Sliwinska, M and Pitcher, D

TMS demonstrates that both right and left superior temporal sulci are important for facial expression recognition

TMS demonstrates that both right and left superior temporal sulci are important for facial expression recognition

Magdalena W. Sliwinska and David Pitcher

Department of Psychology, University of York, Heslington, York, YO10 5DD, UK

Corresponding author: Magdalena W. Sliwinska (email: magdalena.sliwinska@york.ac.uk)

Keywords: face recognition, emotion processing, transcranial magnetic stimulation (TMS), functional magnetic resonance imaging (fMRI)

Acknowledgements: The research reported here was supported by grants from the Simons Foundation Autism Research Initiative (#392150) and the BBSRC (BB/ BB/P006981/1). We thank Andre Gouws for technical assistance.

Declarations of interest: none

Abstract

Prior studies demonstrate that a face-responsive region in the posterior superior temporal sulcus (pSTS) is involved in facial expression recognition. Although this region can be identified in both hemispheres, studies more commonly report it in the right hemisphere. However, the extent to which expression recognition is lateralised in pSTS remains unclear. In the current study, we used transcranial magnetic stimulation (TMS) to systematically compare the causal contribution of the right pSTS (rpSTS) with the left pSTS (lpSTS) during facial expression recognition. TMS was delivered over the functionally localised rpSTS, lpSTS and the control vertex site while participants (N=30) performed an expression matching task and a control object matching task. TMS delivered over the rpSTS impaired expression recognition more than TMS delivered over the lpSTS. Crucially, TMS delivered over the rpSTS and lpSTS impaired task performance more than TMS delivered over the control site. TMS had no effect on the control task. This causally demonstrates that while task disruption was greater in the rpSTS, both the rpSTS and the lpSTS were engaged in facial expression recognition. Our results indicate that cognitive functions that are seemingly lateralized in neuroimaging studies, still rely on computations performed in both hemispheres for optimum task performance.

Introduction

Recognising facial expressions is an important aspect of human social interaction. Expressions provide us with one of the richest sources of information about another person's emotional state. Models of face processing propose that expressions are computed in an anatomically distributed, and highly interacting network in the human brain. Two components in this network are located in the bilateral posterior superior temporal sulcus (pSTS) (Haxby, Hoffman, & Gobbini, 2000, 2002; Palermo & Rhodes, 2007; Vuilleumier, Richardson, Armony, Driver, & Dolan, 2004). While the functional contribution of the right pSTS (rpSTS) to expression recognition has been extensively investigated (Allison, Puce, & McCarthy, 2000; Andrews & Ewbank, 2004; Phillips et al., 1998; Pitcher, 2014; Winston, O'Doherty, & Dolan, 2003), the functional involvement of the lpSTS in expression recognition is less clear. In addition, the extent to which expression recognition is lateralised in the pSTS is unknown. In the current study, we used functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation (TMS) to systematically investigate the causal contribution of the right and left pSTS to expression recognition.

Models of face processing propose that the human STS is a core node of a distributed face network (Adolphs, 2002; Calder & Young, 2005; Haxby et al., 2000). Evidence from a range of experimental techniques demonstrates that the posterior region of the right STS is involved in expression recognition. For example, single-cell recordings in patients undergoing craniotomy showed that expression identification evoked changes in neuronal activity in the rpSTS (Ojemann, Ojemann, & Lettich, 1992). Direct electrical stimulation to the rpSTS also impaired patients' ability to identify facial expressions, demonstrating that the region is causally engaged in expression recognition (Fried, Mateer, Ojemann, Wohns, & Fedio, 1982). Similarly, expression recognition impairments have been reported in patients with lesions to the rpSTS (Fox, Hanif, Iaria, Duchaine, & Barton, 2011; Rapcsak, Kaszniak, & Rubens, 1989) and when TMS was delivered over the rpSTS of healthy participants (Pitcher, 2014). Many neuroimaging studies have also demonstrated an increased response in the pSTS during expression recognition tasks (e.g., Andrews & Ewbank, 2004; Engell & Haxby, 2007; Gur, Skolnick, & Gur, 1994; Narumoto, Okada, Sadato, Fukui, & Yonekura, 2001; Phillips et al., 1998; Streit et al., 1999; Winston, Henson, Fine-Goulden, & Dolan, 2004; Winston et al., 2003). It is important to note that in the majority of these studies, the rpSTS was more robustly identified across participants than the lpSTS (but see Engell & Haxby, 2007).

This functional asymmetry of the face-responsive pSTS suggests that expression recognition may be preferentially processed in the right hemisphere (Narumoto et al., 2001). Such a hypothesis is consistent with an earlier neuropsychological study in which patients with lesions in the right hemisphere were significantly worse in performing tasks using emotional faces than patients with left-hemispheric lesions (DeKosky, Heilman, Bowers, & Valenstein, 1980). A right hemisphere advantage was also demonstrated by the left visual field superiority for the recognition of emotional facial expressions in healthy individuals (Sackeim, Gur, & Saucy, 1978). The neuropsychological and behavioural evidence demonstrates that faces are preferentially processed in the right hemisphere but does not address whether this asymmetry is due to the asymmetry of the face-responsive area in the pSTS. As stated above, neuroimaging studies report that the rpSTS is more commonly

identified than the lpSTS, but the neuroimaging methods do not causally address whether only the rpSTS, or the bilateral pSTS, is engaged in expression recognition.

In the current study, we systematically investigated the causal contributions of the right and left pSTS to facial expression recognition using TMS. Functional magnetic resonance imaging (fMRI) was used to individually localise the face-responsive area in the right and left pSTS of every participant. TMS was then delivered over the rpSTS, lpSTS and the vertex while participants performed facial expression and object recognition tasks. The vertex acted as a control site, and the object task acted as a control task for the non-specific effects of TMS. Our aim was to provide a fuller picture of the functional properties of the pSTS in the extended face processing network, and to further contribute to the debate about hemispheric specialisation of expression recognition.

Materials and Methods

Participants

Thirty-one right-handed volunteers participated in this study. One participant found TMS uncomfortable; he withdrew from the study and his data were discarded. All remaining participants (15 women and 15 men; aged between 18 – 44 years, mean: 23, SD: 6) were neurologically healthy with normal or corrected-to-normal vision. Informed consent was obtained after the experimental procedures were explained. A *post hoc* power analysis in GPower (Erdfelder, Faul, & Buchner, 1996) indicated that with the present sample, power of 97% was achieved with alpha set at 0.05. All participants were paid for their participation. The study was approved by the York Neuroimaging Centre (YNiC) Research Ethics Committee at the University of York.

Experimental Procedures

Each participant completed two sessions, performed on different days. During the first session, participants were scanned using fMRI to functionally localise face-responsive regions in the right and left pSTS. These regions were then used as stimulation targets in the TMS study that was performed in the subsequent session. The fMRI session lasted approximately 1 hour while the TMS session lasted approximately 1.5 hours.

