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The role of superior temporal sulcus in the control of irrelevant emotional face processing: A transcranial direct current stimulation study

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ABSTRACT

Emotional faces are often salient cues of threats or other important contexts, and may therefore have a large effect on cognitive processes of the visual environment. Indeed, many behavioral studies have demonstrated that emotional information can modulate visual attention and eye movements. The aim of the present study was to investigate (1) how irrelevant emotional face distractors affect saccadic behaviors and (2) whether such emotional effects reflect a specific neural mechanism or merely biased selective attention. We combined a visual search paradigm that incorporated manipulation of different types of distractor (fearful faces or scrambled faces) and delivered anodal transcranial direct current stimulation (tDCS) over the superior temporal sulcus and the frontal eye field to investigate the functional roles of these areas in processing facial expressions and eye movements. Our behavioral data suggest that irrelevant emotional distractors can modulate saccadic behaviors. The tDCS results showed that while rFEF played a more general role in controlling saccadic behavior, rSTS is mainly involved in facial expression processing. Furthermore, rSTS played a critical role in processing facial expressions even when such expressions were not relevant to the task goal, implying that facial expressions and processing may be automatic irrespective of the task goal.

1. Introduction

Human beings' information processing system is limited and often deals with an overwhelming amount of stimuli that are competing for attention at the same time. Thus, an important function of attention is to select relevant information and ignore irrelevant information for further processing (Desimone and Duncan, 1995). Attention has been shown to be easily captured by salient signals such as abrupt onset of colorful and emotional stimuli (Vuilleumier, 2005; Yantis and Jonides, 1984). Of these, emotional stimuli are specifically important to attentional orienting because they are often temporally close to dangerous events that may threaten survival. One of the commonly used emotional stimuli is a face, or facial expressions, that carry biological and social information such as age, gender, identity, and emotion. Facial expressions are also important for guiding social interactions with others in the community.

The use of several paradigms such as the visual search task (Fox et al., 2000, 2001), dot-probe task (Mogg and Bradley, 1999), and RSVP task (Stein et al., 2009) have indicated that emotional faces are detected faster and are more distracting than neutral faces. Moreover, human patients with visual neglect also show less visual extinction for emotional faces (e.g. fearful expression) than neutral faces (Vuilleumier et al., 2001). These studies have shown that participants detect emotional faces faster than neutral faces, suggesting that specific emotional information may modulate human attention.

A range of brain areas have been functionally linked to processing emotional face information depending on the affective significance of the faces, particularly in the case of fearful expressions (for a review see Vuilleumier and Pourtois (2007)). A number of studies

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have demonstrated that the amygdala is specifically involved in emotional processing and is critically associated with fear processing and fear-related learning (LeDoux, 2000; Pessoa, 2008; Phelps, 2006; Vuilleumier et al., 2001; Vuilleumier and Driver, 2007), while orbitofrontal cortex (OFC) and anterior cingulate cortex (ACC) are involved in emotional and social behaviors (Rudebeck et al., 2007, 2008; Rushworth et al., 2007). The amygdala also plays a central role in emotional modulation of face processing. In addition, studies have also begun to uncover other brain regions and their roles in emotional face processing. For example, activity changes are seen in regions such as the visual cortex, superior temporal sulcus, the middle occipital cortex, the fusiform gyri, and the orbitofrontal and parietal cortex (Pessoa and Ungerleider, 2004; Phelps, 2006). Recently evidence from functional brain-imaging studies has also shown that face perception processing is principally associated with three cortical regions, the inferior occipital gyrus, the lateral fusiform gyrus, and the superior temporal sulcus (Haxby et al., 2000). Damage to the ventral occipitotemporal cortex, which includes the above three regions, renders patients unable to recognize faces but other objects are unaffected (McNeil and Warrington, 1993). In particular, the superior temporal sulcus, according to Haxby's face processing model, is associated with the coding of changeable facial cues, i.e. perception of eye gaze; lip movement; and facial expressions. Several nonhuman primates studies have also demonstrated the superior temporal sulcus as a critical region that responds selectively to facial expression processing with single cell recordings data (Hasselmo et al., 1989) and showed activation for emotional body postures and movements with fMRI data (de Gelder and Partan, 2009). Moreover, fMRI studies have demonstrated that selective attention to facial expressions elicit stronger right STS activation (Narumoto et al., 2001), activations in the STS specifically for dynamic fear bodies action (Grezes et al., 2007). A serial of TMS pulses over the STS studies causes disturbed facial perception (Pourtois et al., 2004), disrupted trustworthiness judgements (Dzhelyova et al., 2011) and altered accuracy in detecting changes of threatening human body postures (Candidi et al., 2011). Consequently, the STS region has been considered as a crucial region in facial expression and threat related information processing.

There are two main perspectives regarding the relationship between attentional and emotional modulation of visual processing (Pessoa and Ungerleider, 2004; Vuilleumier, 2005; Vuilleumier and Driver, 2007). One viewpoint is that the neural processing of emotional stimuli is not automatic and instead needs some degree of attention (Pessoa et al., 2002). From this point of view, the faster detection of emotional faces and increased activation of the fusiform face area for fearful faces might reflect enhanced attentional bias to emotional stimuli. The hypothesis is that the emotional processing and attention processing are coupled together. Emotional information would serve to rapidly inform attentional control, depending on the allocation of attentional resources. Another view specifies that emotional stimuli enjoy specific neural mechanisms for their processing (such as those involving the amygdala) that boost processing and give emotional stimuli competitive strength against other stimuli (Vuilleumier et al., 2001; Vuilleumier and Driver, 2007). In this hypothesis emotional processing and attention processing are separated and emotional information is processed in a truly automatic pathway that does not depend on attentional resources. Therefore, the emotion modulations reflect a stronger engagement of attention towards the more salient facial stimuli, indirectly mediated by top-down signals from frontal–parietal areas involved in attentional control (Desimone and Duncan, 1995) or the modulation of neuronal responses to facial expressions would be consistent with the existence of direct connections between visual cortex and the amygdala or other emotion-related regions (Amaral et al., 2003), reflecting a limbic region that is crucially involved in rapid emotional processing (LeDoux, 2000).

