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Spontaneity matters! Network alterations before and after spontaneous and active facial self-touches: An EEG functional connectivity study

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ABSTRACT

Background: Despite humans frequently performing spontaneous facial self-touches (sFST), the function of this behavior remains speculative. sFST have been discussed in the context of self-regulation, emotional homeostasis, working memory processes, and attention focus. First evidence indicates that sFST and active facial self-touches (aFST) are neurobiologically different phenomena. The aim of the present analysis was to examine EEG-based connectivity in the course of sFST and aFST to test the hypotheses that sFST affect brain network interactions relevant for other than sensorimotor processes.

Methods: To trigger spontaneous FST a previously successful setting was used: 60 healthy participants manually explored two haptic stimuli and held the shapes of the stimuli in memory for a 14 min retention interval. Afterwards the shapes were drawn on a sheet of paper. During the retention interval, artifact-free EEG-data of 97 sFST by 32 participants were recorded. At the end of the experiment, the participants performed aFST with both hands successively. For the EEG-data, connectivity was computed and compared between the phases before and after sFST and aFST and between the respective before-and the after-phases.

Results: For the before-after comparison, brainwide distributed significant connectivity differences ($p < .00079$) were observed for sFST, but not for aFST. Additionally, comparing the before- and after-phases of sFST and aFST, respectively, revealed increased similarity between the after-phases than between the before-phases.

Conclusion: The results support the assumption that sFST and aFST are neurobiologically different phenomena. Furthermore, the aligned network properties of the after-phases compared to the before-phases indicate that sFST serve self-regulatory functions that aFST do not serve.

1. Introduction

In a recent review, spontaneous facial self-touches (sFST) have been described as a behavior that is not intended to serve social or communicative functions (Spille et al., 2021). Although sFST are performed up to 800 times per day (extrapolated) by people of different ages, genders, sexual orientations, cultures, and both in the presence and absence of others, the triggers and functions of this behavior remain speculative (Spille et al., 2021). Facial self-touching can cause infections if contaminated surfaces are previously touched (Spencer et al., 2021). In an observational study, people touched mucous membranes during 42.5 % of sFST (Ralph et al., 2021). Conscious suppression of sFST, which could prevent sFST-induced infections, appears to be difficult for humans (Heinicke et al., 2020; Senthilkumaran et al., 2020).

1.1. Empirical evidence on possible functions and triggers of sFST

One study suggested that self-touches promote the feeling of being in possession of a body (body ownership) through communication between efferent and afferent signals (Hara et al., 2015). Other studies speculate that self-touching has the function of distinguishing oneself from other objects or people (Boehme et al., 2019; Rochat and Hespos, 1997) and is

Abbreviations: sFST, Spontaneous facial self-touch(es); aFST, Active facial self-touch(es); b-sFST, Before spontaneous facial self-touch(es); a-sFST, After spontaneous facial self-touch(es); b-aFST, Before active facial self-touch(es); a-aFST, After active facial self-touch(es); EEG, Electroencephalography; HE, Haptic exploration phase; RI, Retention interval; rep, Reproduction phase; ffDTF, Full frequency directed transfer function; NMDA, *N*-methyl-D-aspartate; TMS, Transcranial magnetic stimulation.

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a basic form of self-awareness (Gallagher and Meltzoff, 1996). Since one's face is more frequently self-touched compared to other body parts (D'Alessio and Zazzetta, 1986; Harrigan, 1985), it is questionable whether sFST are functionally distinct from other forms of self-touches (Spille et al., 2021).

A positive relationship was observed between the sFST frequency and state anxiety (Carrillo-Díaz et al., 2021a; Harrigan, 1985; Pang et al., 2022; Reiter et al., 2022), trait anxiety (Carrillo-Díaz et al., 2021b) and stressful situations (Butzen et al., 2005; Heaven and McBrayer, 2000; Maestripieri et al., 1992; Moszkowski and Stack, 2007; Reissland et al., 2015a, 2015b) in humans and primates. Participants rated the likelihood for preceding situations of sFST higher for situations of concern, boredom, or anxiety than for situations of happiness (Kronrod and Ackerman, 2019). Several authors discussed the role of sFST in emotion regulation (Grunwald et al., 2014; Moszkowski and Stack, 2007; Mueller et al., 2019; Reissland et al., 2015a, 2015b; Spille et al., 2021, 2022a, 2022b).

sFST were also discussed in the context of cognitive regulation (Barroso et al., 1978; Barroso et al., 1980; Barroso and Feld, 1986; Grunwald et al., 2014; Mueller et al., 2019; Spille et al., 2021, 2022a, 2022b). Studies observed that humans perform more self-touches when performing more complex tasks than when performing less complex tasks (Barroso et al., 1978; Barroso and Feld, 1986). One study observed that humans with a high sFST frequency retrieved memory content more poorly when sFST were mechanically prevented than humans with a low sFST frequency (Spille et al., 2022b). Studies speculate that sFST affect processes of memory content maintenance and integration of information into coherent object representations (Grunwald et al., 2014; Mueller et al., 2019; Spille et al., 2022a).