FMRI Functional Localisation

Procedure

Functional data were acquired over 6 block-design runs, lasting 234 sec each. During those runs, participants were instructed to watch videos of faces, bodies, scenes, objects, or scrambled objects, without performing any overt task. Each run contained two sets of five consecutive stimulus blocks to form two blocks per stimulus category per run. Each block lasted 18 sec and contained stimuli from one of the five stimulus categories. Each functional run also contained three 18 sec rest blocks, which occurred at the beginning, middle, and end of the run. During the rest blocks, a series of six uniform color fields were presented for 3 sec each. The order

of stimulus category blocks in each run was palindromic (e.g., rest, faces, objects, scenes, bodies, scrambled objects, rest, scrambled objects, bodies, scenes, objects, faces, rest) and randomized across runs. At the end of the session a structural brain scan was collected to anatomically localise the functional data for each participant.

Stimuli

The stimuli consisted of 3 sec movie clips of faces, bodies, scenes, objects and scrambled objects. Movies of bodies and scenes were not relevant to this study hence their data are not presented. The main motivation for using dynamic faces in the localisation procedure was to maximise chances of finding face-responsive areas in pSTS. This region was shown to respond stronger to dynamic stimuli than to the static stimuli, while activations for both types of stimuli spatially overlapped (Pitcher, Dilks, Saxe, Triantafyllou, & Kanwisher, 2011). These stimuli have also been used in prior fMRI and TMS studies of the pSTS (Pitcher, Duchaine, & Walsh, 2014; Pitcher, Japee, Rauth, & Ungerleider, 2017). There were 60 movie clips for each category in which distinct exemplars appeared multiple times. Movies of faces and bodies were filmed on a black background and framed close-up to reveal only the faces or bodies of 7 children as they danced or played with toys or adults (who were out of frame). Movies of scenes included fifteen different locations which were mostly pastoral scenes filmed from a car window while driving slowly through leafy suburbs, along with some other films taken while flying through canyons or walking through tunnels that were included for variety. Movies of objects used 15 different moving objects that were selected in a way that minimizes any suggestion of animacy of the object itself or of a hidden actor pushing the object. Those included mobiles, windup toys, toy planes and tractors, and balls rolling down sloped inclines. Movies of scrambled objects were constructed by dividing each object movie clip into a 15 × 15 box grid and spatially rearranging the location of each of the resulting movie frames. Within each block, stimuli were randomly selected from within the entire set for that stimulus category. This meant that the same movie clip could appear within the same block but given the number of stimuli this did not occur frequently.

Data collection

Imaging data were collected using a 3T GE HDx Excite MRI scanner at YNiC. Functional images were acquired with an 8-channel phased array head coil (GE) tuned to 127.4 MHz and a gradient-echo EPI sequence (38 interleaved slices, repetition time (TR) = 3 sec, echo time (TE) = minimum full, flip angle = 90°; voxel size = 3 × 3 × 3 mm; matrix size = 128 × 128) providing whole brain coverage. Slices were aligned with the anterior to posterior commissure line. Structural images were acquired using the same head coil and a high-resolution T-1 weighted 3D fast spoilt gradient (SPGR) sequence (176 interleaved slices, repetition time (TR) = 7.8 sec, echo time (TE) = minimum full, flip angle = 20°; voxel size = 1 × 1 × 1 mm; matrix size = 256 × 256).

Data analysis

Data were analysed using fMRI Expert Analysis Tool (FEAT) included in the FMRIB (v6.0) Software Library (www.fmrib.ox.ac.uk/fsl). In the first-level analysis, as part of the pre-statistical processing, single-participant functional images underwent extraction of non-brain structures performed with the Brain Extraction Tool (BET). In

addition, interleaved slice timing correction, MCFLIRT motion correction, spatial smoothing using a 5 mm full-width half-maximum Gaussian kernel, high-pass temporal filtering, and pre-whitening were applied to the data. The pre-processed functional images were entered into a general linear model (GLM) with five independent predictors, corresponding to the five categories of visual stimuli (i.e., Faces, Bodies, Scenes, Objects, Scrambled Objects), to compute participant-specific patterns of activation. The model was convolved using a double-gamma hemodynamic response function (HRF) to generate the main regressors. Temporal derivatives for each condition were included.

Face-responsive areas in the right and left pSTS were identified using a contrast of faces greater than objects. First-level functional results for each participant were registered to their anatomical scan using a 12 degree-of-freedom affine registration. All analyses were conducted at the whole-brain level and differences between conditions were considered significant at $Z = 3.1$ and cluster $p = 0.05$, using a cluster-wise significance test.

To examine the hemispheric laterality of facial expression recognition, region-of-interest (ROI) analyses were performed. For each participant, regional masks were created using a sphere with 5 mm radius centred at the strongest peaks within the right and left pSTS activation clusters (i.e., peaks targeted with TMS), defined by the individual contrast of (Faces > Objects). The mean intensity of blood-oxygen-level dependent (BOLD) signal was then extracted from the (Faces > Objects) contrast for the right and left pSTS, and compared using a paired two-tailed *t* test.

In order to report coordinates of TMS target sites in standard space, each participant's structural scan was registered to the Montreal Neurological Institute (MNI)-152 template. Note that all stimulation was done in native anatomical space and the standard space coordinates were computed solely for reporting purposes. In addition, the MNI coordinates from each participant were presented on the MNI brain in order to demonstrate the anatomical variability of the pSTS hot spots across individuals.

TMS Experiment

Procedure

The TMS session involved the acquisition of behavioural data while participants performed computer-based visual facial expression and visual object matching tasks. The object recognition task acted as a control task. Each task was performed under four different stimulation conditions: i) TMS delivered over the rpSTS; ii) TMS delivered over the lpSTS; iii) TMS delivered over the vertex (control site); and iv) no TMS (behavioural baseline). Both tasks were taken and adapted from previous studies ran by Pitcher and colleagues (Pitcher, Charles, Devlin, Walsh, & Duchaine, 2009; Pitcher, Garrido, Walsh, & Duchaine, 2008). The facial expression matching task required participants to judge whether two faces of different people had the same expression. In the object matching task, participants were asked to judge whether two objects were the same. This task was used to control for non-specific to TMS effects that could result from differences in somatosensory sensation of stimulation that varied between the sites. Particularly, TMS over both pSTS sites

produced mild peripheral jaw muscle twitching while the vertex stimulation did not produce any muscular responses. Participants sat 57 cm away from the monitor and used their right index or middle finger to respond “yes” or “no”, respectively, by pressing appropriate keys on a keyboard. They were instructed to respond as accurately and quickly as possible.

Participant completed four runs (one run per TMS condition) of the facial expression matching task followed by four runs of the object matching task, or vice versa. Task order was counterbalanced across participants. The order of the TMS conditions was randomised across participants, but kept the same for both tasks in each participant. Each task run consisted of 72 trials, with half ‘same’ and half ‘different’ trials. The trial design is shown in Figure 1. Each trial commenced with a fixation cross displayed for 2000 msec, followed by the target image displayed for another 250 msec, then a fixation cross displayed for another 1000 msec, and the match image displayed for another 250 msec. A trial ended with a blank white screen that was displayed until the participant responded. All stimuli were presented in the centre of a white screen on a Mitsubishi Diamond Pro 2070SB 22-inch CRT monitor, set at 1024 × 768 resolution and refresh rate of 85 Hz.