Although fMRI studies have often used faces in a paradigm where both emotion and attention are manipulated separately (Pessoa et al., 2002; Vuilleumier et al., 2001), it remains unclear whether the relationship between emotion and attention and the modulation of visual processing by emotion might reflect distinct influences. Thus, the present study employed transcranial direct current stimulation (tDCS) to directly compare the emotion related brain regions and attention related brain regions, using a visual search task with emotional faces as distractors.

Emotional stimuli have also been shown to affect eye movements. The eye movement system provides abundant information on cognitive processing for experimental exploration (Liversedge and Findlay, 2000; Van der Stigchel, 2010; Van der Stigchel et al., 2006). One way to measure the effect of emotional distractors is to observe the intervening path that the eyes move across to reach the target destination. Because eye movement trajectories are seldom straight, the magnitude of eye trajectory curvature can be used as an index of the effect of the distractor (e.g. Chao et al., 2011). Specifically, since previous studies have suggested that curvatures represent the dynamic competition between target selection and distractor suppression (McSorley et al., 2006; Van der Stigchel, 2010; Van der Stigchel et al., 2006; Van der Stigchel and Theeuwes, 2005, 2006), saccade curvatures have often been observed to deviate toward or away from the distractor (while traveling to the target location) depending on the paradigm used, as well as the strength of the distractor. For example, saccade curvatures have been used as an index to gauge the effects of affective pictures or facial expression in allocation of attention: Nummenmaa et al. (2009) used emotional scene pictures or neutral pictures as distractors and measured the effects on saccade curvature while participants made vertical saccades to a target location. They found that saccade curvatures deviated away from the distractors when emotional scene pictures were used. This pattern of results suggested that emotional distractors are relatively more salient than neutral scene pictures even if participants never have to make a saccade to the emotional scenes. Recent studies also demonstrated that emotional stimuli were processed more sensitive in oculomotor system than motor system (Bannerman et al., 2009a, 2009b, 2010). Therefore, it is critical to measure emotional effects on saccade programming during performance of a visual search paradigm involving presentation of emotional stimuli.

There is a broad network contributing to attentional modulation. Neuroimaging studies have indicated two separate attentional networks: the dorsal fronto-parietal network and the ventral network (Bressler et al., 2008; Corbetta and Shulman, 2002). The dorsal fronto-parietal network, involving of the intraparietal sulcus (IPS) and frontal eye field (FEF), performs voluntary attentional control such as orienting to a location or object (Hopfinger et al., 2000; Nobre et al., 2004; Rushworth et al., 2001). Similarly, neurophysiological studies have shown a network of brain regions: the superior colliculus (SC), supplementary eye field (SEF), and frontal eye field (FEF) that are associated with pretarget-related neural activity during visual attention (for a review, see Rushworth and Taylor (2006)).

Several studies have shown that transcranial direct current stimulation (tDCS) may induce either facilitatory effects with anodal stimulation or inhibitory effects with cathodal stimulation. This modulation was first shown in animal studies, where subthreshold DC stimulation increased cerebral excitability with anodal stimulation by depolarizing cell membranes and increasing firing rates, while cathodal stimulation resulted in the opposite effect by hyperpolarization and decreasing firing rates (Bindman et al., 1964; Creutzfeldt et al., 1962; Nitsche et al., 2009; Stagg et al., 2009). Several tDCS studies have also demonstrated this bidirectional effects with behavioral measurement (Hsu et al., 2011; Nitsche and Paulus, 2000; Nitsche et al., 2003; for a review, see Dayan et al. (2013)).

The present study aimed to investigate 1) whether irrelevant emotional faces would affect saccade programming and 2) whether the emotional effects reflect a specific neural mechanism or merely biased selective attention. We used a visual search task, combined with eye-tracking and tDCS over the right STS and right FEF, to further elucidate the contributions of these regions to emotional and attentional processing. To the best of our knowledge, this study is the first to test the effect of irrelevant emotional distractors on saccade programming and directly compare an attention related brain area (i.e. FEF) and an emotion related brain area (i.e. STS) using the tDCS technique. We predicted that irrelevant emotional distractors would modulate saccadic behaviors. We also predicted that the modulation of emotional distractor effects would be seen only under the rSTS tDCS condition with rFEF tDCS inducing a general facilitatory effect on saccadic behaviors due to its role in visual selection.

2. Materials and methods

2.1. Participants

Twenty-six college students (aged 20–26 years, mean age=22.1, 13 males, 13 females, all right handed) from the National Central University participated in the STS tDCS experiment. An additional 26 volunteers (aged 20–30 years, mean 21.7, 13 males, 13 females and all right handed) participated in the frontal eye field tDCS experiments, which served as a site contrast condition to avoid practice effects and carry-over effects on the task. All participants had normal or corrected-to-normal vision and all participants gave informed consent prior to the experiment. All received monetary payment upon the completion of the experimental session. Both experiments were approved by the local ethical committee.

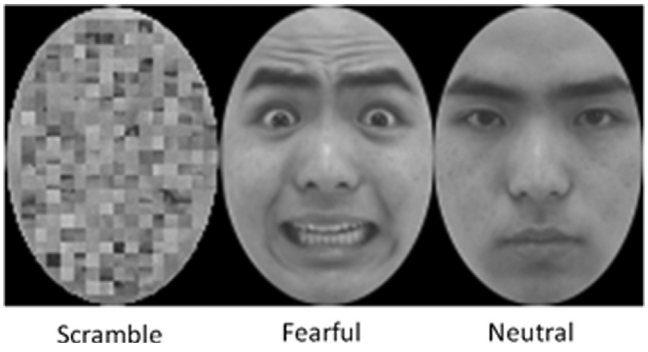

Fig. 1. Example stimuli: the three face categories used in current study. From left to right: scrambled face, fearful face and neutral face.

2.2. Apparatus and stimuli

Testing took place in a sound attenuated room. Stimuli were presented on a 19-in. CRT monitor with a resolution of 1024 × 768 pixels and a vertical refresh rate of 100 Hz. Participants sat facing the monitor, positioned at eye level, at a distance of 85 cm. The position of the left eye was recorded using an EyeLink II tracker (SR Research, Mississauga, Ontario, Canada) with a 500 Hz sampling rate. A 9-point eye tracker calibration was carried out for each participant prior to formal data collection. Saccades were identified by a significant elevation ($>30^{\circ}$/s) in eye movement velocity as well as an increase ($>8000^{\circ}/s^2$) in acceleration. Throughout the experiment, the direction of saccades and saccadic curvature was recorded.