1.2. Neurophysiology of sFST

Studies that examined neurophysiological parameter of self-touch compared to other-touch, indicate that self-touch is a neurobiologically unique phenomenon (Ackerley et al., 2012; Boehme et al., 2019; Kilteni and Ehrsson, 2022). However, these studies neither examined the face as the location of touch nor the differences between spontaneous and active facial self-touch (aFST), which means that the participants were instructed to touch themselves. Two studies compared the spectral EEG-power, a neurophysiological univariate parameter, before and after sFST and observed increased EEG-power in the phase after sFST (a-sFST) compared to the phase before sFST (b-sFST) (Grunwald et al., 2014; Spille et al., 2022a). Both studies analyzed sFST, which were performed during the retention interval of a haptic memory task. The majority of sFST were performed in the presence of auditory distractors. One study additionally compared the before and after phases of aFST and did not observe EEG-power differences (Grunwald et al., 2014). Observing EEG-power differences for the before-after comparison of sFST, but not for aFST, indicates that sFST and aFST are neurobiologically different phenomena. The authors of both studies speculated that the increased power in the phase a-sFST represents regulatory functions and integrating memory network processes (Grunwald et al., 2014; Spille et al., 2022a). Network dynamics were observed during processes that are relevant for the paradigm of both studies, such as haptic memory (Kaas et al., 2008), memory processes (Blinowska et al., 2010, 2013; Dai et al., 2017; D'Esposito and Postle, 2015; Gazzaley et al., 2004; Gazzaley and Nobre, 2012; Kaminski and Blinowska, 2018; Kaminski et al., 2016, 2019; Kamiński et al., 2011) and stress (Katmah et al., 2021). Therefore, examining brain network properties might be promising to approach the function of sFST.

If sFST affect cortical processes that are relevant to other than sensorimotor processes (Grunwald et al., 2014; Spille et al., 2022a), connectivity differences for the comparison b-sFST vs. a-sFST are expected. For the comparison b-aFST vs. a-aFST connectivity differences are not expected. Previous investigations of sFST are inconclusive regarding the frequency bands and brain areas. Hence, in the study at hand connectivity in the frequency bands delta, theta, alpha, beta and gamma are analyzed for all measured EEG-electrodes. Since sFST are assumed to serve regulatory functions, which aFST do not serve, it is expected to find fewer differences for the before-after-comparison of aFST than for sFST (Hypothesis 1).

Grunwald et al. (2014) concluded that an arousal or work-load is necessary for self-touch to have an effect. In the present study, a haptic memory task combined with auditory distractors was employed. Hence, it is assumed that the participants are in a state of cognitive load or arousal before and after sFST, but not before and after aFST. Therefore, connectivity differences for the comparisons b-sFST vs. b-aFST and a-sFST vs. a-aFST are expected. If sFST serve brain regulatory functions, fewer connectivity differences for the after-comparison than for the before-comparison are expected (Hypothesis 2).

2. Methods

2.1. Participants

In the present experiment, data were recorded from 60 participants (30 female; age: mean [M] = 25.72 years, standard deviation [SD] = 3.05; age range: 20–35 years). Inclusion criteria were right-handedness (Edinburgh Inventory; Oldfield, 1971), not taking medications that affect the central nervous system, and no experience regarding EEG recordings. Experience regarding EEG recordings could influence natural sFST behavior in addition to the experimental situation. 54 of the 60 participants performed at least one sFST during the experiment, and 45 of the participants performed at least one sFST during the retention interval, which is the subject of examination in the study at hand. Of 13 participants, all sFST performed during the retention interval had to be excluded due to excessive artifacts in temporal proximity to the sFST. Connectivity and statistical analyses were conducted on the EEG data from 32 participants (9 women, 23 men, age mean: 26.00 years, SD: 3.45 years). Of one of the 32 participants, EEG-data of both the left- and right-handed active facial self-touch had to be excluded due to artifacts. Therefore, analysis that included data of aFST, were performed on 31 participants. Due to artifacts, for five participants the data of only either the left- or the right-handed aFST was included. To disguise the actual purpose of the study, participants were told that the study was investigating neurophysiological memory effects of haptic exploration. The actual study purpose was disclosed after the experiment. The study was approved by the Ethics Committee of the Medical Faculty of the University of Leipzig.