Stimuli

The stimuli in the expression matching task were taken from (Ekman & Friesen, 1976), and consisted of grayscale pictures of six female models (C, MF, MO, NR, SW) expressing six emotions: happy, sad, surprise, fear, disgust, and anger. Each picture was cropped with the same contour to cover the hair and neck of the models. Identity of the two faces within each trial was always different and the six expressions were presented an equal number of times within each run.

For the object matching task, pictures of novel, abstract objects were downloaded from Michael Tarr's website (http://wiki.cnbc.cmu.edu/TarrLab). The “different” trials comprised of two objects that were morphed so that the objects were seen from the same viewing angle and had the same overall shape but varied in local details to different degrees. The percentage difference between the two images was either 20%, 30%, 50%, 80%, or 100%. A number of each morph type was equal across runs.

All stimuli were static in contrast to the stimuli used in the functional localisation. However, we did not expect any significant spatial differences in localisation of the static and dynamic stimuli based on our previous work (Pitcher et al., 2011) that showed similar responses to both types of stimuli in pSTS. Also, the spatial resolution of TMS, measured in tens of millimetres (Brasil-Neto, McShane, Fuhr, Hallett, & Cohen, 1992), provided a degree of spatial tolerance in case of spatial difference and intra-subject variability in the functional location at different time points (Duncan, Pattamadilok, Knierim, & Devlin, 2009).

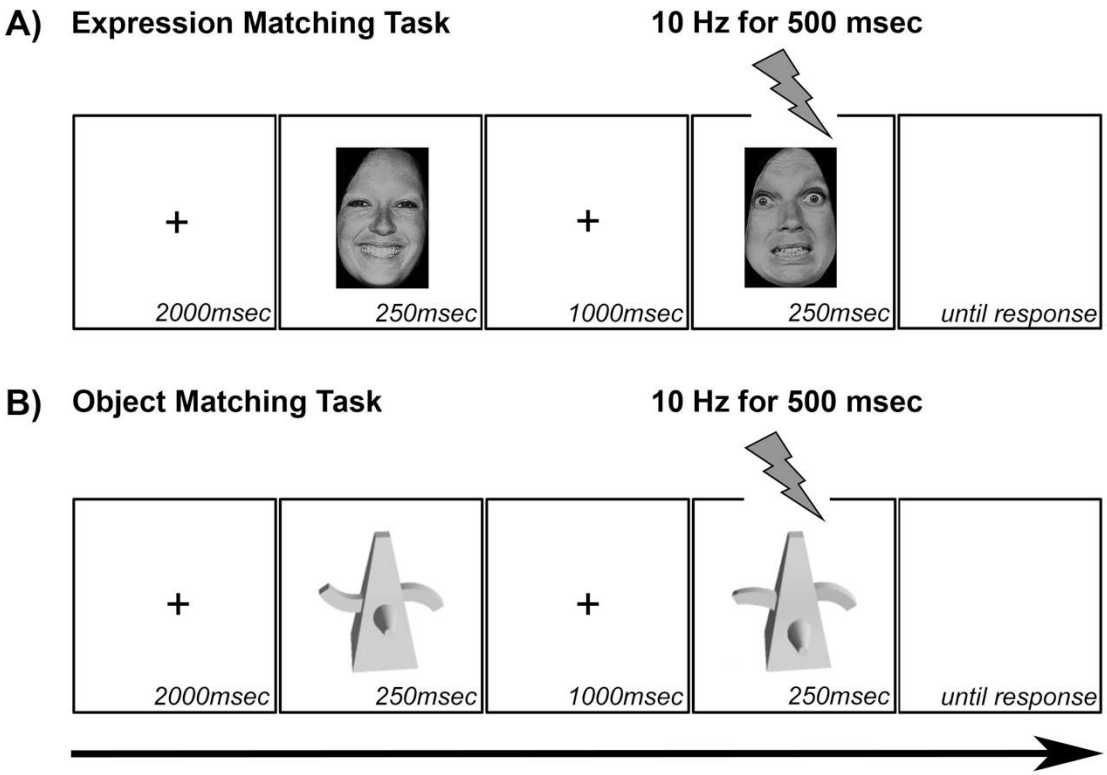

Figure 1: The experimental trial procedure. The expression matching task (A) required the participant to judge whether two faces belonging to different people had the same expression. The object matching task (B) required the participant to judge whether the two objects were identical. TMS was applied at the onset of the match image at a frequency of 10 Hz for 500 msec.

Data collection

TMS was delivered using a Magstim Rapid2 stimulator and a Magstim coated Alpha Flat 50 mm diameter figure-of-eight coil (Magstim, Carmarthenshire, UK). The stimulation intensity was set to 60% of the maximum stimulator output for all participants. A single intensity was used for all participants on the basis of our previous studies (Pitcher et al., 2009; Pitcher et al., 2008). During TMS runs, a train of five pulses at a frequency of 10 Hz was delivered for 500 msec on each trial. The onset of the TMS coincided with the onset of the match image. The TMS frequency, intensity, and duration were within established international safety limits (Rossi, Hallett, Rossini, Pascual-Leone, & Group, 2009; Wassermann, 1998). The TMS coil was held against the participant's head by the experimenter who manually controlled its position throughout testing.

TMS target sites in the right and left pSTS were marked as stimulation targets on each participant's MRI scan using the Brainsight frameless stereotaxy system (Rogue Research, Montreal, Canada). During testing, a Polaris Vicra infrared camera (Northern Digital, Waterloo, ON, Canada) was used in conjunction with the Brainsight to register the participant's head to their MRI scan for accurate stimulation targeting throughout the experiment. All participants wore earplugs in both ears to

attenuate the sound of the coil discharge and avoid damage to the ear (Counter, Borg, & Lofqvist, 1991). In some participants, stimulation affected the peripheral jaw muscle and produced a small jaw twitch. One participant described stimulation to his rpSTS as uncomfortable and was excluded from the study. The remaining participants tolerated TMS well.

Data analysis

A TMS control baseline was calculated as the mean accuracy score for vertex and no TMS condition in each participant. This type of TMS baseline was used as it constitutes a more representative measure of the control condition for stimulation than each of the two measures in isolation. It was possible to average vertex and no TMS conditions (both equal 82% in the expression matching task and 77% in the object matching task) as there was no significant difference in task performance between them (both paired two-tailed *t* tests: $t(29) < 0.79$; $p > 0.44$; Cohen's effect size $d < 0.001$). Analyses of the main data with any of those conditions in separation showed the same pattern of results as when the conditions were averaged together.

Performance accuracy and reaction times (RTs) were analysed using IBM SPSS Statistics (v24.0) in a 2 × 3 repeated measures ANOVA, with Task (Facial Expression Matching Task and Object Matching Task) and Stimulation (TMS to rpSTS, TMS to lpSTS, and TMS Control Baseline) as independent factors. *Post hoc* paired two-tailed *t*-tests (with Bonferroni correction for multiple comparisons) were used to further characterize significant main effects and interactions from the ANOVA.

