moral judgments by stimulating the right temporoparietal junction. *Neuropsychologia* 77, 400–408. doi: 10.1016/j.neuropsychologia.2015.09.016

Shamay-Tsoory, S. G., Aharon-Peretz, J., and Perry, D. (2009). Two systems for empathy: a double dissociation between emotional and cognitive empathy in inferior frontal gyrus versus ventromedial prefrontal lesions. *Brain* 132, 617–627. doi: 10.1093/brain/awn279

Shamay-Tsoory, S. G., Tomer, R., Berger, B. D., and Aharon-Peretz, J. (2003). Characterization of empathy deficits following prefrontal brain damage: the role of the right ventromedial prefrontal cortex. *J. Cogn. Neurosci.* 15, 324–337. doi: 10.1162/089892903321593063

Shamay-Tsoory, S. G., Tomer, R., and Aharon-Peretz, J. (2005). The neuroanatomical basis of understanding sarcasm and its relationship to social cognition. *Neuropsychology* 19, 288–300. doi: 10.1037/0894-4105.19.3.288

Sowden, S., Wright, G. R. T., Banissy, M. J., Catmur, C., and Bird, G. (2015). Transcranial current stimulation of the temporoparietal junction improves lie detection. *Curr. Biol.* 25, 2447–2451. doi: 10.1016/j.cub.2015.08.014

Spengler, S., von Cramon, D. Y., and Brass, M. (2009). Control of shared representations relies on key processes involved in mental state attribution. *Hum. Brain Mapp.* 30, 3704–3718. doi: 10.1002/hbm.20800

Van Overwalle, F. (2009). Social cognition and the brain: a meta-analysis. *Hum. Brain Mapp.* 30, 829–858. doi: 10.1002/hbm.20547

Vogeley, K., Bussfeld, P., Newen, A., Herrmann, S., Happe, F., Falkai, P., et al. (2001). Mind reading: neural mechanisms of theory of mind and self-perspective. *Neuroimage* 14, 170–181. doi: 10.1006/nimg.2001.0789

Vollm, B. A., Taylor, A. N. W., Richardson, P., Corcoran, R., Stirling, J., McKie, S., et al. (2006). Neuronal correlates of theory of mind and empathy: a functional magnetic resonance imaging study in a nonverbal task. *Neuroimage* 29, 90–98. doi: 10.1016/j.neuroimage.2005.07.022

Walter, H. (2012). Social cognitive neuroscience of empathy: concepts, circuits, and genes. *Emot. Rev.* 4, 9–17. doi: 10.1177/1754073911421379

Ye, H., Chen, S., Huang, D., Zheng, H., Jia, Y., and Luo, J. (2015). Modulation of neural activity in the temporoparietal junction with transcranial direct current stimulation changes the role of beliefs in moral judgment. *Front. Hum. Neurosci.* 9:659. doi: 10.3389/fnhum.2015.00659

Young, L., Camprodon, J. A., Hauser, M., Pascual-Leone, A., and Saxe, R. (2010). Disruption of the right temporoparietal junction with transcranial magnetic stimulation reduces the role of beliefs in moral judgments. *Proc. Natl. Acad. Sci. U.S.A.* 107, 6753–6758. doi: 10.1073/pnas.0914826107

Young, L., Cushman, F., Hauser, M., and Saxe, R. (2007). The neural basis of the interaction between theory of mind and moral judgment. *Proc. Natl. Acad. Sci. U.S.A.* 104, 8235–8240. doi: 10.1073/pnas.0701408104

Young, L., and Saxe, R. (2009). An fMRI investigation of spontaneous mental state inference for moral judgment. *J. Cogn. Neurosci.* 21, 1396–1405. doi: 10.1162/jocn.2009.21137

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Electrophysiological correlates of reading the single- and interactive-mind

Yi-Wen Wang[1], Yu-Wei Zheng[1], Chong-De Lin[2]*, Jie Wu[1] and De-Li Shen[1]*

[1] *Academy of Psychology and Behavior, Tianjin Normal University, Tianjin, China*
[2] *State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, China*

Edited by:
Hans-Jochen Heinze, University of Magdeburg, Germany

Reviewed by:
Fernando MaEstú, Complutense University, Spain
Lutz Jäncke, University of Zurich, Switzerland

****Correspondence:***
Chong-De Lin and De-Li Shen, Academy of Psychology and Behavior, Tianjin Normal University, 241# Weijin Road, Tianjin 300074, China.
e-mail: linchongde@263.net; wangeven@126.com

Understanding minds is the cognitive basis of successful social interaction. In everyday life, human mental activity often happens at the moment of social interaction among two or multiple persons instead of only one-person. Understanding the interactive mind of two- or multi-person is more complex and higher than understanding the single-person mind in the hierarchical structure of theory of mind. Understanding the interactive mind maybe differentiate from understanding the single mind. In order to examine the dissociative electrophysiological correlates of reading the single mind and reading the interactive mind, the 64 channels event-related potentials were recorded while 16 normal adults were observing three kinds of Chinese idioms depicted physical scenes, one-person with mental activity, and two- or multi-person with mental interaction. After the equivalent N400, in the 500- to 700-ms epoch, the mean amplitudes of late positive component (LPC) over frontal for reading the single mind and reading the interactive mind were significantly more positive than for physical representation, while there was no difference between the former two. In the 700- to 800-ms epoch, the mean amplitudes of LPC over frontal–central for reading the interactive mind were more positive than for reading the single mind and physical representation, while there was no difference between the latter two. The present study provides electrophysiological signature of the dissociations between reading the single mind and reading the interactive mind.

Keywords: event-related potential, theory of mind, mentalizing, mind-reading, late positive component, Chinese idiom

INTRODUCTION

Theory of mind (ToM) refers to understanding other's mental states, such as beliefs, intentions, emotions, and thoughts, to predict other's behaviors. ToM is also called mentalizing, or mind-reading, which is a major ingredient in successful social interactions (Frith and Frith, 1999). Wimmer and Perner (1983) investigated the representation of wrong beliefs in young children. Since then, studies concerning ToM have largely been driven by questions arising from the field of cognitive neuroscience. Most of the current studies have been focusing on the understanding of the individual mental state. However, we often need to understand two or multi-person minds during social interaction in real life. Based on the hierarchical hypothesis about ToM, understanding the single mind and understanding the interactive mind might be two different levels of ToM processing.

In the field of cognitive neuroscience, researchers often compared reading the single mind (e.g., desire, belief, and intention, etc,) with the non-mental representation. Belief stories and photograph stories were used in an event-related potential (ERP) study to investigate electrophysiological correlates of reasoning belief and non-mental representations (Sabbagh and Taylor, 2000). Results indicated that ERP elicited by these two tasks differed beginning at 300 ms post-stimulus: beliefs were associated with an enhanced positivity over left-frontal sites and a stronger negativity over left parietal sites. The "ToM cartoons" (cartoons involving people and also requiring ToM for comprehension), "person cartoons" (cartoons involving people), and "scene cartoons" (cartoons of scenes without people) were also used in a previous ERP study to explore the time course of person perception and ToM (Wang et al., 2010). They found the peak amplitudes of P200 for person perception and ToM cartoons were significantly more positive than for scene cartoons. During 1000–1300 ms epochs, the mean amplitude of late positive component (LPC) for person perception was more positive than for scene representation, while LPC for ToM was more positive than for person perception. But this study contains a number of shortcomings. Firstly, "person cartoons" and "ToM cartoons" consisted of pictures with one or two persons. The processing of different numbers of people could influence the ERP waveforms, which might affect the experimental results. Secondly, the one-person figures and two-person figures were mixed up in those ToM cartoons. As a result, the above study has not revealed the difference between understanding the one-person mind and understanding interactive minds (Wang et al., 2010). The present study differentiated two kinds of ToM: understanding single-person mind and understanding the interactive mind. Our experiment materials were Chinese idioms, which can guarantee the consistency of the material in visual form.