All participants confirmed informed consent and received 10€ per hour expense allowance for participation.

2.2. Experimental design

To trigger sFST the participants performed a delayed memory task involving complex haptic stimuli (sunken reliefs) with simultaneous EEG recordings (Spille et al., 2022a). Participants were seated in a comfortable armchair in a quiet room where the experiment was explained. Prior to the experiment, the participants were presented with two examples of haptic stimuli (sunken relief) and three example auditory distractors. The experiment consisted of two blocks, which differed with regard to the haptic stimuli (see Fig. 1).

Before the first block, a three-minute EEG baseline measurement was performed in which the participants looked at a black dot. In the haptic exploration (HE) phase, the participants had the task to haptically explore two haptic stimuli in each block (sunken reliefs) without seeing the sunken reliefs (milled into 13 × 13 cm plastic plates, see Fig. 1). An opaque screen obscured the participant's hands and the stimulus from vision during haptic exploration. There was no time limit for the exploration and both hands were allowed to be used. After exploration, the shapes of the two haptic stimuli (sunken reliefs) were to be held in memory during a subsequent 14-min retention interval (RI). Before the

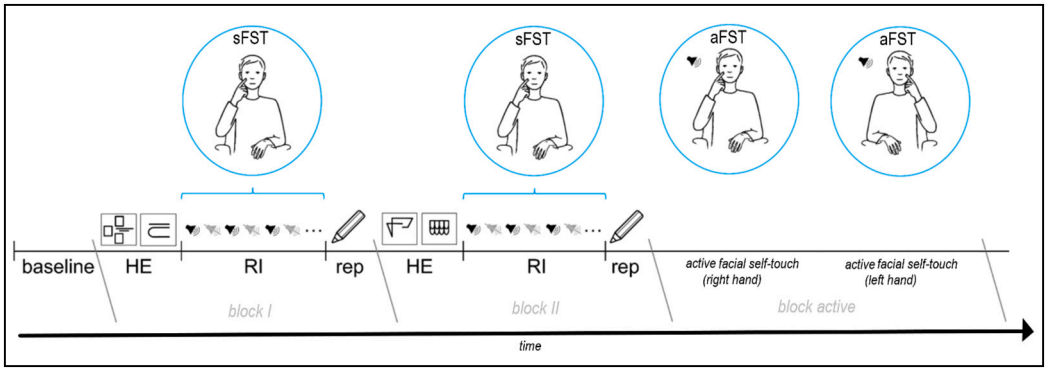

Fig. 1. - Block I & II: After the resting EEG-measurement (baseline), the subjects explored two haptic stimuli (HE) per block, which are shown schematically in the diagram (different haptic stimuli for each block). In the following retention interval (RI), subjects were asked to maintain the shapes of the haptic stimuli in memory in order to draw the shapes later on a sheet of paper (rep). During the RI, auditory distractors were presented in a temporal and order-randomized manner. Spontaneous facial self-touches (sFST) performed during the retention interval, independently of the hand or face laterality, were included in the analysis and compared with active facial self-touches in terms of brain network dynamics. Block active: Subjects were instructed to actively touch their own face five times with their right and five times with their left hand, successively (active facial self-touch (aFST)) (adapted from Spille et al., 2022a).

start of the retention interval, the opaque screen was removed so that the participants' hands were allowed unrestricted movement. During the RI, 40 randomized auditory distractors were presented to the participants (in total, there were 60 auditory distractors e.g., baby cry; for a more detailed description, see Supplemental Material of Spille et al., 2022a). Phases of auditory distractor presentation and sound-free phases alternated. To avoid habituation and anticipation effects, the duration of distractor and sound-free phases was randomly varied between 7 and 13 s.

After the RI, participants were asked to draw the shapes of the haptic stimuli on a sheet of paper in the reproduction period (rep). The time was not limited in the rep. After block I (HE of two haptic stimuli - 14 min RI - replication of the two haptic stimuli), the experimental procedure described above was repeated in block II with different haptic stimuli (see Fig. 1). After performing Block I and II, the study director instructed the participants to successively perform five active facial self-touches with their right hand to the right part of their face and five active facial self-touches with their left hand to the left part of their face. Participants were instructed to put their hand back down in the lap after each active face touch.

2.3. EEG data recording & pre-processing

EEG data and video data were recorded in a Faraday cage using a system and software from IT-Med GmbH (version 4.4.5.7, Germany). For EEG recording, the following 19 Ag-AgCl electrodes/channels were recorded according to the International 10–20 system (Jasper, 1958): Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, T6, P3, Pz, P4, O1, O2, online reference: linked earlobes. Eye movements were recorded using a vertical (VEOG) and a horizontal (HEOG) electrooculogram. Impedance was kept below 5 kΩ, and the sampling rate was 256 Hz. In order to recognize sFST, arm movements were recorded via electromyogram (EMG; two electrodes on the dorsal sides of the left and right arms over the m. extensor carpi ulnaris) and tri-axial accelerometers (ADXL335; attached to both wrists). Throughout the experiment, a video of the participant was recorded through a one-way mirror. The recording system allowed parallel synchronized recording of EEG, EMG, accelerometers, and video.