Stimuli were 8 neutral and 8 fearful faces chosen from the standard data sets of the Taiwanese Facial Expression Image Database (Chen and Yen, 2007). There were also 8 scrambled faces that were created from the same neutral face images. These scrambled faces are not faces but have some of the same visual properties as faces.

There were four possible positions for targets. Target position was 7.5° away from the fixation, and was arranged circularly with 4.5° between locations. The target (neutral face) and distractors (fearful or scrambled face) were 1.85° × 2.6° in size. The stimuli and a typical trial are illustrated in Figs. 1 and 2.

2.3. Procedure

2.3.1. Visual search task

Participants first completed 60 practice trials until they reached 70% accuracy before attempting the 240 formal trials. Each trial began with a fixation stimulus (a white cross 1° in size) that was presented in the center of the display for 800–1300 ms. Following the fixation stimulus, the target and distractor stimuli appeared simultaneously. The target was a neutral face distanced 7.5° from the fixation point, in 4 possible oblique locations: upper left, upper right, lower left, and lower right corners. The distractors were either a scrambled face or a fearful face, appearing randomly at one of the two possible adjacent locations next to the target (i.e., top, bottom, left, and right) while always maintaining a fixed geometrical angle of 45° from the target (see Fig. 2) and 7.5° from the fixation. Note that the distractor location, though 4 possible locations total (top, bottom, left, and right), co-varied with the target location so that the distractor was always restricted to either one of the two locations that are 45° beside the target. Additionally, the absent distractor condition served as a baseline condition for the comparison between the two other conditions (i.e.: scrambled and fearful faces). Participants were required to move their eye to within 4° × 4° of the target stimulus using a single saccade once the target appeared.

2.3.2. tDCS parameters and site localization

Before conducting a tDCS experiment, the stimulation site for the rSTS was localized with the EEG 10-20 system, with the center of the tDCS electrode placed over the site of CP6. The rSTS located and marked on CP6 was also confirmed by TMS study (Pourtois et al., 2004). The accuracy of this localization method was

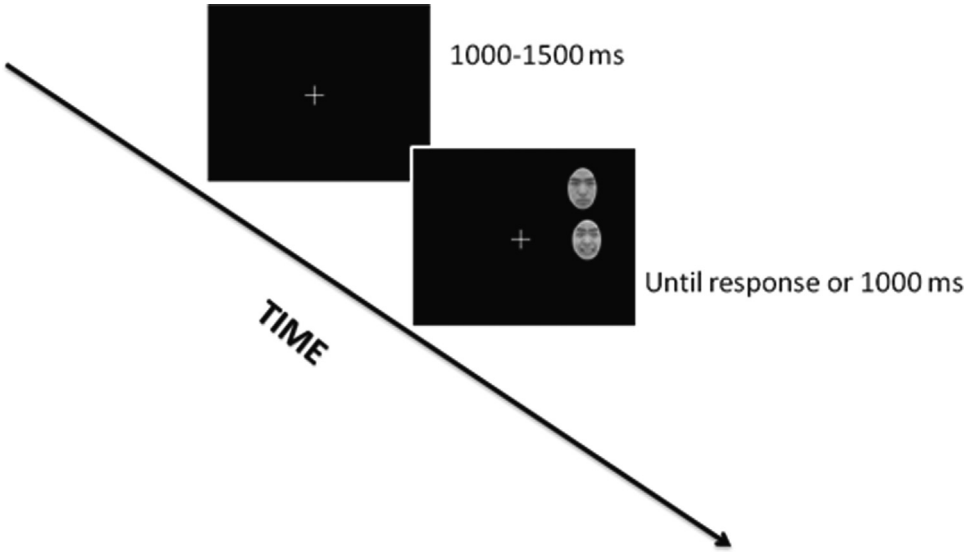

Fig. 2. Visual search task procedure. Participants fixated on the cross. The experiment involved presentation of two types of distractors: fearful faces and scrambled faces. Participants were required to make a saccade towards the neutral face upon its presentation.

confirmed in two participants' using a magnetic resonance image (MRI)-guided frameless stereotaxy system (Brainsight, Rogue Research, Montreal, Canada). Briefly, identification of the rSTS site on the structural scans was achieved by the following procedure. Individual MRIs were normalized against a standard template using the FSL software package (FMRIB, Oxford). This produced a matrix of values describing the transformation from the structural scan to the normalized brain. This was then reverse-applied to the coordinates of rSTS (52,−48,12, Narumoto et al., 2001; see Fig. 3) to obtain the location of the site in the original structural scan for each participant. This location is highly compatible with the STS site in many fMRI studies (e.g.: Candidi et al., 2011; Grezes et al., 2007). The location was then marked on the MRI scan in the Brainsight system to verify the EEG 10-20 localization. For the localization of the FEF, we used transcranial magnetic stimulation (TMS) to functionally localize each participant's FEF. Based on previous studies (Juan et al., 2008; Muggleton et al., 2003) that demonstrated TMS disruption to conjunction visual search and saccade performance. A Magstim Super-Rapid Stimulator and a figure-of-8 coil were used to deliver TMS. The stimulation site for the FEF was localized with the TMS which was delivered for 500 ms at 10 Hz over candidate sites anterior to the hand motor area in the right hemisphere using a grid of points separated from each other by 1 cm (Juan et al., 2008; Liu et al., 2011). A single value of 65% of the maximal stimulator output (2 T) was used based on past studies showing reliable TMS effects across a wide range of tasks (e.g.: Juan et al., 2008; Muggleton et al., 2010, 2003).