Many electrophysiological studies were carried out to investigate the dynamic processing of understanding the single mind and revealed the time course of the processing (Liu et al., 2004, 2009a,b; Sabbagh et al., 2004; Wang et al., 2008). In an ERP study, participants were asked to perform an "unexpected transform" task with cartoon animations (Liu et al., 2004). A late ERP component (peaking around 800 ms post-stimulus) with a left-frontal scalp distribution, which was inconsistent with a source possibly in the left orbitofrontal cortex, differentiated judgments about belief and reality. The false-belief paradigm includes two classic tasks: unexpected-transfer and deceptive-appearance. The unexpected-transfer paradigm was used to study the time course of ToM (Liu et al., 2004). The deceptive-appearance paradigm was used to explore the brain electrophysiological activity with false-belief reasoning and true-belief reasoning in adults (Wang et al., 2008). Compared with true-belief, false-belief reasoning elicited significant declined late negative component (LNC) in the time window from 400 to 800 ms. Both of the two studies we mentioned above used first-order false-belief task. However, Liu et al. (2009a) adopted diverse-desires, diverse-beliefs, and diverse-physical judgment tasks to investigate neural system of desire and belief judgment. They found that a mid-frontal late slow wave (LSW) was associated with desire and belief judgments and a right-posterior LSW was only associated with belief judgments. Most of the studies on the research of ToM were done in adults. However, a study has made comparisons of neural correlates of ToM between adults and children (Liu et al., 2009b). They found that in adults, a LSW, with a left-frontal scalp distribution, was associated with reasoning about beliefs. This LSW was also observed in children who could correctly reason about the characters' beliefs but not in children who failed false-belief questions. In almost all of studies on the neural correlates of ToM, the participants were asked to reason about false belief, desire or intention. However, Sabbagh et al.'s (2004) study on the neural systems underlying mental-state decoding showed that decoding mental states from pictures of eyes was associated with an N270–400 component over inferior frontal and anterior temporal regions of the right hemisphere. In summary, we can conclude that the processing of understanding single-person mind was related to the LSW.

The mentioned above studies about the electrophysiological correlates of ToM were mostly to understand a one-person mind, however "*understanding of the human mind can be further deepened by moving from one-person neuroscience toward two- and multi-person neuroscience, both conceptually and experimentally.*" (Hari and Kujala, 2009; p470). We suppose that the ToM consists of a hierarchical framework. Understanding a one-person mind and understanding an interactive mind were different levels of ToM, and the level of understanding an interactive mind is higher than understanding a one-person mind. Consequently, the present study was to compare the differences between understanding the single mind and understanding the interactive mind. Social interaction is a central concept to understanding the nature of social life. Social interaction involves communication in all its forms, such as cooperation, competition, helping, playing, informing, questioning, negotiating, bargaining, voting, and bluffing (Hari and Kujala, 2009). A study indicated that during the "live" interaction, as compared to the recorded condition (watched a video of the interaction), greater activation was seen in brain regions involved in right temporo-parietal junction (TPJ), anterior cingulated cortex and so on (Redcay et al., 2010). Another study sought to characterize neural processes related to aspects of social cognition and empathy. The results found the medial prefrontal cortex (MPFC), temporal lobe, precuneus, occipital lobe showed an increased level of activation for the stimuli with two persons compared to stimuli with only one-person (Krämer et al., 2010). Leng and Zhou (2010) explored to what extent the brain activity was modulated by the interpersonal relationship between the individual and the other agent, who could be a friend or a stranger. They found the P300 was modulated by the interpersonal relationship between the observer and the other agent. Social cognition suggested that self-projection was the basis of reading the single mind. Perceivers may construct a mental representation of a target's experience, predict the kinds of thoughts and feelings they may have in such a situation and then assume that the target of mentalizing will think or feel much the same thing (Mitchell, 2009). Some scholars believed that understanding of interactive behavior and mind can be explained in the frame of "shared action representation" theory (Sebanz et al., 2006; Knoblich and Sebanz, 2008). This theory indicated that we can only accurately understanding the interactive mind on the basis of representing all individuals' contributions to an action and understanding the relations between persons and their actions in the interaction. According to the hypothesis, we supposed that understanding an interactive mind was more complex than understanding a single mind. And we also wanted to explore the differences of the dynamic processing between understanding an interactive mind and understanding a single mind. The processing of reading interactive mind exists in such two situations. First, the individual, as one of the participants in the interpersonal interaction, responds to other persons' behaviors and minds. Second, the individual infers others' mental states while observing their interactive activities. The present study belongs to the second situation.

Similar to cartoon or picture, the verbal material/story was often used as experimental stimuli in the previous ToM studies (Saxe and Powell, 2006; Abraham et al., 2008, 2010; Liu et al., 2009a). The present study employed the Chinese four-character idioms (cheng-yu) as visual stimuli to convey the descriptive content to ToM. Chinese four-character idioms are brief and concise expressions established by long-term usage and recognized through social practices (Yu et al., 2006). Many idioms describe one-person's mental activity, for example, zi-gao-fen-yong (in Chinese:自告奋勇), which in English means one-person volunteers to do something. Another example depicting the interactive minds of social interaction is fu-chang-fu-sui (in Chinese:夫唱妇随) and its English translation is harmony between husband and wife. Consequently, Chinese four-character idioms are suitable verbal materials to study the ToM and we can investigate reading the single mind and reading the interactive mind by reading different types of Chinese four-character idioms. Previous studies mostly have focused on the electrophysiological correlates of reasoning desire, belief, and intention, but the present study has been made on the investigation of the neural dynamics that underlie understanding mental state from Chinese idioms.

Using three types of Chinese four characters idioms – "physical representation idioms," "the single mind idioms," and "the interactive-mind idioms," the present study was designed to explore the dissociative electrophysiological correlates between reading the single mind and reading the interactive mind. Based on previous fMRI results that the MPFC, temporal lobe, precuneus, occipital lobe showed an increased level of activation for the stimuli with two persons compared to stimuli with only one-person (Krämer et al., 2010) and previous ERPs study that the mean amplitude of LPC for ToM was more positive than for person perception (Wang et al., 2010), we hypothesized that the amplitude of ERP related to reading the interactive mind would be larger than that of reading the single mind, and that the amplitude of ERP related to reading the single mind would be larger than that of physical representation. According to the study (Wang et al., 2010), they found the P200 for the ToM and person perception conditions was significantly larger than that for the scene condition; then, the LPC amplitude elicited by ToM was larger than that induced by person perception. We proposed that the ERP component at an earlier period would be associated with reading the single mind that separates from that of physical representation, and that the ERP component at later period would be associated with understanding the interactive mind that separates from that of understanding the single mind.

Table 1 | Lexical–statistical properties for three types of Chinese idioms.

Idioms' types	Stroke (M ± SD)	Frequency	Sentimental color (M ± SD)
Physical representation	30.39 ± 6.58	48	2.27 ± 0.72
Reading the single mind	30.10 ± 7.81	83	2.03 ± 0.82
Reading the interactive mind	29.67 ± 6.29	96	2.04 ± 0.75

Chinese idiom frequency is measured as a word-per-million figure using the People's daily Character Frequency Statistics (1998).