The recorded videos, data from the EMG electrodes and accelerometers of the participants were reviewed and sFST were marked . For the further analysis sFST were included according to the following criteria (1) performing sFST with right or left hand (2) touching the vertical midline of the face, the ipsi- or contralateral side of the participants' face (touches to the hair, head, neck, or ears were excluded) (3) no obvious functional reason for self-touch such as yawning, scratchingor nose picking (4) performance of sFST within the RI (for a more detailed description, see Spille et al., 2022a). Recorded EEG data were preprocessed in Brain Vision Analyzer software (version 2.2.1.8266, Brain Products, Munich, Germany). EEG data were filtered with an IIR filter (zero phase shift Butterworth filter, low cutoff 0.3 Hz, high cutoff 49 Hz, order 2, notch filter 50 Hz). Ocular artifacts were corrected, based on the vertical and horizontal ocular electrodes, using the algorithm of Gratton et al. (1983). Subsequently, automatic artifact correction was performed (criteria: (1) Maximal allowed voltage step: 80 μV/ms - Mark as Bad: Before Event: 200 ms After Event: 200 ms; (2) Check difference (max-min): Maximal allowed difference of values in intervals: 150 μV - Interval Length: 1000 ms - Mark as Bad: Before Event: 200 ms After Event: 200 ms and (3) Check Low Activity: Lowest allowed activity in intervals: 0.5 μV - Interval Length: 100 ms - Mark as Bad: Before Event: 200 ms After Event: 200 ms). If at least one artifact was found in one of the 1-s EEG segments before or after the sFST/aFST in one or more EEG electrodes, the complete segment and the sFST/aFST was excluded from further analysis. Subsequently, the data were each segmented per participant according to the following artifact-free epochs of interest: (1) the first second before the onset of arm movement before an sFST/aFST (2) the first second after the termination of arm movement after an sFST/aFST. In the following, the before and after phases of 97 sFST performed by 32 participants were analyzed. The EEG-data of the phases before and after the first (of five) right-handed and the first (of five) left-handed aFST were included. The segments of b-sFST, a-sFST, b-aFST and a-aFST were each exported as one file in the European Data Format (EDF+) format.

2.4. EEG connectivity analysis

All further analyses were performed in Matlab® (version: R2019b Update 4 (9.7.0.1296695), (RRID:SCR_001622), The Mathworks, Massachusetts, USA). For each segment, the multivariate autoregressive (MVAR) model was calculated for each electrode pair using the mvar.m and mvfreqz.m functions implemented in the BioSig toolbox (Schlögl and Brunner, 2008 (RRID:SCR_008428)). To estimate the multivariate autoregressive model, partial correlation estimation with unbiased covariance estimates (Marple, 1987) was used, which was shown to be the estimate with the lowest prediction error (Schlögl, 2006). The model order used was $p = 2$. Based on the estimation of the multivariate autoregressive model, the transfer function and the connectivity measure of the full frequency Directed Transfer Function (ffDTF; Kaminski and Blinowska, 1991; Korzeniewska et al., 2003) were calculated in 0.5 Hz steps from 1 to 49 Hz. The ffDTF is based on the principle of Granger causality (Granger, 1969). High reliability between two resting measurements was observed for ffDTF compared to other connectivity markers (Höller et al., 2017a, 2017b), which might point to a stable

classification of mental states. ffDTF is a directional connectivity measure, therefore the calculation results in two values per channel combination and frequency, one value for information flow from channel a to channel b and one value for information flow from channel b to channel a (19 (channels) × 19 (channels) × 49 (frequencies)). These values were averaged over the EEG frequency bands theta (θ): 4–8 Hz, alpha (α): 8–13 Hz, beta (β): 13–24 Hz, and gamma (γ): 24–49 Hz. The ffDTF values were averaged over all before sFST segments per participants. The same procedure was conducted for the phases after sFST, before aFST and after aFST, respectively. The script used to calculate the connectivity can be found at the following link: https://haptiklabor.medizin.uni-leipzig.de/index.php?id=315&L=1 .