The main bodies of the STS tDCS and FEF tDCS experiments consisted of two conditions: anodal tDCS condition and sham condition. The time interval between each condition was least at 24 h. tDCS was delivered with a Neuroconn Eldith DC-stimulator and a pair of electrodes housed in 4×4 cm^2 saline-soaked sponge coverings. The center of the stimulation electrode was placed over the target site (rSTS or rFEF) and the reference electrode was placed over the left cheek of the participant. The cheek was chosen over other cortical regions because placing the reference electrode anywhere else over the cortex would inevitably induce an opposite (cathodal) effect over that region, rendering the results more difficult to interpret. The same protocol has been successful applied in several previous studies (e.g. Hsu et al., 2011, 2014; Tseng et al., 2012; Xue et al., 2012). For the anodal condition, a current of 1.5 mA for 10 min was delivered (e.g.: Hsu et al., 2011; Tseng et al., 2012). Based on the safety criteria proposed by Nitsche et al. (2003), both current density and stimulation strength are important when considering the safety limits of stimulation. In the present study, both indexes are below the safety criterion. The criterion for current densities is 25 mA/cm^2 (McCreery et al., 1990). In our protocol, the current densities were 0.0937 mA/cm^2, well below the criterion. With regard to stimulation strength, tissue damage has been detected at a minimum total charge of 216 C/cm^2 (Yuen et al., 1981). The total charge in our current experiment was 0.0056 C/cm^2, which is also below the safety criterion. Therefore, the parameters in the present study were in accordance with the literature and safe for the participants.

For the sham condition, the anodal electrode was placed over the same positions as for active stimulation (rSTS and rFEF), but the stimulator was turned on only for 30 s duration and was then turned off. Therefore, participants could feel the initial itching sensation associated with tDCS, but they received no actual active current for the stimulation period. This method of sham stimulation has been demonstrated to be reliable (e.g.: Gandiga et al., 2006). For each tDCS site an ABBA design was used to control for sequence effects. Participants began the formal session after the 10-min tDCS session was completed. The procedure of the experiment is illustrated in Fig. 4.

2.3.3. Data analysis

Participants' saccadic end points that landed inside a computer-defined $4^\circ \times 4^\circ$square region centered on the target were defined as accurate saccades

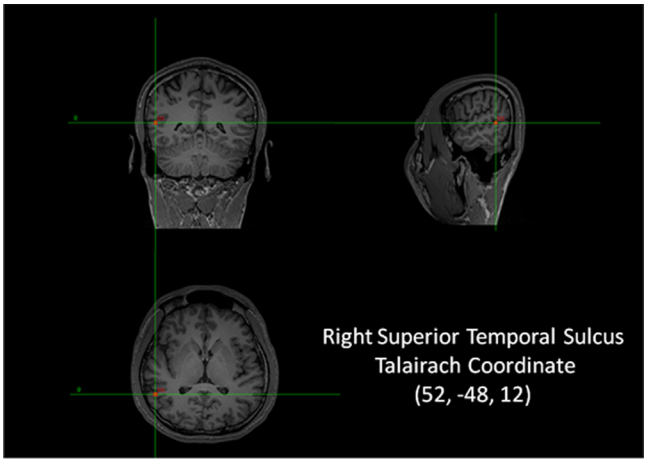

Fig. 3. The STS stimulation site shown for one participant. The location corresponds to the standard coordinates of 52,–48,12.

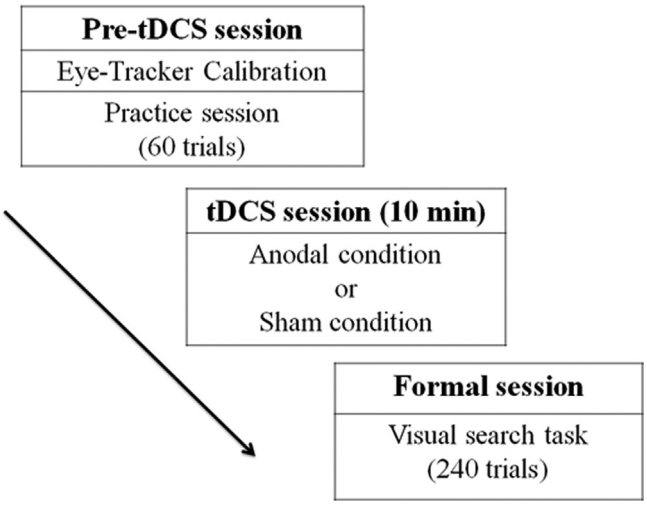

Fig. 4. Experimental session procedure.

(see Fig. 5a). Participants' saccadic end points that landed outside the $4^\circ \times 4^\circ$ square were identified as error saccades. These error saccades were further divided into three categories: undershoot error, overshoot error, and distractor-induced error. The undershoot and overshoot errors are saccades that failed to land within the pre-defined target square boundary, defined by saccade amplitude less than or equal to 5.5 visual degrees (undershoot; see Fig. 5b) and amplitude more than or equal to 9.5 visual degrees (overshoot; see Fig. 5c). The distractor-induced errors are saccades that first landed within a pre-defined triangular area toward the distractor before making a second saccade to the target. The triangular boundaries were defined by drawing an equilateral triangle (11.5 visual degrees on all three sides) that projected outwards from the fixation point (vertex) towards the distractor, covering an angle of 45°. This triangle was bisected by the distance (extending 10 visual degrees) between the fixation and the distractor so that the 45° opening was composed by one boundary that projected 22.5° to the left as well as one boundary 22.5° to the right in the vertically positioned distractor (or up and down for horizontally positioned distractors) from the fixation point (see Fig. 5d). This triangle was used to define the distractor-induced errors since these error saccades, although induced by the distractors (as shown by their initial trajectories), did not always land in close proximity to the distractors. Thus, a square boundary around the distractor locations would not have been sensitive enough to capture these error saccades. Any error that does not belong to any of these three categories was defined as 'other' errors. Saccade latency was defined as the interval between target onset and the initiation of a saccadic eye movement (in milliseconds). If a saccadic latency was lower than 50 ms or higher than 800 ms, the latency was identified as an outlier and removed from analysis.