MATERIALS AND METHODS

PARTICIPANTS

Twenty graduate or undergraduate students (mean age = 22 years; range = 19–26 years; 10 males and 10 females) participated in the study for pay. Four participants provided excessive electrophysiological artifact during recording and were excluded from the final sample of sixteen participants (mean age = 23 years; range = 19–26 years; seven males and nine females) for ERP analyses. All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of organic or acquired brain damage. Informed written consent was obtained from all participants prior to EEG recording.

STIMULI AND PROCEDURE

In the study we grouped Chinese idioms into three types: the first type was physical representation idiom, which described natural scenery or living environment. For example, chong-shan-jun-ling (in Chinese:崇山峻岭), which in English means lofty and precipitous peaks. The second type was reading the single mind idiom, which described a single personal activity and their typical themes were about people's feelings or behavior. For example, gu-ku-ling-ding (in Chinese:孤苦伶仃), which in English means friendless and wretched. The third type was reading the interactive-mind idiom, which described the interaction of two or more people and their typical themes were about competition, cooperation, help, love, and so on. For example, fu-chang-fu-sui (in Chinese:夫唱妇随).

First, we found all types of idioms in the "Dictionary of Chinese Idioms." Then we arranged all idioms at random. Afterward, we found 14 college students to judge which kind the idioms were. Finally, we selected 70 idioms each kind based on the students' judgment. All the idioms were presented as picture. They were of uniform size (4.5 cm in width, 1.2 cm in height), and each photograph was 960 × 720 pixels. Each idiom is Song font and its font size was 26. Idioms in white color were presented in the centerfield of a black background. The participants watched the experimental stimuli subtending a visual angle of approximate 3°. We also matched the word stroke number, the term frequency, the word sentimental color (commendatory term or derogatory term; shown in **Table 1**): stroke number: $F(2, 209) = 0.19$, $p > 0.05$; term frequency: $F(2, 209) = 1.93$, $p > 0.05$; sentimental color: $F(2, 209) = 2.23$, $p > 0.05$. In addition, we also found two types of probe words: a category of words described the form of scene and the other described people's mentality; each category consisted of 17 words. All words were nouns. The scene probe words included narrowness, expansion, majesty, and so on, and the mental probe words included pleasure, relaxation, sorrow, and so on.

The time course of a trial was as follows: First, the fixation point appeared in the center of the screen for 500 ms indicating the start of a new trial. Then, participants saw a screen with an idiom for 1500 ms. Finally, a probe word was present for 2000 ms. The ITI among the trials were randomized from 400 to 600 ms. In the experiment, participants were required to understand the meaning of the Chinese idioms, and imagine the scene shape or reason the people's mentality in idioms. Then, they judged whether the contents of the Chinese idioms were consistent with the contents of the probe words by pressing a number key. The inconsistent probe words were opposite to the contents of the idioms, which ensured the participants to understand the meaning of the idioms when they pressed the inconsistent key. The experiment consisted of 210 trials and each of three categories of the idioms included 70 trials. The experiments were divided into two blocks, with 105 trials of approximately 8 min in each block. The idioms were presented in pseudo-random order. The experimental order was balanced among participants. The responses to three types of cartoons were counterbalanced between participants to avoid the sequence effects. Before the formal experiment, participants were first to have practice experiments that consist of 15 trials. These trials were similar but different from the following formal session in the ERP experiment.

ELECTROPHYSIOLOGICAL RECORDING AND ANALYSIS

The electroencephalogram (EEG) was recorded from 64 scalp sites using Ag–AgCl electrodes mounted in an elastic cap according to the International 10/20 System. All electrode recordings were referenced to an electrode placed at the right mastoid, and the EEG data were re-referenced off-line to linked mastoid electrodes by subtracting from each sample of data recorded at each channel one-half the activity recorded at the left mastoid. The horizontal electro-oculogram (EOG) was recorded from electrodes placed 1.5 cm lateral to the left and right external canthi. Eye blinks were recorded from left supraorbital and infraorbital electrodes. All inter-electrode impedance was maintained below 5 kΩ. EEG and EOG were amplified using a 0.05 to 100-Hz band pass and continuously sampled at 1000 Hz/channel for off-line analysis. EOG artifacts of eyes blink and horizontal move were revised from all trials automatically using Scan software. EEG contaminated with artifacts due to amplifier clipping, bursts of electromyographic (EMG) activity, or peak-to-peak deflection exceeding ±75 μV were excluded from trials. In the present study, EEG of idiom representation period was selected for critical analysis, and only the trials that subjects correctly responded were overlapped and averaged. The ERP were time-locked to the onset of idiom representation. The data were transformed off-line to epochs of −200–1000 ms. According to the previous studies (Sabbagh and Taylor, 2000; Liu et al., 2009a) and the ERP data of present study, the nine electrode sites were chosen for statistical analysis. The electrodes in a 3×3 grid encompassing scalp locations from left to right (laterality) and from anterior to posterior (caudality) were: F3, Fz, F4, C3, Cz, C4, P1, Pz, and P2. The amplitudes of P200 and N400 were measured from baseline to peak, and the mean amplitudes of the LPC were measured in 100 ms intervals over 500–1000 ms. The ERP components were analyzed using three-way repeated-measures analysis of variance (ANOVAs): condition (physical representation, reading the single mind, reading the interactive mind), laterality (left, midline, right), caudality (frontal, central, parietal). When necessary, for all of our analyses, p values were adjusted using the Greenhouse–Geisser correction. Bonferroni correction was used for multiple comparisons.

RESULTS

BEHAVIORAL PERFORMANCE

There were no significant differences in the participants' accuracy for physical representation, reading the single mind, and reading the interactive-mind Chinese idioms (92%, 91%, and 91% correct, respectively), $F(2, 45) = 0.43$, $p = 0.65$. This indicated that the difficulty of three conditions was equivalent. There were no significant differences in the participants' reaction time for three conditions either (850.61 ± 187.61 ms, 885.87 ± 212.33 ms, 846.76 ± 197.90 ms reaction time, respectively), $F(2, 45) = 0.19$, $p = 0.83$.

ERP RESULTS

We designed the physical representation condition to provide a control baseline. Therefore, any differences in waveforms between the reading the single mind and physical representation conditions reveals the components associated with reading the single mind, and any differences in waveforms between the reading the interactive-mind and physical representation conditions revealed the components associated with reading the interactive mind. Any difference in waveforms between the reading the single mind and reading the interactive-mind conditions revealed the components that differed between reading the single mind and reading the interactive mind. **Figure 1** displays the grand average waveforms for all three conditions from nine electrodes: F3, Fz, F4, C3, Cz, C4, P1, Pz, and P2. After artifact rejection, the mean numbers of valid trials were 54, 54, and 53 epochs used in the ERP averaging for physical representation, reading the single mind, and reading the interactive-mind condition.