2.5. Statistics

Kolmogorov-Smirnov-tests were calculated for all electrode pairs, frequency bands and conditions. All data are not normally distributed, hence, non-parametric statistics were employed. To test the first

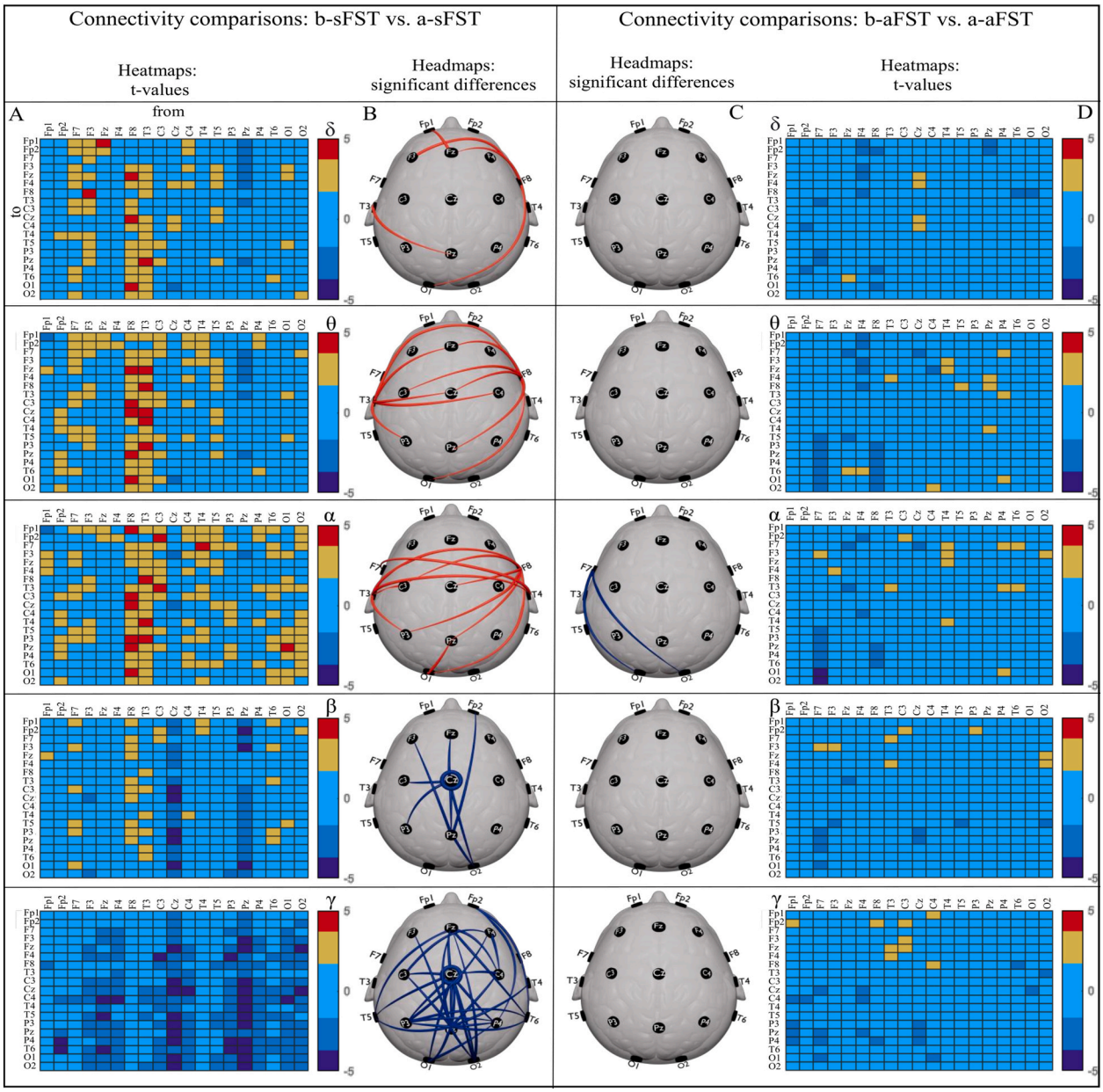

Fig. 2. – Heatmaps (A & D): Illustration of the t-values (Wilcoxon signed rank test) for the comparisons before spontaneous facial self-touches (sFST) vs. after sFST and before active facial self-touches (aFST) vs. after aFST in the frequency bands delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–25 Hz) and gamma (25–49 Hz). In each case, information flow is to be read from electrodes in rows (x-axis) to electrodes in rows (y-axis), i.e., from top to left. Positive values (red color) mean that higher connectivity was observed in each case in the phase before self-touch. Negative values (dark blue color) mean that higher connectivity was observed in each case in the phase after self-touch. The value 0 (light blue color) means that no difference was observed in terms of connectivity for the respective electrode pair, comparison and frequency band. Headmaps (B & C): Illustration of significantly differences of connectivity for the comparisons bsFST vs. a-sFST and b-aFST vs. a-aFST in the delta, theta, alpha, beta, and gamma frequency bands. Red connection lines indicate that higher connectivity was observed in the phase before the respective self-touch. Blue connection lines mean that higher connectivity was observed in the phase after the respective self-touch. Colored rings around respective electrodes indicate significant different autoregression. The connections are to be read from the thick end to the thin end of the connection lines. Frequency bands: δ = delta, θ = theta, α = alpha, β = beta, γ = gamma. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