Results

FMRI Functional Localisation

We were able to successfully identify a face-responsive area in the right and left pSTS in all participants. The coordinates and strength of the peak activation varied across individuals (see Table 1 for information on individual peak coordinates in the standard MNI space and Figure 2 for their illustration). The group mean peak coordinates in the standard space [rpSTS: $x = 55$, $y = -39$, $z = 9$; lpSTS: $x = -56$, $y = -45$, $z = 9$] were consistent with previous studies (e.g., Engell & Haxby, 2007).

The ROI analyses of the average mean voxel intensity showed significantly stronger response in the rpSTS (7.9 a.u.) than in the lpSTS (6.0 a.u.; $t(29) = 3.56$; $p = 0.001$; Cohen's effect size $d = 0.68$). In 22 participants, activation intensity was greater in the rpSTS than in the lpSTS while in the remaining 8 participants the opposite pattern was observed (see Table 1).

Table 1: Information about the rpSTS and lpSTS, including individual peak coordinates in the standard MNI space; BOLD intensity for ROIs and TMS effects on accuracy durig the expression matching task. A TMS effect is a difference between the TMS and baseline conditions where negative values indicate succesful disruption of processing.

	rpSTS					lpSTS				
Participant (G)	*x*	*y*	*z*	BOLD intensity (a.u.)	TMS effect (%)	*x*	*y*	*z*	BOLD intensity (a.u.)	TMS effect (%)
1 (F)	59	-37	8	6.24	-9	-60	-45	10	6.68	-6
2 (F)	50	-38	16	12.34	-2	-47	-61	12	6.37	-2
3 (F)	46	-24	-1	4.83	-3	-66	-32	2	3.45	-6
4 (F)	56	-39	4	11.53	-2	-49	-45	1	9.81	8
5 (F)	53	-39	0	7.30	-1	-57	-43	0	2.94	-2
6 (F)	58	-42	10	7.07	1	-52	-44	13	4.19	-3
7 (M)	54	-43	15	11.75	-3	-52	-40	12	9.89	0
8 (F)	54	-33	8	5.54	-3	-49	-30	1	4.36	-1
9 (F)	50	-43	12	8.27	-1	-51	-42	10	5.09	-2
10 (M)	58	-49	10	5.55	-6	-64	-47	9	5.62	-2
11 (M)	50	-38	-3	4.04	-1	-65	-33	6	3.26	1
12 (F)	51	-38	5	11.00	-3	-48	-45	7	13.42	1
13 (M)	46	-42	17	7.43	2	-48	-45	4	3.55	-3
14 (M)	43	-30	3	12.76	-4	-53	-43	11	7.35	-3
15 (M)	51	-37	4	14.99	-1	-61	-38	0	7.60	2
16 (F)	55	-44	16	9.40	-3	-45	-43	17	10.63	2
17 (M)	50	-43	9	6.61	-6	-49	-52	16	8.54	1
18 (M)	51	-38	10	8.54	-6	-62	-52	11	11.48	-4
19 (F)	65	-29	4	7.12	-6	-47	-58	15	4.70	-4
20 (M)	61	-48	8	5.39	-13	-58	-35	10	3.87	-8
21 (M)	60	-33	5	6.31	-3	-65	-35	13	2.59	-1
22 (M)	64	-52	8	7.81	-10	-56	-62	7	5.22	-3
23 (M)	59	-39	12	13.52	-6	-66	-27	8	6.81	1
24 (M)	58	-36	12	4.12	-9	-62	-41	6	2.56	-10
25 (F)	55	-29	6	12.36	-11	-65	-46	14	3.89	-6
26 (F)	68	-36	10	4.94	-4	-61	-43	6	4.78	2
27 (M)	64	-43	27	5.34	-1	-60	-44	9	7.55	-2
28 (M)	52	-48	0	7.11	1	-51	-50	3	6.09	-3
29 (F)	56	-43	3	2.20	-15	-54	-68	14	2.82	-6
30 (F)	53	-46	33	5.53	-5	-66	-52	8	4.78	-12
Mean:	**55**	**-39**	**9**	**7.90**	**-4**	**-56**	**-45**	**9**	**6.00**	**-2**