In the current study, the coordinate system of the eye movement trace was rotated such that the new *x*-axis was in the direction of the saccade target. Consequently, the new *y*-axis was in the direction perpendicular to the new *x*-axis. The two aforementioned directions, the new *x*-axis and the new *y*-axis, are referred to as the radial direction and the transverse direction, respectively. The purpose of this coordinate system rotation is to observe the dynamic properties that cause curvatures toward or away from the distractor. Saccade curvature is defined by slope curvature (Chen-Harris et al., 2008; Liang and Juan, 2012). Saccade trajectories were divided into four equal segments. The curvature was defined as the slope of the fourth segment minus the slope of the first segment. To apply this measure of curvatures, the slope was defined in the rotated new coordinate system. Since saccade trajectories are never straight, the curvatures from the non-distractor condition were used to serve as the baseline curvatures, thus were subtracted from the curvatures from trials with a distractor. Positive values indicated saccade trajectories toward the distractor, whereas negative values indicated saccade trajectories away from the distractor. Eye movement data were analyzed by off-line programs in Matlab (The Mathworks Inc, Natick, MA, USA)

3. Results

3.1. Saccade error rates (distractor-induced error)

Mean percent error rates from the rSTS and rFEF conditions were 18.9% (absent = 1.8%, scrambled = 7.5%, fearful = 9.6%) and 20.8% (absent = 1.8%, scrambled = 8.5%, fearful = 10.5%), respectively. Since the distractor-induced error is the error of interest here, we performed separate one-way repeated measures analysis

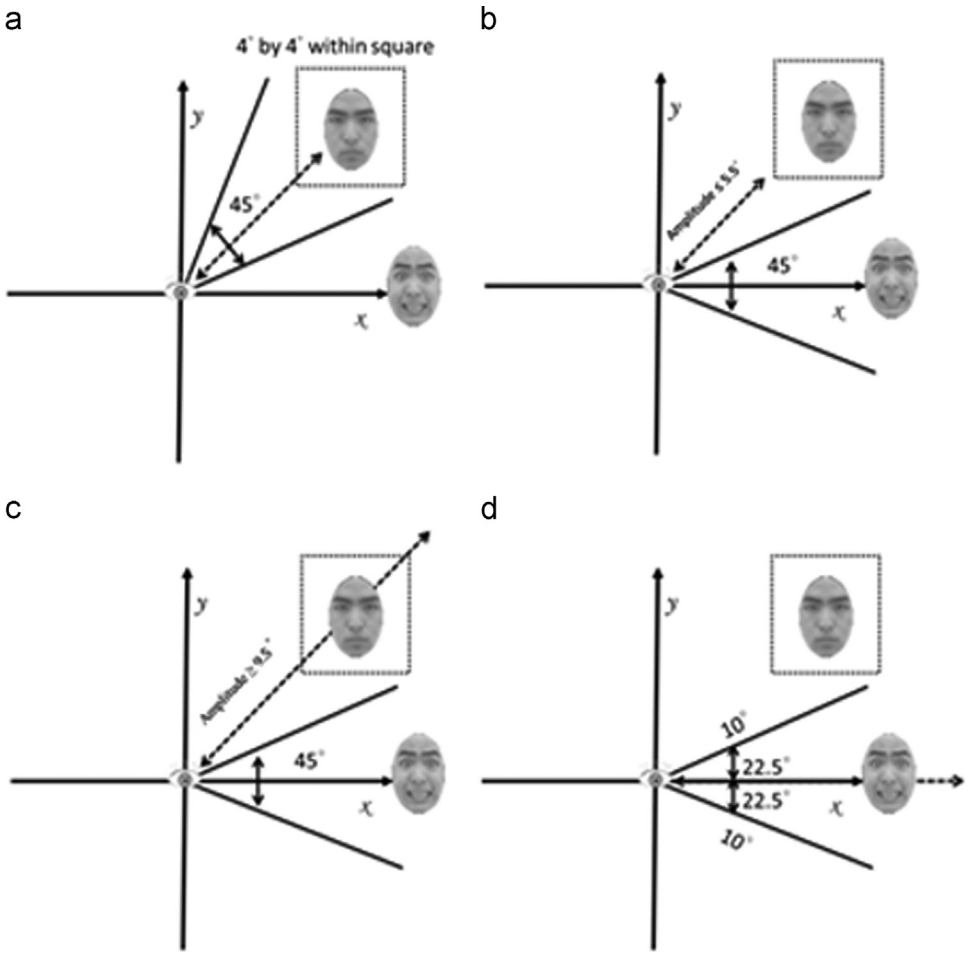

Fig. 5. Types of saccade. (a) Correct saccade. (b) Undershoot error. (c) Overshoot error. (d) Distractor induced error.

of variance (ANOVA) across different distractor types (distractor-induced, overshoot, undershoot, and others) under all sham conditions (STS and FEF collated) in order to check whether distractor-induced errors was indeed worth looking into. First, under the fearful distractor condition, there was a main effect of saccade error type ($F(3,75)=34.170$, MSE <0.001, $p<0.001$), where posthoc t-tests showed that participants made more distractor-induced errors (4.7%) than any other error types, including overshoot (1%, $t(25)=-6.664$, $p<0.001$), undershoot (1.2%, $t(25)=-6.967$, $p<0.001$), and others (3%, $t(22)=-2.746$, $p<0.01$). Second, under the scrambled distractor condition, there was also a main effect of saccade error type ($F(3,75)=11.812$, MSE <0.001, $p<0.001$), where posthoc t-tests showed that the participants made more distractor induced-errors (2.7%) than other types of errors such as overshoot (1.1%, $t(25)=-3.216$, $p<0.01$) and undershoot (1.3%, $t(25)=-3.079$, $p<0.01$), with the exception of 'other' errors (3%, $t(25)=0.541$, $p=0.593$). These numbers verify that the distractor-induced error was indeed a more meaningful type of saccade error in the context of this paradigm and for the purpose of the present study. The following ANOVA and separate comparisons are therefore done on the error rates that are induced by the distractors, including fearful and scrambled ones.

A three-way mix-effect ANOVA was performed to investigate whether brain region (rSTS and rFEF), distractor type (absent, scrambled, and fearful), and tDCS condition (sham and anodal) have an effect on distractor-induced saccade error rate (Fig. 6). There was a significant main effect for distractor type ($F_{(1,50)}$50.131, MSE <0.001, $p<0.001$), and no effect for brain region ($F_{(1,50)}=0.781$, MSE $=0.004$, $p=0.381$), tDCS condition ($F_{(1,50)}=0.547$, MSE <0.01, $p=0.463$), or their three way interaction ($F_{(1,50)}=0.204$, MSE <0.001, $p=0.654$). Post-hoc comparison revealed that participants committed significantly more distractor-induced errors under the fearful face condition (4.8%) than in the scrambled face (2.9%; $p<0.001$).