hypothesis, whether sFST affect cortical mechanism that are relevant for other than sensorimotor processes, the connectivity values per electrode pair, frequency band, and segment (e.g., b-sFST vs. a-sFST and b-aFST vs. a-aFST) were compared by calculating a two-tailed Wilcoxon signed rank test. To correct for multiple testing (74 tests per electrode), the Bonferroni-Holm method was used (Holm, 1979), which resulted in $p = .00079$ as the last statistically significant value. To test the second hypothesis, whether the before-phase of sFST and aFST and after-phases of sFST and aFST differ neurobiologically, the same statistic as for the first hypothesis was calculated. In order to compare the different states (b-sFST, a-sFST, b-aFST, a-aFST) with regard to the number of significant different electrodes pairs, Cochran's Q-test was conducted.

3. Results

For the 32 participants who performed sFST during RI, an average of M = 3.03 (SD = 2.26) sFST per participant were observed. The number of sFST analyzed per participant during the RI ranged from 1 to 9. The mean duration for the analyzed sFST was M = 5.77 s (SD = 4.31 s), for the analyzed aFST M: 3.89 s (SD: 0.87). Significantly more of the analyzed sFST were performed during the presentation of auditory distractors (sum = 70) than during the noise-free phases (sum = 27; binomial test $p < .001$).

3.1. Do sFST affect cortical mechanisms that are relevant for other than sensorimotor processes? (Hypothesis 1)

For the comparison b-sFST vs. a-sFST, significant differences were observed in the delta, theta, alpha, beta, and gamma frequency bands regarding connectivity distributed over 68 electrode pairs (see Fig. 2). For the frequency bands delta, theta and alpha increased connectivity was observed in the phase b-sFST, for the frequency bands beta and gamma decreased connectivity was observed in the phase b-sFST relative to the phase a-sFST. Significantly increased delta-band connectivity in the phase b-sFST compared to the phase a-sFST was observed (1) from frontal to frontal and posterior electrodes and (2) from temporal left to a parieto-central electrode. Significantly increased theta-band connectivity in the phase b-sFST compared to a-sFST was observed (1) from fronto-lateral right to fronto-central, central, and posterior electrodes and (2) from temporal left (T3) to frontal, central, and posterior electrodes. Significantly increased alpha-band connectivity in the phase b-sFST compared to a-sFST was observed (1) from fronto-lateral right to central and posterior electrodes (2) from temporal to frontal, temporal, and posterior electrodes (3) from central to temporal and (4) from posterior to posterior electrodes. Significantly increased beta-band connectivity in the phase a-sFST compared to b-sFST was observed (1) from centro-central to central and posterior and (2) from posterior to frontal and posterior electrodes. Significantly increased gamma band connectivity in the phase a-sFST compared to b-sFST was observed (1) from frontal to central, temporal and posterior electrodes, (2) from central to frontal, central, temporal and posterior electrodes and (3) from posterior to frontal, central, temporal, and posterior electrodes.

For the comparison b-aFST vs. a-aFST, significantly increased connectivity was observed in the alpha band for two electrode pairs in the phase a-aFST (see Fig. 2), from fronto-lateral left to posterior was observed in the phase a-aFST. Heatmaps of the t-values and headmaps of significant differences of the comparisons b-sFST vs. a-sFST and b-aFST vs. a-aFST are illustrated for the frequency bands delta, theta, alpha, beta and gamma in Fig. 2. The detailed statistical parameters for the frequency bands delta, theta, alpha, beta and gamma of the comparison b-sFST vs. a-sFST are listed in tables S1-S5 (Supplemental Material) and for the comparison b-aFST vs. a-aFST in the tables S6-S10 (Supplemental Material).

Cochran's Q-tests revealed that the number of significant different electrode pairs was larger for all frequency bands for the before-after-sFST than for the before-after-aFST comparison (delta: $Q_{1/361} = 5$, $p < .05$; theta: $Q_{1/361} = 10$, $p < .01$; alpha: $Q_{1/361} = 6{,}23$, $p < .05$; beta: $Q_{1/361} = 8$, $p < .01$; gamma: $Q_{1/361} = 35$, $p < .001$).