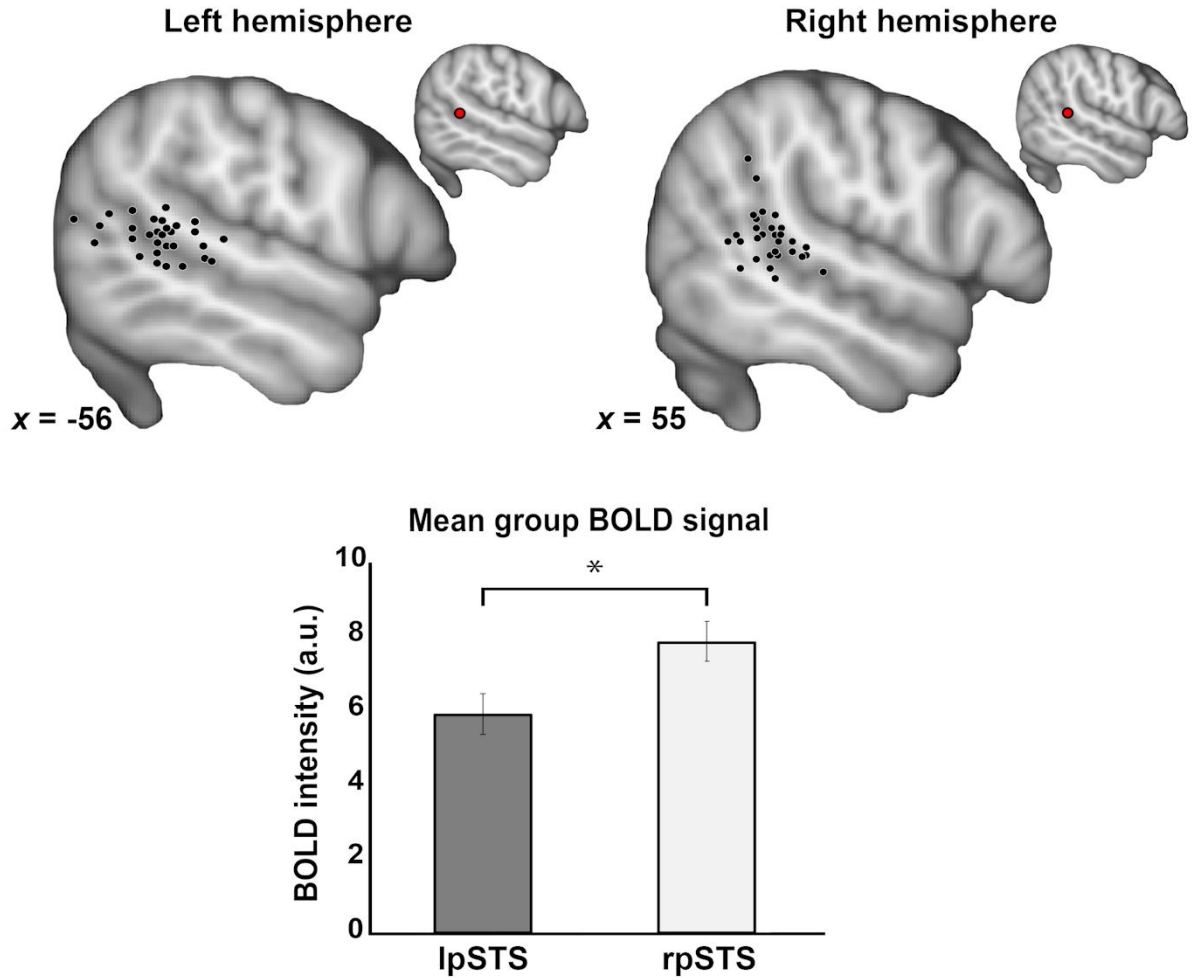

Figure 2: Top panel illustrates the individual peak coordinates for all 30 participants (black circles) and the mean group coordinates (red circles) in the left and right pSTS, presented in the standard MNI-152 space. Bottom panel shows bar plots for the mean group BOLD signal intensity extracted from the (Faces > Objects) contrast for the left and right pSTS. Error bars represent SEM. *p < 0.05.

TMS Study

The mean accuracy results are shown in Figure 3. The main effects of Task ($F(1, 29) = 2.54$; $p = 0.12$; partial $\eta^2 = 0.08$) and Stimulation ($F(2, 58) = 2.22$; $p = 0.12$; partial $\eta^2 = 0.07$) were not significant. However, there was a significant two-way interaction between Task and Stimulation ($F(2, 58) = 11.20$; $p < 0.001$; partial $\eta^2 = 0.28$). *Post hoc t*-tests showed that during the expression matching task, TMS delivered over the rpSTS (78%; $t(29) = 6.21$; $p < 0.001$; Cohen's effect size $d = 1.05$) and lpSTS (80%; $t(29) = 3.31$; $p = 0.003$; Cohen's effect size $d = 0.49$) significantly impaired accuracy in relation to the TMS control baseline condition (82%). TMS delivered over the rpSTS (79%; $t(29) = 1.72$; $p = 0.1$; Cohen's effect size $d = 0.34$) and lpSTS (78%; $t(29) = 0.50$; $p = 0.62$; Cohen's effect size $d = 0.19$) had no effect on performance of the object matching control task in relation to the baseline condition (77%).

In addition, the difference between the accuracy in the rpSTS and lpSTS in the expression matching task was significantly different (t(29) = 2.75; p = 0.01; Cohen's effect size *d* = 0.49). In the facial expression task, TMS delivered over the rpSTS impaired accuracy in 26 participants while TMS delivered over the lpSTS impaired accuracy in 21 participants. 18 participants showed effect of TMS in both hemispheres while in the remaining 9 and 3 participants TMS had an effect only in the rpSTS and the lpSTS, respectively.

RTs showed no significant two-way interaction between Task and Stimulation ($F(2, 58) = 1.51$; $p = 0.23$; partial $\eta^2 = 0.05$) or main effects of Task ($F(1, 29) = 1.89$; $p = 0.18$; partial $\eta^2 = 0.06$) and Stimulation ($F(2, 58) = 0.62$; $p = 0.54$; partial $\eta^2 = 0.02$).

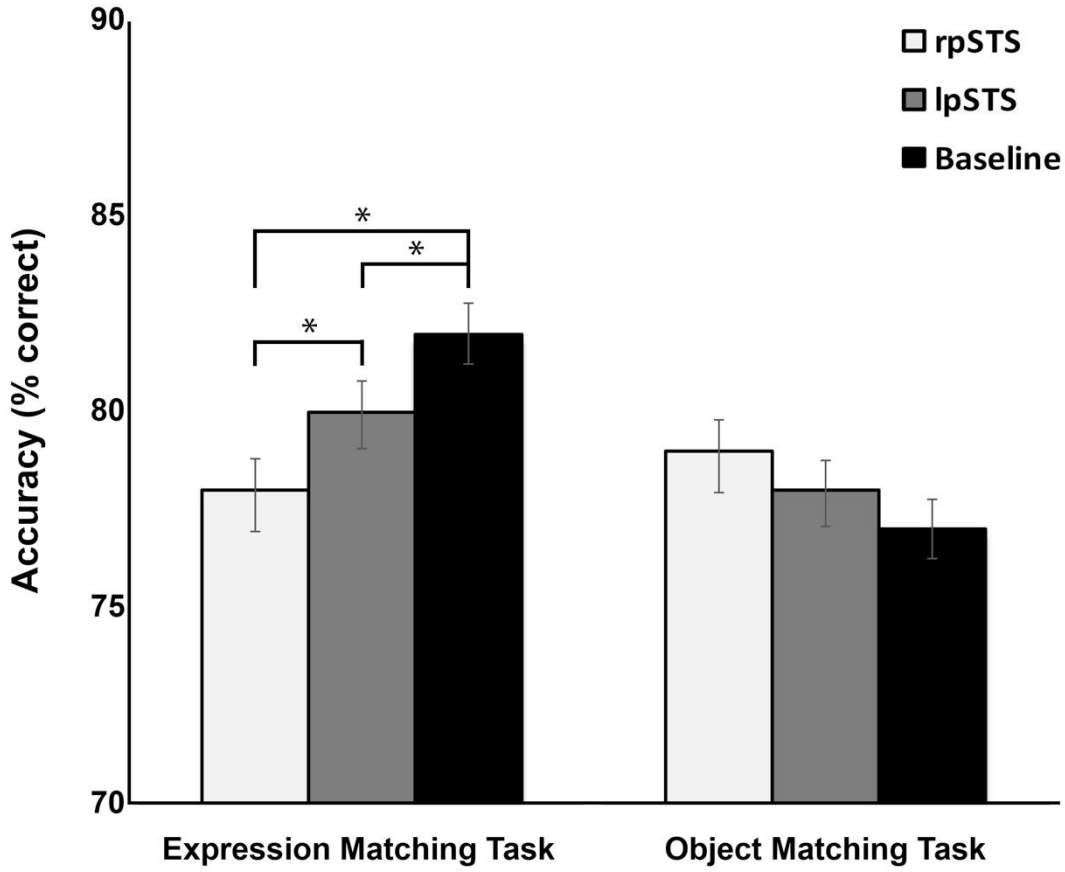

Figure 3: Group mean accuracy scores during the expression and object matching tasks for the three stimulation conditions: i) TMS over the rpSTS (light grey) ii) TMS over the left pSTS (dark grey), and iii) TMS control baseline (black). Error bars represent SEM. *p < 0.05.

Discussion

In the present study we used fMRI and TMS to systematically investigate the causal

contributions of the right and left pSTS to facial expression recognition. fMRI results showed that the rpSTS response to faces was greater than the response of the lpSTS. The TMS results revealed that both the right and left pSTS are causally involved in recognizing facial expressions. However, consistent with the fMRI results, TMS delivered over the rpSTS produced a greater disruption in task performance than TMS delivered over the lpSTS. Our results demonstrate that the rpSTS was more engaged in task performance than its left homologue, but optimal facial expression recognition requires computations performed in both right and left pSTS.