3.2. Saccade curvature

Saccade curvature results are depicted in Fig. 7. Since the absent-distractor curvatures served as a baseline for computing the slopes for the fearful and scrambled conditions, only curvature from these latter two conditions was analyzed. There was a significant main effect for distractor type ($F_{(1,50)}=12.131$, MSE <0.05, $p<0.01$), but no significant effect of brain region ($F_{(1,50)}=0.212$, MSE $=0.076$, $p=0.647$), tDCS condition ($F_{(1,50)}=0.011$, MSE $=0.01$, $p=0.916$), or the three way interaction ($F_{(1,50)}<0.001$, MSE <0.01, $p=0.989$). Separate comparisons within the effect of distractor type indicated that saccade curvatures were on average more away when a fearful face distractor was presented (slope $=-0.178$) in comparison to a scrambled face (slope $=-0.144$, $p<0.01$).

3.3. Saccade latency

Saccade latencies are shown in Fig. 8. Three-way mix-effect ANOVA consisting of factors of brain region (rSTS and rFEF), distractor type (absent, scrambled, and fearful), and tDCS condition (sham and anodal) revealed a significant main effect of distractor type ($F_{(2,100)}=70.705$, MSE $=653.243$, $p<0.001$), and tDCS condition ($F_{(1,50)}=7.625$, MSE $=1728.84$, $p<0.01$). There was no significant effect of brain region ($F_{(1,50)}=0.523$, MSE $=29988.395$, $p=0.473$). But most

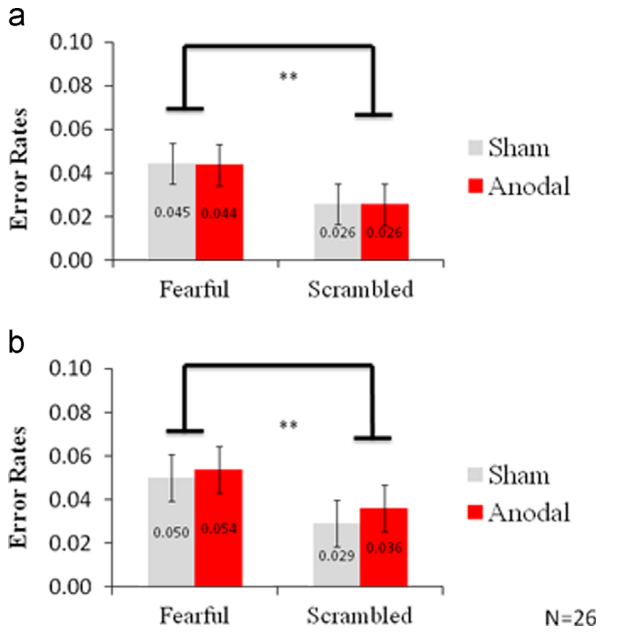

Fig. 6. Saccade error rates for each condition in (a) STS experiment and (b) FEF experiment. Overall, fearful face distractors increased the number of saccade errors regardless of tDCS stimulation. Each error bar shows the 95% confidence interval (*$p < 0.05$, **$p < 0.001$).

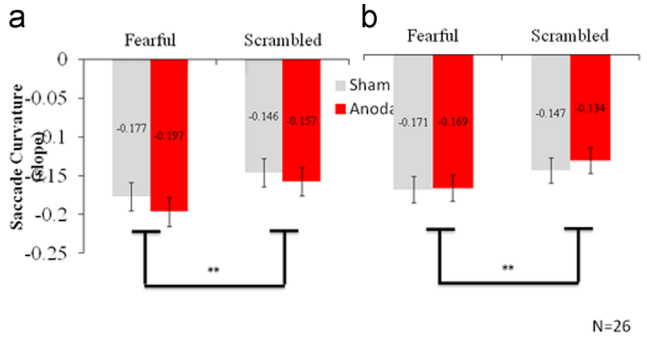

Fig. 7. Saccade curvatures for each condition in (a) STS experiment and (b) FEF experiment. The *Y* axis shows saccade curvatures where negative values indicate curvature away from the distractors. Overall, fearful face distractors increased the magnitude of the curvature away regardless of tDCS stimulation. Each error bar shows the 95% confidence interval (*$p < 0.05$, **$p < 0.001$).

importantly, the three way interaction also reached statistical significance ($F_{(2,100)}=3.124$, MSE=56.195, $p<0.05$). To investigate whether tDCS affected the emotional distractor effect, two 3×2 repeated measures ANOVAs were performed separately for each different stimulation brain region with the factors of distractor type and tDCS condition.

3.3.1. rSTS tDCS condition

A two-way repeated measures ANOVA with the factors of distractor type and tDCS condition revealed a significant main effect for distractor type ($F_{(2,50)}=74.203$, MSE=259.26, $p<0.001$) and not tDCS ($F_{(1,25)}=2.65$, MSE=1555.195, $p=0.116$). There was also a significant interaction between distractor type and tDCS condition. ($F_{(2,50)}=7.441$, MSE=43.539, $p<0.01$). For the significant interaction, post-hoc analysis showed that the saccade latency difference between the anodal condition and the sham condition reached statistical significance only when a fearful face distractor was presented ($t_{(25)}=2.2$, $p<0.05$), and not in the absence of distractors ($t_{(25)}=0.879$, $p=0.378$) or with scrambled face distractors ($t_{(25)}=1.58$, $p=0.125$). Therefore,