3.2. Which network states precede and follow sFST? (Hypothesis 2)

For the comparison b-sFST vs. b-aFST, significant differences were observed in the delta, theta, alpha, beta, and gamma frequency bands regarding connectivity distributed over 135 electrode pairs. In the phase b-sFST, increased delta-band connectivity was observed relative to the phase b-aFST. In the phase b-aFST, increased beta and gamma-band connectivity was observed relative to the phase b-sFST. For the frequency bands theta and alpha mixed results were found. Significantly increased delta-band connectivity in the phase b-sFST compared to the phase b-aFST was observed (1) from frontal to frontal, temporal, central and posterior electrodes and (2) from temporal to frontal, central, temporal and posterior electrodes. Significantly increased theta-band connectivity in the phase b-sFST compared to the phase b-aFST was observed from left temporal to frontal and temporal electrodes. Increased theta-band connectivity in the phase b-aFST compared to the phase b-sFST was observed from posterior to frontal electrodes. Significantly increased alpha-band connectivity in the phase b-sFST compared to the phase b-aFST was observed from frontal and central to frontal electrodes. Significantly increased alpha-band connectivity in the phase b-aFST compared to the phase b-sFST was observed from temporal to temporal electrodes. Significantly increased beta-band connectivity in the phase b-aFST compared to the phase b-sFST was observed (1) from frontal to frontal (2) from central to frontal, temporal and posterior and (3) from posterior to frontal and temporal electrodes. Significantly increased gamma-band connectivity in the phase b-aFST compared to the phase b-sFST was observed (1) from frontal to frontal, temporal and posterior (2) from central to frontal, temporal, central and posterior (3) from temporal to temporal and (4) from posterior to frontal, temporal, central and posterior electrodes.

For the comparison a-sFST vs. a-aFST, significant differences were observed in the delta, theta, alpha, beta, and gamma frequency band regarding connectivity distributed over 82 electrode pairs. Significantly increased delta-band connectivity in the phase a-sFST compared to the phase a-aFST was observed (1) from frontal to frontal and temporal (2) from temporal to frontal and temporal and (3) from posterior to frontal and temporal electrodes. Significantly increased theta-band connectivity in the phase a-aFST compared to the phase a-sFST was observed from frontal to frontal electrodes. Significantly increased alpha-band connectivity in the phase a-aFST compared to the phase a-sFST was observed (1) from frontal to frontal and temporal (2) from central to frontal and central and (3) from posterior to frontal and posterior electrodes. Significantly increased beta-band connectivity in the phase a-aFST compared to the phase a-sFST was observed (1) from frontal to frontal, temporal and posterior (2) from central to frontal and temporal and (3) from posterior to frontal electrodes. Significantly increased gamma-band connectivity in the phase a-aFST was observed (1) from frontal to frontal and temporal (2) from central to frontal, temporal and central and (3) from posterior to frontal electrodes.

Heatmaps of the t-values of the comparisons b-sFST vs. b-aFST and a-sFST vs. a-aFST are illustrated for the frequency bands delta, theta, alpha, beta and gamma in Fig. 3. The detailed statistical parameters for the frequency bands delta, theta, alpha, beta and gamma of the comparison b-sFST vs. b-aFST are listed in tables S11-S15 and for the comparison a-aFST vs. a-aFST in the tables S16-S20 (Supplemental Material). To get an overview of the absolute connectivity values, the graph-theoretical parameter outdegree for all investigated electrodes and frequency bands are shown in Fig. S1 (Supplemental Material).

Cochran's Q-tests revealed that the number of significant different electrode pairs was larger for the before-comparison than for the after-comparison in the frequency bands delta ($Q_{1/361} = 18.67$, $p < .001$) and gamma ($Q_{1/361} = 24.93$, $p < .001$). For the after-comparison the number of significant different electrode pairs was larger in the alpha-