Our neuroimaging results are consistent with the previous neuroimaging study (Engell & Haxby, 2007) that revealed increased activation in the right and left pSTS during expression recognition tasks. It is also in line with the face processing model proposed by Haxby and colleagues (Haxby et al., 2000) that include both the right and left pSTS in the face network. These results are, however, seemingly inconsistent with other neuroimaging studies (e.g., Narumoto et al., 2001; Streit et al., 1999; Winston et al., 2004; Winston et al., 2003) that demonstrated a neural response to expressions in the rpSTS only, and consequently focused solely on the role of the rpSTS in processing expressions. Such a discrepancy in detecting responses in both hemispheres may result from differences in the experimental design. Our functional localiser used dynamic, rather than static, face stimuli as those have been demonstrated to be more suitable for eliciting responses in the pSTS, a brain region preferentially engaged in moving faces (Pitcher et al., 2011; Polosecki et al., 2013). Also, using static face stimuli in the current TMS study supported our previous findings (Pitcher et al., 2011) which showed that static faces and dynamic faces activate the same face-responsive areas in the pSTS. Based on our previous findings of a stronger response to dynamic faces than static faces in pSTS, we would predict that TMS effects in the expression matching task would be greater if dynamic stimuli was used.

Our findings are inconsistent with a recent fMRI study (De Winter et al., 2015) that specifically measured lateralization in face processing areas while humans and monkeys watched dynamic expressions. In humans, the rpSTS was found to be the only region that showed a clear lateralisation for visual non-linguistic facial expressions, with no involvement of the left hemisphere. In contrast, visual linguistic expressions were found to fully engage lpSTS, but not its right homologue. No consistent pattern of lateralisation was found in monkeys. The authors argued that their findings support the verbal versus visuospatial model (Corballis, Funnell, & Gazzaniga, 2000), which proposes that the right hemispheric dominance for visual stimuli evolved as a cost of language specialisation in the opposite hemisphere. While our results are still consistent with the idea of the hemispheric specialisation for visual and language functions, they do not support the absolute segregation of these functions into different hemispheres.

The extent to which cognitive functions are functionally lateralized in the human brain remains an active debate in the cognitive neuroscience. One of the issues is the extent to which we investigate the functional contribution of the less dominant hemisphere to our chosen cognitive operation. The current study addresses this debate by looking specifically at facial expression recognition in the right and left pSTS. By using a robust functional localiser, we were able to identify the face-responsive pSTS in both hemispheres for each participant, and then demonstrate

with TMS that although both regions contribute to accurate expression identification, the rpSTS contribution dominates over the lpSTS. Although our study focused on lateralisation of face processing in the pSTS, this region is also implicated in other cognitive functions, some related to language (for review see Price, 2012). Left-hemispheric dominance for language processing was proposed in the first lesion-based neurological model of language (Geschwind, 1970), and later supported by neuroimaging studies (Petersen, Fox, Posner, Mintun, & Raichle, 1989; Pujol, Deus, Losilla, & Capdevila, 1999; Scott, Blank, Rosen, & Wise, 2000; Springer et al., 1999; Zatorre, Evans, Meyer, & Gjedde, 1992). Based on our findings, we predict that both the right and the left pSTS are important for optimum performance of language functions, but lpSTS involvement would dominate over the rpSTS.

A discrepancy in evidence for functional lateralisation between brain stimulation studies and neuroimaging studies has also been reported in brain areas engaged in other cognitive tasks. For example, Santiesteban and colleagues (2015) examined the lateralisation of socio-cognitive abilities in the temporoparietal junction (TPJ) using transcranial direct current stimulation (tDCS). Their results demonstrated that the right and left TPJ is causally involved in tasks requiring imitation control and visual perspective-taking. This contrasts with the evidence from the neuroimaging literature suggesting unilateral activation of the right TPJ during imitation control (Brass, Derrfuss, & von Cramon, 2005; Spengler, von Cramon, & Brass, 2009) or left TPJ during visual perspective-taking (Schurz, Aichhorn, Martin, & Perner, 2013). As the authors argue, those differences can result from the application of the over-conservative statistical thresholds in neuroimaging studies to avoid Type I errors while potentially creating Type II errors. It is also possible that those differences are caused by the propagation of the effects of the unilateral stimulation to the opposite hemisphere. However, the reports of selective effects on cognitive tasks following unilateral stimulation over the right and left TPJ (Heinisch, Dinse, Tegenthoff, Juckel, & Brüne, 2010; Uddin, Iacoboni, Lange, & Keenan, 2007) and in our case pSTS (e.g., Oliveri, Romero, & Papagno, 2004; Pobric, Mashal, Faust, & Lavidor, 2008) do not support this conclusion.

It is also worth noting that our study demonstrated that the strength of activation and size of TMS effect varied across individuals. Some participants exhibited a greater activation, or a greater TMS effect in the left rather than the right pSTS (see Table 1). Similar inter-individual variability in the magnitude of lateralisation in pSTS was found by De Winter and colleagues (2015). In their study, a number of participants showed lateralisation of dynamic facial expressions to the lpSTS. These differences could be explained by inter-individual differences in i) the development of hemispheric lateralisation for language and faces (Dundas, Plaut, & Behrmann, 2012); ii) strategies used for face recognition; iii) functional location between the static and dynamic faces; or iv) lack of individualised stimulation parameters.

The current TMS results replicate and extend the results from our earlier TMS study in which TMS delivered over the rpSTS impaired expression recognition (Pitcher, 2014). The present study, additionally demonstrates that the lpSTS is causally important for recognising expressions, albeit to a lesser extent. In another preceding study (Dzhelyova, Ellison, & Atkinson, 2011), TMS delivered over the right and left pSTS impaired judgments of facial trustworthiness. However, this study did not systematically explore the differences between the left and right pSTS. In contrast,

our results are not consistent with another set of findings in which TMS delivered over the rpSTS impaired eye gaze discrimination, but did not impair expression recognition (Pourtois et al., 2004). This may be due to methodological differences in how TMS target sites were selected. Pourtois and colleagues identified the pSTS based on the EEG electrode system while we used functional fMRI localisers to identify target sites individually in each participant. It is apparent from our localisation results (Figure 2) that the location of the target sites varied greatly across the two hemispheres in each individual and across individuals, indicating the need for using a more precise localisation method when studying the pSTS.