It was clear from visual inspections of the waveforms in **Figure 1** that there was a LPC differentiation between the reading the single mind (more positive) and physical representation conditions and that there was also a LPC differentiation between the reading the interactive-mind (more positive) and physical representation conditions. These differentiations were around 500 ms post-stimulus. To ensure this, mean amplitude in the 500- to 700-ms post-stimulus epoch was computed for each condition from all electrodes in the 3×3 grid of scalp locations. Visual inspections of the waveforms in **Figure 1** also suggested that there was an effect of condition around 700–900 ms post-stimulus. To ensure this, mean amplitudes in the 700- to 800 and 800- to 900-ms post-stimulus epochs were computed for each condition from all electrodes in the 3×3 grid of scalp locations. The results indicated that there were no

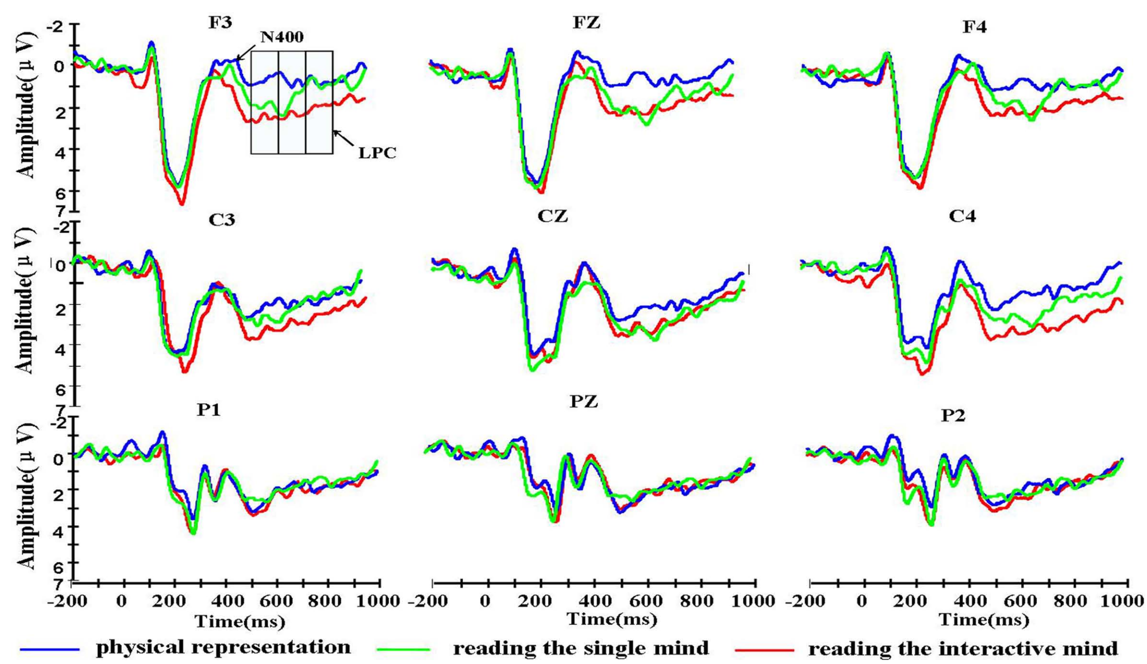

FIGURE 1 | Grand average event-related brain potential waveforms for the three types of Chinese idioms of physical representation, reading the single mind, and reading the interactive mind from nine electrodes.

differences among three task conditions in P200 [$F(2, 30) = 1.95$, MSE = 10.55, $p = 0.16$], and N400 [$F(2, 30) = 1.23$, MSE = 7.15, $p = 0.31$; shown in **Table 2**].

Late positive component

A 3 (condition) × 3 (laterality) × 3 (caudality) repeated-measures ANOVA was conducted on the mean amplitudes of single electrodes in the 3 × 3 grid of scalp locations for the 500- to 600-ms post-stimulus epochs. The results of the ANOVAs showed that there was not a significant two-way interaction between condition and laterality, $F(4, 60) = 0.69$, MSE = 0.60, $p = 0.557$, nor a significant three-way interaction between condition, laterality, and caudality, $F(8, 120) = 0.49$, MSE = 0.58, $p = 0.777$. There were moderately significant main effects of task condition, $F(2, 30) = 3.19$, MSE = 10.45, $p = 0.056$. We also found there was a significant two-way interaction between condition and caudality, $F(4, 60) = 7.86$, MSE = 1.72, $p = 0.001$ (shown in **Figure 2**). Follow-up means contrasts revealed that in the frontal area, there were significant differences between the conditions, $F(2, 30) = 8.90$, $p = 0.001$. Bonferroni-corrected pairwise comparisons showed that there were significant differences between the reading the single mind (1.71 ± 0.77 μV) and physical representation condition (0.60 ± 0.64 μV), $p = 0.04$, and there were significant differences between the reading the interactive-mind (2.17 ± 0.75 μV) and physical representation condition (0.60 ± 0.64 μV), $p = 0.002$, but there was no significant difference between reading the single mind (1.71 ± 0.77 μV) and reading the interactive mind (2.17 ± 0.75 μV), $p = 0.736$. We also found in the central area where there were significant differences between the conditions, $F(2, 30) = 4.13$, $p = 0.026$. Bonferroni-corrected pairwise comparisons showed that there were significant differences between the reading the interactive-mind (3.22 ± 0.67 μV) and physical representation condition (2.07 ± 0.67 μV), $p = 0.042$, but there was no significant differences between the reading the single mind (2.67 ± 0.79 μV) and physical representation condition

Table 2 | ANOVA of P200, N400, and the LPC amplitudes measured at 100 ms intervals during the 500- to 1000-ms period.

Time window (ms)	Condition main effects *F*(2, 30)	Condition × Caudality interaction effects *F*(4, 60)	M ± SE (amplitudes, μV)			*Post hoc* test
			Physical representation	Reading the single mind	Reading the interactive mind	
P200	1.954	1.372	5.61 ± 0.47	6.21 ± 0.57	6.30 ± 0.49	1–2, 2–3, 1–3
N400	1.232	1.455	–1.59 ± 0.58	–1.29 ± 0.54	–1.14 ± 0.51	1–2, 2–3, 1–3
500–600	3.193	7.861**	0.60 ± 0.64	1.71 ± 0.77	2.17 ± 0.75	1–2*, 2–3, 1–3**
600–700	5.035*	6.546**	1.58 ± 0.62	2.74 ± 0.71	2.96 ± 0.59	1–2, 2–3, 1–3*
700–800	2.847	13.45*	1.44 ± 0.56	1.90 ± 0.64	2.67 ± 0.56	1–2, 2–3, 1–3*
800–900	1.13	2.122	1.14 ± 0.42	1.31 ± 0.56	1.71 ± 0.44	1–2, 2–3, 1–3
900–1000	0.955	1.556	0.87 ± 0.40	1.00 ± 0.53	1.39 ± 0.40	1–2, 2–3, 1–3

*In the post hoc test, the number 1 physical representation, 2 reading the single mind, and 3 reading the interactive mind. (***P < 0.001, **P < 0.01, *P < 0.05).*

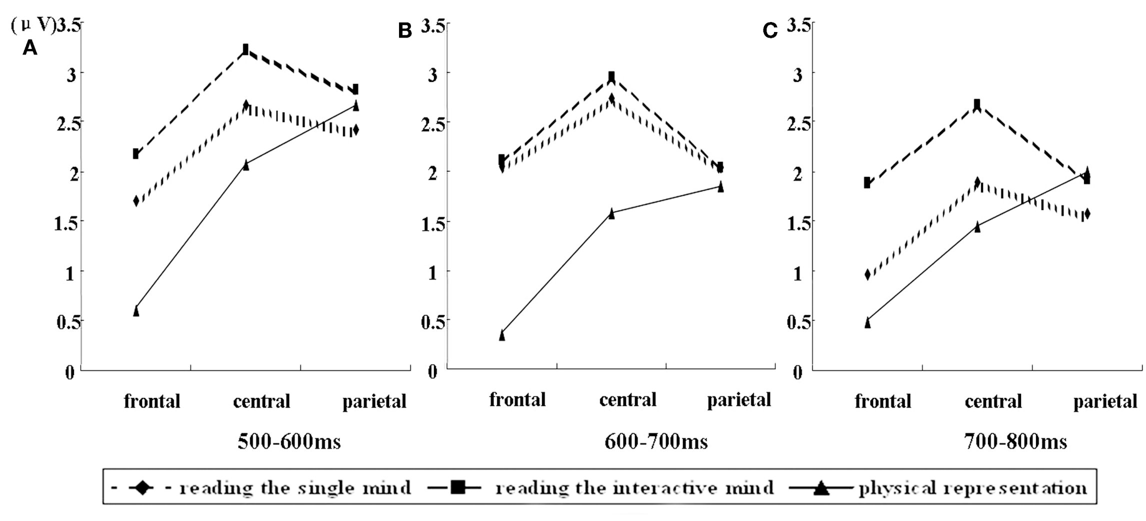

FIGURE 2 | (A) Interaction between condition and caudality in 500–600 ms. **(B)** Interaction between condition and caudality in 600–700 ms. **(C)** Interaction between condition and caudality in 700–800 ms.