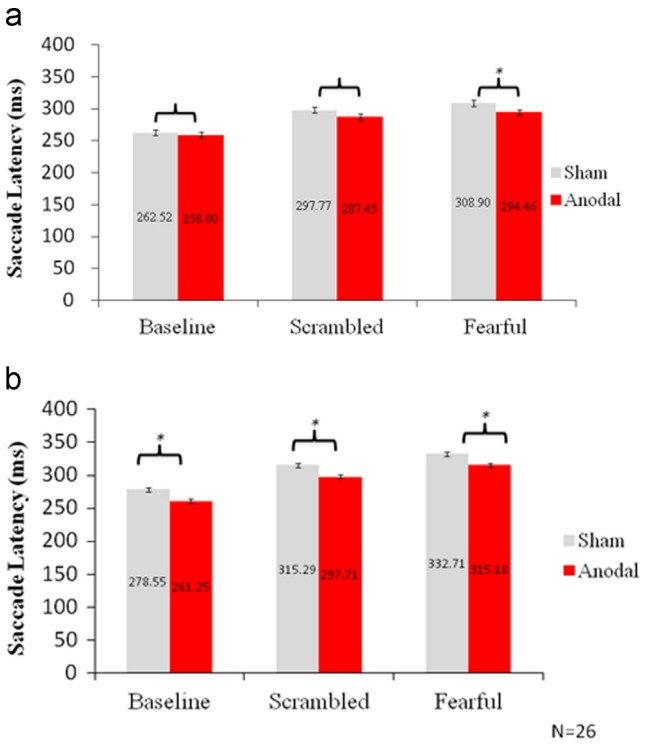

Fig. 8. Saccade latency for each condition in (a) STS experiment and (b) FEF experiment. STS tDCS significantly decreased the saccade latency only under the fearful face distractor condition. However, FEF tDCS decreased saccade latency regardless of the type of distractors. Each error bar shows the 95% confidence interval (*$p < 0.05$, **$p < 0.001$).

anodal tDCS was effective only under the fearful-distractor condition when applied over rSTS.

3.3.2. rFEF tDCS condition

A two-way repeated measures ANOVA revealed a significant main effect for distractor type ($F_{(2,50)}=26.284$, MSE=1047.226, $p<0.001$) and tDCS condition ($F_{(1,25)}=5.066$, MSE=1902.485, $p<0.05$), with no significant interaction between the two ($F_{(2,50)}=0.038$, MSE=68.851, $p=0.962$). Separate comparisons under tDCS condition revealed that participants were faster under the anodal tDCS condition (290 ms) than under the sham condition (306 ms, $p<0.05$). Separate comparisons under distractor type also revealed that participants were the slowest under the fearful distractors condition (318 ms) than under the scrambled (303 ms, $t_{(25)}=2.83$, $p<0.001$) and absent-distractor condition (273 ms, $t_{(25)}=5.26$, $p<0.001$), with the scrambled RT also slower than the absent-distractor condition ($t_{(25)}=7.12$, $p<0.001$). These trends, however, remained the same with or without tDCS, as evidenced by the lack of a significant interaction between distractor type and tDCS that was present when we looked at rSTS. These results suggest that the rFEF is critical for all kinds of distractors, consistent with its role in general oculomotor control.

4. Discussion

The aim of the present study was twofold. First, we investigated whether irrelevant emotional distractors would influence saccade programming. Second, we employed tDCS to explore the underlying neural mechanisms of such effects. The results from the behavioral data suggest that irrelevant emotional distractors could indeed modulate saccadic behaviors in error rate, curvature, and latency. Participants made more distractor-induced errors when the distractors were fearful faces than scrambled faces. They

also showed much longer saccade latencies with fearful-face distractors. In terms of saccade curvature, these fearful-face distractors increased the magnitude of saccade curvature.

In the current study, we also employed tDCS to investigate the role of the STS in the network of areas involved in facial expression processing. We also compared it with the FEF, an area involved in attention and eye movement processing (Table 1). We first found that tDCS delivered over the right STS specifically disrupted the fearful face distractor effect, or face processing in general. In terms of saccade latency, rSTS tDCS improved performance only under the fearful distractor condition and did not affect the scrambled distractor or distractor-absent baseline condition. In contrast, data showed that tDCS delivered over the right FEF benefited target selection: rFEF tDCS decreased saccade latency under all of three conditions after anodal stimulation, suggesting a general oculomotor function that is not specific to the processing of emotion.

4.1. Behavioral data

Previous study has used saccade curvature to be an index to measure the effect of competition between distractor and target selection (Doyle and Walker, 2001). Modulation of saccade curvature reflects activity related to distractor inhibition when participants' saccade to a target location (Liu et al., 2010, 2011). The present results showed that when a distractor and a target were presented simultaneously, participants' saccade curvature to the target location deviated away from the distractor location, implying a strong inhibition of the distractor location (Van der Stigchel, 2010; Van der Stigchel et al., 2006; Van der Stigchel and Theeuwes, 2005, 2006). Our results also showed that participants had more difficulty in visual search when encountering a fearful face as the distractor. From an evolutionary viewpoint, it is assumed that the cognitive system should process highly salient and novel information even when it is perceived outside the fovea (Nummenmaa et al., 2006, 2009). It is important to note that in the current study the fearful face was always irrelevant, as the participants' main objective was to search for a neutral face and make a saccade to that location. The results are consistent with previous results showing that emotional stimuli are processed very rapidly (Bannerman et al., 2010; Dolan, 2002; Phelps, 2006; Vuilleumier and Driver, 2007).

4.2. Neural mechanism

The early cognitive face processing model (Bruce and Young, 1986) specifies two parallel information processing systems that process face perception independent of each other: one involving the recognition of identity and the other for recognition of expression (for a more recent account, see Mattavelli et al. (2013)). For example, the region in the lateral fusiform gyrus is involved in processing face identity, whereas the region in the STS is involved in the changeable aspects of faces. Early studies in monkeys have demonstrated face-selective responses of single neurons located in both superior and inferior temporal cortex: STS showed activation while distinguishing between images of faces showing neutral expressions and open-mouthed strong threat gestures (Hasselmo et al., 1989), implying coding of facial expressions within the STS area. Moreover, a fMRI study comparing facial expressions and complex emotional pictures found that facial expressions resulted in more activation of the STS than did non-facial emotional pictures (Britton et al., 2006). A recent study delivering TMS over the STS resulted in effects consistent with the current hypothesis: increased accuracy in detecting changes of threatening human postures (Candidi et al., 2011). Electrical stimulation of the STS in patients that showed impaired labeling of facial expression can also induce improvement (Fried et al., 1982). Our latency data are consistent with these findings. Specifically, anodal tDCS shortened target selection time when a fearful face distractor was presented, suggesting an inhibition of the emotional distractor effect. These results are also consistent with previous fMRI data suggesting that STS responds to invisible fearful faces subconsciously (Jiang and He, 2006) because, although emotional distractors in the current paradigm were not invisible, they were nonetheless always irrelevant. Therefore, the fact that our participants did not, or could not, use top-down control to filter out such irrelevant emotional expressions seems to suggest that the STS may automatically process facial expression.