Although our study provided strong evidence for the importance of the right and left pSTS in recognising expressions, the precise role of this region requires further investigation. It has been suggested that the pSTS may be involved in extracting information about the eye gaze in order to interpret expressions, and may be homologous to a region in the superior bank of the monkey's STS where cells respond preferentially to gaze direction (Hasselmo, Rolls, & Baylis, 1989; Perrett et al., 1985). Also in humans, a number of studies demonstrated that the pSTS is involved in eye gaze discrimination (Engell & Haxby, 2007; Pourtois et al., 2004; Puce, Allison, Bentin, Gore, & McCarthy, 1998). It is not possible to determine from our fMRI data whether the pSTS responded to changes in eye gaze because we did not systematically manipulate this factor. There is evidence in the neuroimaging literature (Engell & Haxby, 2007) suggesting that gaze-direction and expressions are represented by distinct but overlapping regions in the rpSTS. Therefore, the specifics of the functional contributions of various sub-regions of the pSTS to facial expression processing still require further investigation, especially with the causal methods like TMS. It is also worth noting that the pSTS is engaged in a range of other cognitive tasks including recognition of intentional actions (Saxe, Xiao, Kovacs, Perrett, & Kanwisher, 2004) or body perception (Basil, Westwater, Wiener, & Thompson, 2017), and future TMS studies could assess how these functions are lateralised.

Our study demonstrated that both the right and left pSTS make a functional contribution to accurate facial expression recognition. Nevertheless, the engagement of the rpSTS was greater than the lpSTS, suggesting the functional domination of this process in the rpSTS. Although this study supports the concept of right-hemispheric specialisation of face processing, it also shows that the face regions in the left hemisphere play a crucial role in this process and their contribution should not be neglected.

References

Adolphs, R. (2002). Neural systems for recognizing emotion. *Current Opinion in Neurobiology, 12*, 169-177.

Allison, T., Puce, A., & McCarthy, G. (2000). Social perception from visual cues: role of the STS region. *Trends in Cognitive Sciences, 4*(7), 267-278.

Andrews, T. J., & Ewbank, M. P. (2004). Distinct representations for facial identity and changeable aspects of faces in the human temporal lobe. *NeuroImage, 23*, 905-913.

Basil, R. A., Westwater, M. L., Wiener, M., & Thompson, J. C. (2017). A causal role of the right superior temporal sulcus in emotion recognition from biological motion. *Open Mind, 1*(3), 148-158.

Brasil-Neto, J. P., McShane, L. M., Fuhr, P., Hallett, M., & Cohen, L. G. (1992). Topographic mapping of the human motor cortex with magnetic stimulation: factors affecting accuracy and reproducibility. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 85*(1), 9-16.

Brass, M., Derrfuss, J., & von Cramon, D. Y. (2005). The inhibition of imitative and overlearned responses: a functional double dissociation. *Neuropsychologia, 43*(1), 89-98.

Calder, A. J., & Young, A. W. (2005). Understanding the recognition of facial identity and facial expression. *Nature Reviews Neuroscience, 6*, 641-651.

Corballis, P. M., Funnell, M. G., & Gazzaniga, M. S. (2000). An evolutionary perspective on hemispheric asymmetries. *Brain and Cognition, 43*(1-3), 112-117.

Counter, S. A., Borg, E., & Lofqvist, L. (1991). Acoustic trauma in extracranial magnetic brain stimulation. *Electroencephalography and Clinical Neurophysiology, 78*, 173-184.

De Winter, F. L., Zhu, Q., Van den Stock, J., Nelissen, K., Peeters, R., de Gelder, B., et al. (2015). Lateralization for dynamic facial expressions in human superior temporal sulcus. *NeuroImage, 106*, 340-352.

DeKosky, S. T., Heilman, K. M., Bowers, D., & Valenstein, E. (1980). Recognition and discrimination of emotional faces and pictures. *Brain and Language, 9*, 206-214.

Duncan, K. J., Pattamadilok, C., Knierim, I., & Devlin, J. T. (2009). Consistency and variability in functional localisers. *NeuroImage, 46*(4), 1018-1026.

Dundas, E. M., Plaut, D. C., & Behrmann, M. (2012). The joint development of hemispheric lateralization for words and faces. *Journal of Experimental Psychology: General, 142*, 348-358.

Dzhelyova, M., Ellison, A., & Atkinson, A. (2011). Event-related repetitive TMS reveals distinct, critical roles for right OFA and bilateral posterior STS in judging the sex and trustworthiness of faces. *Journal of Cognitive Neuroscience, 23*(10), 2782-2796.

Ekman, P., & Friesen, W. (1976). *Pictures of facial affect*. Palo Alto, CA: Consulting Psychologists.

Engell, A. D., & Haxby, J. V. (2007). Facial expression and gaze-direction in human superior temporal sulcus. *Neuropsychologia, 45*, 3234-3241.

Erdfelder, E., Faul, F., & Buchner, A. (1996). GPOWER: A general power analysis program. *Behavior Research Methods, Instruments, & Computers, 28*(1), 1-11.

Fox, C. J., Hanif, H. M., Iaria, G., Duchaine, B. C., & Barton, J. J. S. (2011). Perceptual and anatomic patterns of selective deficits in facial identity and expression processing. *Neuropsychologia, 49*, 3188-3200.

Fried, I., Mateer, C., Ojemann, G., Wohns, R., & Fedio, P. (1982). Organization of visuospatial functions in human cortex. Evidence from electrical stimulation. *Brain, 105*, 349-371.

Geschwind, N. (1970). The organization of language and the brain. *Science, 170*, 940-944.
Gur, R. C., Skolnick, B. E., & Gur, R. E. (1994). Effects of emotional discrimination tasks on cerebral blood flow: regional activation and its relation to performance. *Brain and Cognition, 25*, 271-286.
Hasselmo, M. E., Rolls, E. T., & Baylis, G. C. (1989). The role of expression and identity in the face-selective responses of neurons in the temporal visual cortex of the monkey. *Behavioural Brain Research, 32*, 203-218.
Haxby, J. V., Hoffman, E. A., & Gobbini, M. I. (2000). The distributed human neural system for face perception. *Trends in Cognitive Sciences, 4*(6), 223-233.
Haxby, J. V., Hoffman, E. A., & Gobbini, M. I. (2002). Human neural systems for face recognition and social communication. *Biological Psychiatry, 51*, 59-67.
Heinisch, C., Dinse, H. R., Tegenthoff, M., Juckel, G., & Brüne, M. (2010). An rTMS study into self-face recognition using video-morphing technique. *Social Cognitive and Affective Neuroscience, 6*(4), 442-449.
Narumoto, J., Okada, T., Sadato, N., Fukui, K., & Yonekura, Y. (2001). Attention to emotion modulates fMRI activity in human right superior temporal sulcus. *Cognitive Brain Research, 12*, 225-231.
Ojemann, J. G., Ojemann, G. A., & Lettich, E. (1992). Neuronal activity related to faces and matching in human right nondominant temporal cortex. *Brain, 115*, 1-13.
Oliveri, M., Romero, L., & Papagno, C. (2004). Left but not right temporal involvement in opaque idiom comprehension: A repetitive transcranial magnetic stimulation study. *Journal of cognitive Neuroscience, 16*(5), 848-855.
Palermo, R., & Rhodes, G. (2007). Are you always on my mind? A review of how face perception and attention interact. *Neuropsychologia, 45*, 75-92.
Perrett, D. I., Smith, P. A. J., Potter, D. D., Mistlin, A. J., Head, A. S., Milner, A. D., et al. (1985). Visual cells in the temporal cortex sensitive to face view and gaze direction. *Proc. R. Soc. London B Biol Sci., 223*, 293-317.
Petersen, S. E., Fox, P. T., Posner, M. I., Mintun, M., & Raichle, M. E. (1989). Positron emission tomographic studies of the processing of singe words. *Journal of Cognitive Neuroscience, 1*(2), 153-170.
Phillips, M. L., Young, A. W., Scott, S. K., Calder, A. J., Andrew, C., Giampietro, V., et al. (1998). Neural responses to facial and vocal expressions of fear and disgust. *Proc. R. Soc. London B Biol Sci., 265*, 1809-1817.
Pitcher, D. (2014). Facial expression recognition takes longer in the posterior superior temporal sulcus than in the occipital face area. *Journal of Neuroscience, 34*(27), 9173-9177.
Pitcher, D., Charles, L., Devlin, J. T., Walsh, V., & Duchaine, B. (2009). Triple dissociation of faces, bodies, and objects in extrastriate cortex. *Current Biology, 19*(4), 319-324.
Pitcher, D., Dilks, D. D., Saxe, R. R., Triantafyllou, C., & Kanwisher, N. (2011). Differential selectivity for dynamic versus static information in face-selective cortical regions. *NeuroImage, 56*, 2356-5363.
Pitcher, D., Duchaine, B., & Walsh, V. (2014). Combined TMS and fMRI reveal dissociable cortical pathways for dynamic and static face perception. *Current Biology, 24*(17), 2066-2070.