(2.07 ± 0.67 μV), $p = 0.302$, and there was no significant difference between reading the single mind (2.67 ± 0.79 μV) and reading the interactive mind (3.22 ± 0.67 μV), $p = 0.691$ (shown in **Table 2**). This result confirms what is observed in the waveforms in **Figure 1**, a LPC differentiation between the reading the single mind (more positive) and physical representation conditions and a LPC differentiation between the reading the interactive mind (more positive) and physical representation conditions. This pattern of results suggests that in the 500- to 600-ms epoch, there was a frontal ERP component associated with both reading the single mind and reading the interactive mind. This was further illustrated in **Figure 3**, which displays the mean amplitude difference between the conditions (physical representation subtracted from reading the single mind) at the Fz site, as well as the corresponding scalp topographic map. Darker red indicates positive wave of conditions in scalp topographic map.

A 3 (condition) × 3 (laterality) × 3 (caudality) repeated-measures ANOVA was conducted on the mean amplitudes of single electrodes in the 3 × 3 grid of scalp locations for the 600- to 700-ms post-stimulus epochs. The results of the ANOVAs showed that there were main effects of task condition, $F(2, 30) = 5.04$, MSE = 11.60, $p = 0.013$. We also found there was a significant two-way interaction between condition and caudality, $F(4, 60) = 6.55$, MSE = 2.85, $p = 0.003$ (shown in **Figure 2**). Follow-up means contrasts revealed that in the frontal area, there were significant differences between the conditions, $F(2, 30) = 11.53$, $p < 0.001$. Bonferroni-corrected pairwise comparisons showed that there were significant differences between the reading the single mind (2.05 ± 0.70 μV) and physical representation condition (0.35 ± 0.57 μV), $p = 0.014$, and there were significant differences between the reading the interactive mind (2.11 ± 0.63 μV) and physical representation condition (0.35 ± 0.57 μV), $p < 0.001$, but there was no significant difference between reading the single mind (2.05 ± 0.70 μV) and reading the interactive mind (2.11 ± 0.63 μV), $p = 1.000$. We also found in the central area where there were significant differences between the conditions, $F(2, 30) = 6.09$, $p = 0.006$. Bonferroni-corrected pairwise comparisons showed that there were significant differences between the reading the single mind (2.74 ± 0.71 μV) and physical representation condition (1.58 ± 0.62 μV), $p = 0.044$, and there were significant differences between the reading the interactive mind (2.96 ± 0.59 μV) and physical representation condition (1.58 ± 0.62 μV), $p = 0.030$, but there was no significant difference between reading the single mind (2.74 ± 0.71 μV) and reading the interactive mind (2.96 ± 0.59 μV), $p = 1.000$ (shown in **Table 2**). This result confirms what is observed in the waveforms in **Figure 1**, a LPC differentiation between the reading the single mind (more positive) and physical representation conditions and a LPC differentiation between the reading the interactive mind (more positive) and physical representation conditions. The results of the ANOVAs showed that there was not a significant two-way interaction between condition and laterality, $F(4, 60) = 1.36$, MSE = 0.60, $p = 0.267$, nor a significant three-way interaction between condition, laterality, and caudality, $F(8, 120) = 0.42$, MSE = 0.71, $p = 0.829$. This pattern of results suggested that in the 600- to 700-ms epoch, there was a frontal–central ERP component associated with both reading the single mind and reading the interactive mind. This was further illustrated in **Figure 3**, which displays the mean amplitude difference between the conditions (physical representation subtracted from reading the single mind) at the Fz site, as well as the corresponding scalp topographic map. Darker red indicates positive wave of conditions in scalp topographic map.

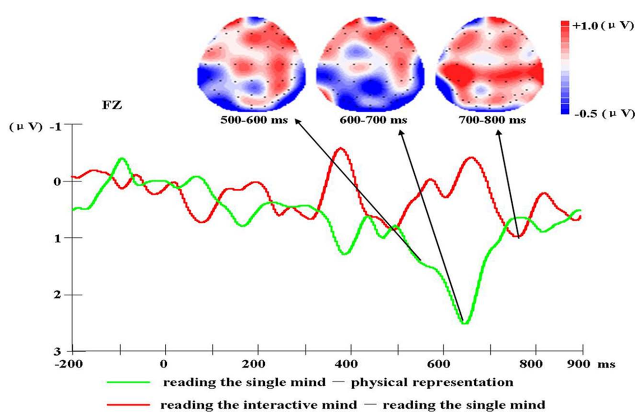

FIGURE 3 | The mean amplitude difference between conditions (physical representation subtracted from reading the single mind and reading the single mind subtracted from reading the interactive mind) at the Fz site, as well as the corresponding scalp topographies (physical representation subtracted from reading the single mind in the 500- to 600 and 600- to 700-ms epoch and reading the single mind subtracted from reading the interactive mind in the 700- to 800-ms epoch).

A 3 (condition) × 3 (laterality) × 3 (caudality) repeated-measures ANOVA was conducted on the mean amplitudes of single electrodes in the 3 × 3 grid of scalp locations for the 700- to 800-ms post-stimulus epochs. The results of the ANOVAs showed that there were no main effects of task condition, $F(2, 30) = 2.85$, MSE = 13.66, $p = 0.092$, and there was not a significant two-way interaction between condition and laterality, $F(4, 60) = 0.68$, MSE = 0.96, $p = 0.57$, nor a significant three-way interaction between condition, laterality, and caudality, $F(8, 120) = 0.79$, MSE = 1.18, $p = 0.545$. There was a significant two-way interaction between condition and caudality, $F(4, 60) = 3.85$, MSE = 3.50, $p = 0.024$ (shown in **Figure 2**). Follow-up means contrasts revealed that in the frontal area, there were significant differences between the conditions, $F(2, 30) = 5.54$, $p = 0.009$. Bonferroni-corrected pairwise comparisons showed that there were significant differences between the reading the interactive mind (1.88 ± 0.56 μV) and reading the single mind condition (0.96 ± 0.56 μV), $p = 0.019$, and there were significant differences between the reading the interactive mind (1.88 ± 0.56 μV) and physical representation condition (0.48 ± 0.46 μV), $p = 0.017$, but there was no significant difference between reading the single mind (0.96 ± 0.56 μV) and physical representation (0.48 ± 0.46 μV), $p = 1.000$. We also found in the central area where there were significant differences between the conditions, $F(2, 30) = 5.02$, $p = 0.013$. Bonferroni-corrected pairwise comparisons showed that there were significant differences between the reading the interactive-mind (2.67 ± 0.56 μV) and physical representation condition (1.44 ± 0.56 μV), $p = 0.027$, and there were moderately significant differences between the reading the interactive-mind (2.67 ± 0.56 μV) and reading the single mind condition (1.90 ± 0.64 μV), $p = 0.085$, but there was no significant differences between the reading the single mind (1.90 ± 0.64 μV) and physical representation conditions (1.44 ± 0.56 μV), $p = 0.950$ (shown in **Table 2**). This result confirms what is observed in the waveforms in **Figure 1**, a LPC differentiation between the reading the interactive mind (more positive)and physical representation conditions and a LPC differentiation between the reading the interactive mind (more positive) and reading the single mind conditions. This pattern of results suggested that in the 700- to 800-ms post-stimulus epoch, there was a frontal–central ERP component associated with reading the interactive mind only but not reading the single mind. This was further illustrated in **Figure 3**, which displays the mean amplitude difference between the conditions (reading the single mind subtracted from reading the interactive mind) at the Fz site, as well as the corresponding scalp topographic map. Darker red indicates positive wave of conditions in scalp topographic map. In the 800- to 900-ms, there were no main or interaction effect of any of the condition contrasts. Finally, there were no significant differences between the conditions at any locations for any of the epochs. Thus, the effects of conditions appeared in the 500- to 600, 600- to 700, and 700- to 800-ms.