In contrast to facial expression processing from the STS, the role of the right FEF is associated with visual attention and saccade programming. Evidence from many studies has shown that FEF is critical for visual attention and eye movements (Chambers and Heinen, 2010; Chambers et al., 2004; Juan et al., 2008, 2004; Morris et al., 2007; Muggleton et al., 2003; Prime et al., 2008, 2010; Rushworth and Taylor, 2006; Taylor et al., 2007). Neurophysiological studies have also shown a network of brain regions that are associated with tracking external regularities (Tseng et al., 2013). Specifically, the FEF tends to produce pretarget-related neural activity during saccade preparation that is closely associated with the processes of visual selection and eye movement execution (Bichot and Schall, 2002; Juan et al., 2004; Liu et al., 2011). Recently, Walker et al. (2009) used TMS to investigate the relationship between FEF and saccade curvature. They applied single-pulse TMS during a left- or rightward saccade and found that TMS to the right FEF increased saccadic curvature away from a distractor location. This finding is consistent with research in monkeys (McPeek, 2006) that show higher FEF activity towards a distractor can lead to saccades curving towards the distractor, and vice versa. These studies propose a role of FEF in the representation of salience in visual search tasks. Our data reveal a beneficial effect on target selection after tDCS stimulation. However, there were additional effects of emotion on saccade latency. Participants showed much longer saccade latencies with fearful face distractors; consistent with the hypothesis that emotional modulation may reflect modulatory signals from emotional related brain regions (i.e. amygdala) that can still operate despite disruption of attentional related brain regions. For example, parietal patients can show significantly less severe extinction overall for emotional stimuli relative to neutral stimuli (Vuilleumier and Schwartz, 2001), presumably because emotional modulation of visual processing can still enhance the perceptual weight of such stimuli in any competition, thus partly compensating for reduced attention to contralesional inputs caused by the parietal lesion.

The lack of tDCS effect in saccade curvatures may be due to the restrictions of the current experimental design. Previous studies have demonstrated a closely linked relationship between saccade latency and saccade curvature (McSorley et al., 2006), reporting that saccades with longer latencies tend to curve more away from the distractors. For the excitatory (anodal) tDCS, modulation effects were not seen on saccade curvatures in either experiment. This may be due to the fact that tDCS reduced saccade latency, thereby limiting its effects on saccade curvature. Moreover, the

Table 1
The comparison between STS and FEF in saccade latency.

	Baseline condition (ms)	Scrambled face condition (ms)	Fearful face condition (ms)
STS-Sham	262.52	297.77	308.90
STS-Anodal	258.80	287.45	294.46
FEF-Sham	278.55	315.29	332.71
FEF-Anodal	261.25	297.71	315.18

task here involved voluntary control to search for a neutral face, which requires strong inhibition of the distractor locations, and may consequently induce the saccade curvatures away from the distractor. Therefore, it may be difficult to observe saccade curvature towards the target with tDCS stimulation in the current experimental context. Another limitation of the current study is that the present results from STS can possibly be driven by the presence of a face distractor, instead of a fearful or emotional one. Neutral faces were used as target and therefore were not used as distracters. Thus, future research should employ a variety of different facial expressions, as well as neutral faces instead of scrambled ones, to pinpoint the specific role of STS in emotion and face processing.

4.3. Electrical stimulation

Although we observed fear-specific tDCS effect in STS, one word of caution towards tDCS is that the large electrodes tend to allow the current to distribute within the brain. As such, any tDCS effects on behavioral performance may be a result of current diffusion that involves a larger area under the cortex, such as the right temporal lobe in this case. Therefore, one alternative explanation for the current findings is that tDCS may have affected stimulus-driven attentional orienting and the ability to detect salient stimulus outside the current focus of attention, a function that is known to involve the temporoparietal junction (Corbetta and Shulman, 2002; Chang et al., 2013). Further research is needed, especially those involving the use of neuroimaging tools and computational models, in order to clarify how tDCS stimulation spreads out throughout the cortex during cognitive processing (for a review, see Bikson and Datta (2012)). For now, a limited number of studies combining tDCS and fMRI seems to suggest that the effect of tDCS is the strongest in the cortical areas immediately underneath the electrode; this is true so far for visual cortex (Halko et al., 2011), frontal lobe (DLPFC in human: Pereira et al., 2013; in rat: Takano et al., 2011), sensorimotor cortex (Antal et al., 2011; Jang et al., 2009), and medial-temporal areas (Antal et al., 2012). In particular, Pereira et al. (2013) assessed verbal fluency in patients with Parkinson's disease after tDCS over either DLPFC or temporo-parietal cortex and found a dissociation in the effect of tDCS: that improvement in verbal fluency was only observed when tDCS was applied over DLPFC, but not temporo-parietal cortex. Our previous work has also reported similar dissociation in function and brain regions between the motor and parietal cortex in the context of visual working memory (Tseng et al., 2012). Therefore, although the resolution of tDCS is not extremely high-definition, basic localization at the cortical level (e.g., posterior parietal cortex) without further specificity beyond that (e.g., superior vs. inferior parietal lobule) seems to be warranted from the above-mentioned fMRI studies. It is important to note, however, that although local spread-over of electrical current stays limited, there are several studies documenting co-activation of brain areas that are functionally relevant to the tDCS-stimulated area (the default mode network and frontoparietal networks: Keeser et al., 2011; right frontoparietal network: Ellison et al., 2014; bilateral primary motor cortex: Zheng et al., 2011). As such, it is possible that our STS tDCS may have recruited additional areas within the same network that are not anatomically close but nonetheless functionally relevant, which should be further investigated by future studies.

5. Conclusion

The present study provides evidence for differentiation between the roles of rFEF and rSTS in saccade generation when emotional faces are present as distractors. Results showed that rSTS is involved in facial processing, and possibly facial expression processing, while rFEF plays a critical role in saccadic behaviors but not in emotional processing. The involvement of rSTS occurs even though the emotional facial expressions are not relevant to the task. The results demonstrate that the emotional effect can be modulated only after tDCS stimulation over an emotion-related brain region but not an attention-related brain region. These results imply that emotional modulation might boost the processing of certain stimuli, and that attention may not override emotional effects. The findings support the proposal that emotion and attention can result in independent effects, subserved by different brain regions.

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