Pitcher, D., Garrido, L., Walsh, V., & Duchaine, B. C. (2008). Transcranial magnetic stimulation disrupts the perception and embodiment of facial expressions. *Journal of Neuroscience, 28*(36), 8929-8933.

Pitcher, D., Japee, S., Rauth, L., & Ungerleider, L. G. (2017). The superior temporal sulcus is causally connected to the amygdala: A combined TBS-fMRI study. *Journal of Neuroscience, 37*(5), 1156-1161.

Pobric, G., Mashal, N., Faust, M., & Lavidor, M. (2008). The role of the right cerebral hemisphere in processing novel metaphoric expressions: a transcranial magnetic stimulation study. *Journal of Cognitive Neuroscience, 20*(1), 170-181.

Polosecki, P., Moeller, S., Schweers, N., Romanski, L. M., Tsao, D. Y., & Freiwald, W. A. (2013). Faces in motion: selectivity of macaque and human face processing areas for dynamic stimuli. *Journal of Neuroscience, 33*(29), 11768-11773.

Pourtois, G., Sander, D., Andres, M., Grandjean, D., Reveret, L., Olivier, E., et al. (2004). Dissociable roles of the human somatosensory and superior temporal cortices for processing social face signals. *European Journal of Neuroscience, 20*, 3507-3515.

Price, C. J. (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage, 62*, 816-847.

Puce, A., Allison, T., Bentin, S., Gore, J. C., & McCarthy, G. (1998). Temporal cortex activation in humans viewing eye and mouth movements. *Journal of Neuroscience, 18*(6), 2188-2199.

Pujol, J., Deus, J., Losilla, J. M., & Capdevila, A. (1999). Cerebral lateralization of language in normal left-handed people studied by functional MRI. *Neurology, 52*, 1038-1043.

Rapcsak, S. Z., Kaszniak, A. W., & Rubens, A. B. (1989). Anomia for facial expressions: evidence for a category specific visual-verbal disconnection syndrome. *Neuropsychologia, 27*(8), 1031-1041.

Rossi, S., Hallett, M., Rossini, P. M., Pascual-Leone, A., & Group, S. o. T. C. (2009). Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. *Clinical Neurophysiology, 120*, 2008-2039.

Sackeim, H. A., Gur, R. C., & Saucy, M. C. (1978). Emotions are expressed more intensely on the left side of the face. *Science, 202*(4366), 434-436.

Santiesteban, I., Banissy, M. J., Catmur, C., & Bird, G. (2015). Functional lateralization of temporoparietal junction–imitation inhibition, visual perspective-taking and theory of mind. *European Journal of Neuroscience, 42*(8), 2527-2533.

Saxe, R., Xiao, D. K., Kovacs, G., Perrett, D. I., & Kanwisher, N. (2004). A region of right posterior superior temporal sulcus responds to observed intentional actions. *Neuropsychologia, 42*(11), 1435-1446.

Schurz, M., Aichhorn, M., Martin, A., & Perner, J. (2013). Common brain areas engaged in false belief reasoning and visual perspective taking: a meta-analysis of functional brain imaging studies. *Frontiers in Human Neuroscience, 7*, 712.

Scott, S. K., Blank, C. C., Rosen, S., & Wise, R. J. S. (2000). Identification of a pathway for intelligible speech in the left temporal lobe. *Brain, 123*, 2400-2406.

Spengler, S., von Cramon, D. Y., & Brass, M. (2009). Control of shared representations relies on key processes involved in mental state attribution. *Human Brain Mapping, 30*(11), 3704-3718.
Springer, J. A., Binder, J. R., Hammeke, T. A., Swanson, S. J., Frost, J. A., Bellgowan, P. S. F., et al. (1999). Language dominance in neurologically normal and epilepsy subjects. A functional MRI study. *Brain, 122*, 2033-2045.
Streit, M., Ioannides, A. A., Liu, L., Wölwer, W., Dammers, J., Gross, J., et al. (1999). Neurophysiological correlates of the recognition of facial expressions of emotion as revealed by magnetoencephalography. *Cognitive Brain Research, 7*, 481-491.
Uddin, L. Q., Iacoboni, M., Lange, C., & Keenan, J. P. (2007). The self and social cognition: the role of cortical midline structures and mirror neurons. *Trends in Cognitive Sciences, 11*(4), 153-157.
Vuilleumier, P., Richardson, M. P., Armony, J. L., Driver, J., & Dolan, R. J. (2004). Distant influences of amygdala lesion on visual cortical activation during emotional face processing. *Nature Neuroscience, 7*(11), 1271-1278.
Wassermann, E. M. (1998). Risk and safety of repetitive transcranial magnetic stimulation: report and suggested guidelines from the International Workshop on the Safety of Repetitive Transcranial Magnetic Stimulation, June 5-7, 1996. *Electroencephalography and Clinical Neurophysiology, 108*, 1-16.
Winston, J. S., Henson, R. N. A., Fine-Goulden, M. R., & Dolan, R. J. (2004). fMRI-adaptation reveals dissociable neural representations of identity and expression in face perception. *Journal of Neurophysiology, 92*, 1830-1839.
Winston, J. S., O'Doherty, J., & Dolan, R. J. (2003). Common and distinct neural responses during direct and incidental processing of multiple facial emotions. *NeuroImage, 20*, 84-97.
Zatorre, R. J., Evans, A. C., Meyer, E., & Gjedde, A. (1992). Lateralization of phonetic and pitch discrimination in speech processing. *Science, 256*(5058), 846-849.