DISCUSSION

THEORY OF MIND VERSUS PHYSICAL REPRESENTATION

The present study was designed to explore the time course of the dissociation between reading the single mind and reading the interactive mind. The ERP results revealed that in 500–700 ms, the mean amplitudes of LPC over frontal for reading the single mind and reading the interactive mind was significantly greater than that for physical representation, while there was no difference between the former two. The above results suggest that individuals can distinguish mental processing from non-mental processing in 500–700 ms. Sabbagh and Taylor (2000) indicated that ERPs elicited by mental representation and non-mental representation differed in 600–840 ms. Our study also found similar results. These results suggest that individuals can distinguish mental processing from non-mental processing at later post-stimulus stage.

ToM processing depends upon at least two kinds of representation: representation of another person and a representation of that other person's mental state. While representation of a person is a likely prerequisite for ToM, achieving a representation of another's mental state is the core feature of ToM (Leslie, 1999). Reading the single mind and reading the interactive mind both need the representation of person. In this study, the N400 indicated possibly the individual represented person or natural objects and these two processing both belong to the level of consciousness, therefore there were no significant difference among three task conditions in N400. In 500–700 ms, reading the single and interactive mind both need the representation person perception and person's mental states, while physical representation only needs representation natural objects, therefore the mean amplitudes of LPC for reading the single mind and reading the interactive mind were significantly more positive than that for physical representation.

Over the past decade, a highly consistent observation in cognitive neuroscience had been the demonstration that ToM engaged a set of brain regions including MPFC, TPJ, and superior temporal sulcus (STS) as well as temporal poles and amygdale (Frith and Frith, 2001, 2003, 2006; Calarge et al., 2003; Saxe and Kanwisher, 2003; Blakemore et al., 2004; Gallagher and Frith, 2004; Saxe and Wexler, 2005; Amodio and Frith, 2006; Kobayashi et al., 2006; Mitchell, 2006, 2008; Perner et al., 2006; Saxe and Powell, 2006; Sommer et al., 2007; Abraham et al., 2008, 2010; Coricelli and Nagel, 2009). While the previous fMRI studies have been limited by the fact that the temporal resolution of fMRI is relatively low, the advantage made in the present study is that, by taking advantage of the greater temporal resolution of ERPs, we have revealed the time course by which the physical representation precedes the representation of ToM. Esslen et al. (2008) found in the reflective self condition, only dorsal parts of the MPFC were activated, while the pre-reflective self condition showed strong involvement of the ventral MPFC. Therefore, MPFC plays a predominant role was in the understanding self and understanding other's mind. That is, the MPFC was a necessary component of reasoning of ToM.

A study found the questions of false-belief and true-belief elicited LNC at centro-frontal sites in the 400- to 800-ms epoch (Wang et al., 2008). Another neuroscience study identified a mid-frontal LSW was associated with desire and belief judgments in the 800- to 850-ms epoch (Liu et al., 2009a). Wang et al. (2010) indicated a LPC associated with ToM and maximal amplitudes of the LPC at the frontal sites. We also found reading the single mind and reading the interactive-mind conditions elicited more intense and extensive electrical activity than physical representation conditions in the frontal area of the scalp, which is consistent with previous findings. These results demonstrated that a late ERP component over frontal regions was associated with ToM processing. The ToM processing requires several cognitive processes. Firstly, we must perceive the characters. Secondly, based on those perceptions about the person, we can read the others' mind. It is possible that the late ERP component over frontal regions reflect the processes associated with integrating mental representation versus person representation within a given context.

The present study has both similarities with and differences to prior ERP study. In the study Liu et al. (2009b) and Wang et al. (2010), the dissociation of mental representation and non-mental representation emerged at 775–850 ms and 300–1500 ms, whereas in the present study, the dissociation of mental representation and non-mental representation emerged at 500–700 ms. This difference may be due to experimental material. Neuroscience studies of ToM used many experimental paradigms, including the recognition of mental-state terms (Baron-Cohen et al., 1994), stories (Saxe and Powell, 2006; Liu et al., 2009a), single-frame cartoons (Gallagher et al., 2000), comic strip cartoons (Kobayashi et al., 2007a,b; Sommer et al., 2007), and interactive games (Gallagher et al., 2002; Polezzi et al., 2008; Kamarajan et al., 2009; Boksem and De Crener, 2010). The present study task is more difficult than single-frame cartoon task and less difficult than comic strip cartoons task and interactive games task, due to different task difficulty, the results of the present study differed from the previous ERP studies.

READING THE SINGLE MIND VERSUS READING THE INTERACTIVE MIND

A major finding of the present study is the dissociation between understanding the single mind and understanding the interactive mind. In the 700- to 800-ms epoch, the mean amplitudes of LPC over frontal–central for reading the interactive mind was more positive than that for reading the single mind and physical representation, while there was no difference between the latter two. That is, the dissociation between understanding the interactive mind and understanding the single mind occurred in the 700- to 800-ms. As indicated above, we also found a frontal ERP component was associated with both reading the single mind and reading the interactive mind in the 500- to 700-ms epoch. It means that the individual firstly distinguished mental processing from non-mental processing, and then distinguished understanding the single mind from understanding the interactive mind.

Tager-Flusberg and Sullivan (2000) argued that there were two distinct components of ToM: a social-cognitive and a social-perceptual component. The social-cognitive component entails the conceptual understanding of the mind as a representational system, the social-perceptual component includes the capacity to distinguish between people and objects, and to make on-line rapid judgments about people's mental state from their facial and body expressions. Reading the single mind and reading the interactive mind both belong to social-cognitive component and they need to reason about mental state. Reading the interactive mind first needs to reading individual's mind in the interaction, which consists with processing of reading the single mind. In 500–700 ms, reading the interactive mind possibly indicated reading individual's mind in the interaction, therefore there was no significant difference between reading the single mind and reading the interactive mind in 500–700 ms. Sebanz indicated that we can only accurately understanding the interactive mind on the basis of representing all individuals' contributions to an action and understanding the relations between persons and their actions in the interaction, whereas reading the single mind only understands one-person contributes to action. In 700–800 ms, reading the interactive mind possibly processed all individuals' contributions to an action and understood the relations of "the individual and the individual," "the behavior and the behavior" in the interaction. Reading the single mind only understands one-person contributes to action, therefore there were significant difference between reading the interactive mind and reading the single mind in 700–800 ms.

Arguments in favor of brain modules often begin with the assumption that social interaction gives rise to benefits that are associated with the selection pressure necessary for developing specialized brain modules responsible for carrying out domain-specific social-cognitive processes (Adolphs et al., 2001). To some extent, the differences of the LPC between reading the single mind and reading the interactive mind are consistent with this view. It is likely that in 700–800 ms, a cognitive process specialized for reading the interactive mind. Hari and Kujala (2009) emphasized the organism–environment system was important for communications. Understanding the organism–environment system for reading the interactive mind is more complex than for reading the single mind. Therefore, in 700–800 ms, reading the interactive mind recruits higher activity than reading the single mind.

Up to now, researches about the neural basis of social interaction were still in its infancy. Krämer et al. (2010) found that the MPFC, temporal lobe, precuneus, occipital lobe showed an increased level of activation for the stimuli with two persons compared to stimuli with only one-person. To some extent, the present study results are consistent with fMRI findings. These results indicated that reading the single mind and reading the interactive mind are two different processing. Previous neuroimaging researches found several brain areas associated with social interaction. These brain areas includes: MPFC (Iacoboni et al., 2004), precuneus (Iacoboni et al., 2004), paracingulate cortex (Rilling et al., 2004; Walter et al., 2004), amygdale (Spezi et al., 2007). It was clear from **Figure 1** that the differentiation between reading the interactive mind and reading the single mind in lateral frontal sites was bigger than in medial frontal sites. A previous study also demonstrated a role for lateral frontopolar cortex in the social domain (Raposo et al., 2010). They found that medial frontopolar cortex was modulated by other judgment relative to self judgment. Lateral frontopolar cortex was significantly activated during relational condition compared to self judgment. The relational condition was a more sophisticated mentalizing task that required participants to compare their own judgments with their beliefs about another person's judgments. The combined results demonstrate that there are several "core" regions – including MPFC, precuneus, paracingulate cortex, amygdale – may contribute to interactive-mind reasoning. Understanding interactive mind needs the interaction of these core regions. Compared to other regions, the MPFC maybe plays a more important role in understanding interactive mind. The likelihood that the MPFC involved in understanding interactive mind is higher than other regions.

We know little about the dynamics processing of social interaction. Almost all of studies about the neuroimaging of social interaction utilized Ultimatum game or monetary gain and loss game (Kamarajan et al., 2009; Mobbs et al., 2009; Boksem and De Crener, 2010; Maarten et al., 2010). And participants were asked to actually participate in the game. These paradigms used money as a feedback stimulus to study people's evaluation on the feedback results and found feedback related negativity (FRN) was associated with monetary gain and loss feedback. However, the present study required participants to understand the interactive mind from Chinese idioms. This may be the reason why the results we have gotten were not consistent with previous researches. We used verbal form-idiom-as experimental material and found that a frontal–central LPC was observed for reading the interactive mind only in 700–800 ms. In summary, we believe that the dynamic processing of reading the interactive mind occurs mainly in the 500- to 800-ms, especially in the 700- to 800-ms. The present study indicated reading the single mind can be seen to underlie reading the interactive mind. This hierarchical framework support social cognition and interpersonal interaction.

Our data provide a direct comparison between the electrophysiological correlates for reading the single mind as well as reading the interactive mind. Our findings show that reading the interactive mind overlaps the neural system capable of reading the single mind but requires the involvement of an additional system. This suggests a developmental account where people's reading the interactive mind builds upon their reading the single mind. That is, people firstly are able to read the single mind, and the reading the interactive mind builds on that earlier understanding by involving the same mental-state processing characteristic of reading the single mind plus an additional the interactive-mind processing as well. We believe that reading the single mind and reading the interactive mind are two different levels of ToM.

Reading the single mind is the basis for reading the interactive mind and the level of reading the interactive mind is higher than the level of reading the single mind. In the future, understanding social interaction can be further deepened in neuroscience, and our findings will illuminate electrophysiological correlates of social interaction.

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REFERENCES

Abraham, A., Rakoczy, H., Werning, M., Cramon, D. Y., and Schubotz, R. I. (2010). Matching mind to world and vice versa: functional dissociations between belief and desire mental state processing. *Soc. Neurosci.* 5, 1–18.

Abraham, A., Werning, M., Rakoczy, H, Cramon, D. Y., and Schubotz, R. I. (2008). Minds, persons, and space: an fMRI investigation into the relational complexity of higher-order intentionality. *Conscious. Cogn.* 17, 438–450.

Adolphs, R., Tranel, D., and Damasio, H. (2001). Emotion recognition from faces and prosody following temporal lobectomy. *Neuropsychology* 15, 396–404.

Amodio, D. M., and Frith, C. D. (2006). Meeting of minds: the medial frontal cortex and social cognition. *Nat. Rev. Neurosci.* 7, 268–277.

Baron-Cohen, S., Ring, H. A., Moriarty, J., Schmitz, B., Costa, D., and Ell, P. (1994). Recognition of mental state terms: clinical findings in children with autism and a functional neuroimaging study of normal adults. *Br. J. Psychiatry* 165, 640–649.

Blakemore, S. J., Winston, J., and Frith, U. (2004). Social cognitive neuroscience: where are we heading? *Trends Cogn. Sci.* 8, 216–222.

Boksem, M. A. S., and De Crener, D. (2010). Fairness concerns predict medial frontal negativity amplitude in ultimatum bargaining. *Soc. Neurosci.* 5, 118–128.

Calarge, C., Andreasen, N. C., and O'Leary, D. S. (2003). Visualizing how one brain understands another: a PET study of theory of mind. *Am. J. Psychiatry* 160, 1954–1964.

Coricelli, G., and Nagel, R. (2009). Neural correlates of depth of strategic reasoning in medial prefrontal cortex. *Proc. Natl. Acad. Sci. U.S.A.* 106, 9163–9168.

Esslen, M., Metzler, S., Pascual-Marqui, R., and Jancke, L. (2008). Pre-reflective and reflective self-reference: a spatiotemporal EEG analysis. *Neuroimage* 42, 437–449.

Frith, C. D., and Frith, U. (1999). Interacting minds – a biological basis. *Science* 286, 1692–1695.

Frith, C. D., and Frith, U. (2006). The neural basis of mentalizing. *Neuron* 50, 531–534.

Frith, U., and Frith, C. D. (2001). The biological basis of social interaction. *Curr. Dir. Psychol. Sci.* 10, 151–155.

Frith, U., and Frith, C. D. (2003). Development and neurophysiology of mentalizing. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 358, 459–473.

Gallagher, H. L., and Frith, C. D. (2004). Dissociable neural pathways for the perception and recognition of expressive and instrumental gestures. *Neuropsychologia* 42, 1725–1736.

Gallagher, H. L., Happe, F., Brunswick, N., Fletcher, P. C., Frith, U., and Frith, C. D. (2000). Reading the mind in cartoons and stories: an fMRI study of "theory of the mind" in verbal and nonverbal tasks. *Neuropsychologia* 38, 11–21.

Gallagher, H. L., Jack, A. I., Roepstorff, A., and Frith, C. D. (2002). Imaging the intentional stance in a competitive game. *Neuroimage* 16, 814–821.

Hari, R., and Kujala, M. V. (2009). Brain basis of human social interaction: from concepts to brain imaging. *Physiol. Rev.* 89, 453–479.

Iacoboni, M., Lieberman, M. D., Knowlton, B. J., Molnar-Szakacs, I., Moritz, M., Throop, C. J., and Fiske, A. P. (2004). Watching social interactions produces dorsomedial prefrontal and medial parietal BOLD fMRI signal increases compared to a resting baseline. *Neuroimage* 21, 1167–1173.

Kamarajan, C., Porjesz, B., Rangaswamy, M., Tang, Y. Q., Chorlian, D. B., Padmanabhapillai, A., Saunders, R., Pandey, A. K., Roopesh, B. N., Manz, N., Stimus, A. T., and Begleiter, H. (2009). Brain signatures of monetary loss and gain: Outcome-related potentials in a single outcome gambling task. *Behav. Brain Res.* 197, 62–76.

Knoblich, G., and Sebanz, N. (2008). Evolving intentions for social interaction: from entrainment to joint action. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 363, 2021–2031.

Kobayashi, C., Glover, G. H., and Temple, E. (2006). Cultural and linguistic influence on neural bases of 'Theory of Mind': an fMRI study with Japanese bilinguals. *Brain Lang.* 98, 210–220.

Kobayashi, C., Glover, G. H., and Temple, E. (2007a). Cultural and linguistic effects on neural bases of "theory of mind" in American and Japanese children. *Brain Res.* 1164, 95–107.

Kobayashi, C., Glover, G. H., and Temple, E. (2007b). Children's and adults' neural bases of verbal and nonverbal "theory of mind." *Neuropsychologia* 45, 1522–1532.

Krämer, U. M., Mohammadi, B., Donamaor, N., Samii, A., and Münte, T. F. (2010). Emotional and cognitive aspects of empathy and their relation to social cognition-an fMRI study. *Brain Res.* 1311, 110–120.

Leng, Y., and Zhou, X. L. (2010). Modulation of the brain activity in outcome evaluation by interpersonal relationship: an ERP study. *Neuropsychologia* 48, 448–455.

Leslie, A. M. (1999). "Theory of mind as a mechanism of selective attention," in *The New Cognitive Neurosciences*, 2nd Edn, ed. M. Gazzaniga (Cambridge: MIT Press), 1235–1247.

Liu, D., Meltzoff, A. N., and Wellman, H. M. (2009a). Neural correlates of belief- and desire-reasoning. *Child Dev.* 80, 1163–1171.

Liu, D., Sabbagh, M. A., Gehring, K. W., and Wellman, H. M. (2009b). Neural correlates of children's theory of mind development. *Child Dev.* 80, 318–326.

Liu, D., Sabbag, M. A., Gehring, W. J., and Wellman, H. M. (2004). Decoupling beliefs from reality in the brain: an ERP study of theory of mind. *Neuroreport* 15, 991–995.

Maarten, A. S., Boksem, M. A., and Cremer, D. D. (2010). Fairness concerns predict medial frontal negativity amplitude in ultimatum bargaining. *Soc. Neurosci.* 5, 118–128.

Mitchell, J. P. (2006). Mentalizing and Marr: an information processing approach to the study of social cognition. *Brain Res.* 1079, 66–75.

Mitchell, J. P. (2008). Activity in right temporo-parietal junction is not selective for theory-of-mind. *Cereb. Cortex* 18, 262–271.

Mitchell, J. P. (2009). Inferences about mental states. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 364, 1309–1316.

Mobbs, D., Yu, R. J., Meyer, M., Passamonti, L., Seymour, B., Calder, A. J., Schweizer, S., Frith, C. D., and Dalgleishi, T. (2009). A key role for similarity in vicarious reward. *Science* 324, 900.

Perner, J., Aichhorn, M., Kronbichler, M., Staffen, W., and Ladurner, G. (2006). Thinking of mental and other representations: the roles of left and right temporo-parietal junction. *Soc. Neurosci.* 1, 245–258.

Polezzi, D., Daum, I., Rubaltelli, E., Lotto, L., Civai, C., Sartori, G., and Rumiati, R. (2008). Mentalizing in economic decision-making. *Behav. Brain Res.* 190, 218–223.

Raposo, A., Vicens, L., Clithero, J. A., Dobbins, I. G., and Huettel, S. A. (2010). Contributions of frontopolar cortex to judgments about self, others and relations. *Soc. Cogn. Affect. Neurosci.* 5, 1–10.

Redcay, E., Dodell-Feder, D., Pearrow, M. J., Mavros, P. L., Kleiner, M., Gabrieli, J. D., and Saxe, R. (2010). Live face-to-face interaction during fMRI: a new tool for social cognitive neuroscience. *Neuroimage* 50, 1639–1647.

Rilling, J. K., Sanfey, A. G., Aronson, J. A., Nystrom, L. E., and Cohen, J. D. (2004). The neural correlates of theory of mind within interpersonal interactions. *NeuroImage* 22, 1694–1703.

Sabbagh, M., and Taylor, M. (2000). Neural correlates of theory-of-mind reasoning: an event-related potential study. *Psychol. Sci.* 11, 46–50.

Sabbagh, M. A., Moulson, M. C., and Harkness, K. L. (2004). Neural correlates of mental state decoding in human adults: an event-related potential study. *J. Cogn. Neurosci.* 16, 415–426.

Saxe, R., and Kanwisher, N. (2003). People thinking about thinking people: the role of the temporo-parietal junction in "theory of mind." *Neuroimage* 19, 1835–1842.

Saxe, R., and Powell, L. J. (2006). It's the thought that counts: specific brain regions for one component of theory of mind. *Psychol. Sci.* 17, 692–699.

Saxe, R., and Wexler, A. (2005). Making sense of another mind: the role of the right temporo-parietal junction. *Neuropsychologia* 43, 1391–1399.

Sebanz, N., Bekkering, H., and Knoblich, G. (2006). Joint action: bodies and minds moving together. *Trends Cogn. Sci. (Regul. Ed.)* 10, 70–76.

Sommer, M., Katrin Döhnel, Sodia, B., Jörg Meinhardt, Thoermer, C., and Hajaka, G. (2007). Neural correlates of true and false belief reasoning. *Neuroimage* 35, 1378–1384.

Spezi, M. L., Huang, P. Y., Castelli, F., and Adolphs, R. (2007). Amygdala damage impairs eye contact during conversations with real people. *J. Neurosci.* 27, 3994–3997.

Tager-Flusberg, H., and Sullivan, K. (2000). A componential view of theory of mind: evidence from Williams syndrome. *Cognition* 76, 59–90.

Walter, H., Adenzato, M., Ciaramidaro, A., Enrici, I., Pia, L., and Bara, B. G. (2004). Understanding intentions in social interaction: the role of the anterior paracingulate cortex. *J. Cogn. Neurosci.* 16, 1854–1863.

Wang, Y. W., Lin, C. D., Yuan, B., Huang, L., Zhang, W. X., and Shen, D. L. (2010). Person perception precedes theory of mind: an event related potential analysis. *Neuroscience* 170, 238–246

Wang, Y. W., Liu, Y., Gao, Y. X., Chen, J., Zhang, W. X., and Lin, C. D. (2008). False belief reasoning in the brain: an ERP study. *Sci. China C Life Sci.* 51, 72–79.

Wimmer, H. P., and Perner, J. (1983). Beliefs about beliefs: representation and constraining function of wrong beliefs in young children's understanding of deception. *Cognition* 13, 103–128.

Yu, Y., Read, S. J., and Miller, L. C. (2006). A taxonomy of situations from Chinese idioms. *J. Res. Pers.* 40, 750–778.

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