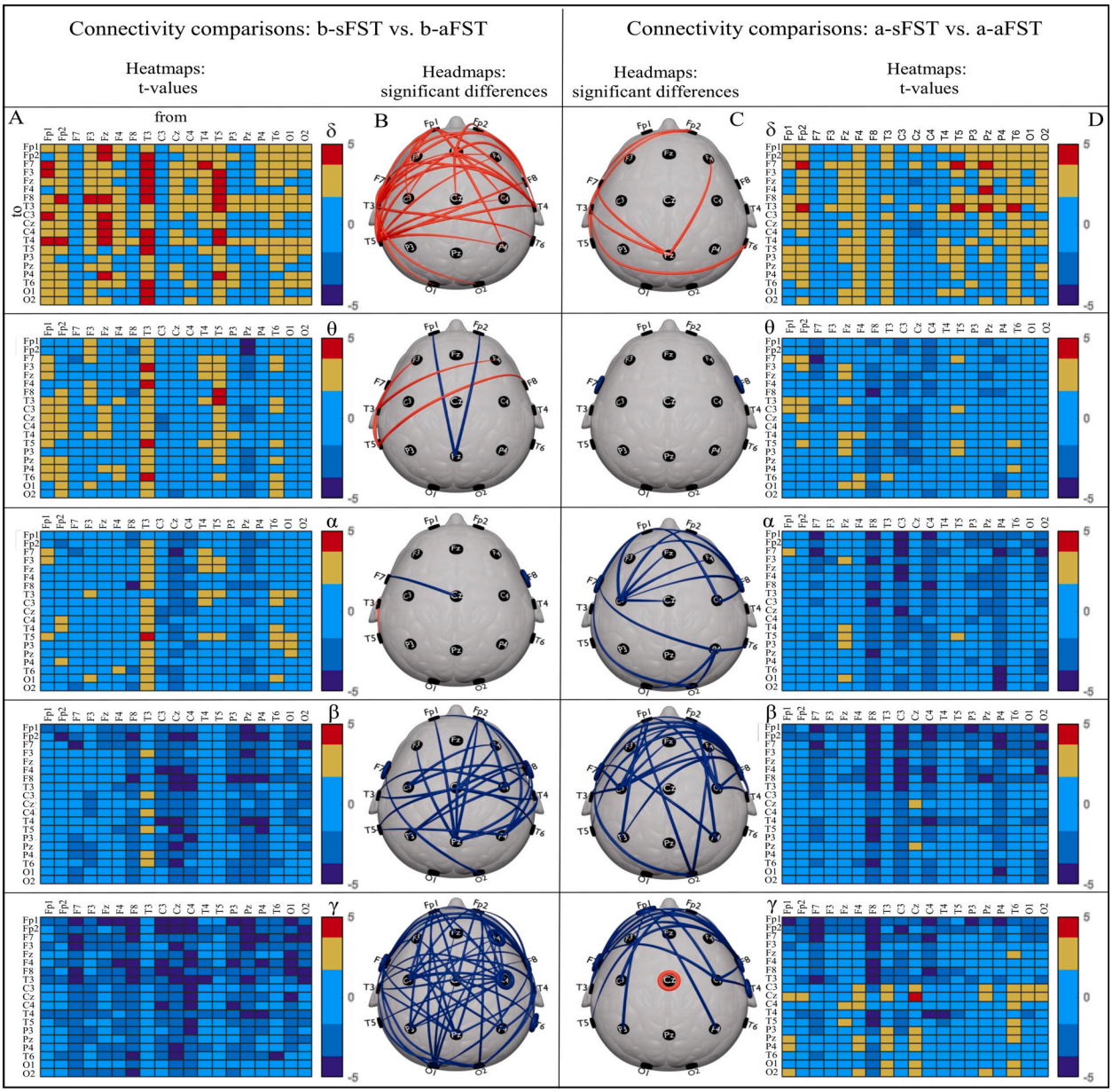

Fig. 3. – Heatmaps (A & D): Illustration of the t-values (Wilcoxon signed rank test) for the comparisons before spontaneous facial self-touches (sFST) vs. before active facial self-touches (aFST) and after sFST vs. after aFST in the frequency bands delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–25 Hz) and gamma (25–49 Hz).The information flow is to be read from electrodes in columns (x-axis) to electrodes in rows (y-axis). i.e., from top to left. Positive values (red color) indicate higher connectivity in the phase of spontaneous facial self-touch. Negative values (dark blue color) indicate higher connectivity in the phase of instructed facial self-touch. Low values around zero (light blue color) indicate that no difference was observed in terms of connectivity for the respective electrode pair, comparison and frequency band. Headmaps (B & C): Illustration of significant differences of connectivity for the comparisons before sFST vs. before aFST and after sFST vs. after aFST comparisons for the delta, theta, alpha, beta, and gamma frequency bands. The color coding is similar to the headmaps (red lines indicate higher connectivity in the phase of spontaneous facial self-touch; blue lines higher connectivity in the phase of active facial self-touch. Colored rings around respective electrodes indicate significant different autoregression. The connectivity direction is to be read from the thick end to the thin end of the lines. Frequency bands: δ = delta. θ = theta. α = alpha. β = beta. γ = gamma. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

frequency ($Q_{1/361} = 11.84$, $p < .001$).

4. Discussion

Spontaneous facial self-touches occur in manifold situations, such as stress, anxiety and boredom (Bull, 1978; Carrillo-Diaz et al., 2021a, 2021b; Kronrod and Ackerman, 2019; LeCompte, 1981), which might point to different functions of sFST. Due to the combination of the memory task and the presentation of auditory distractors, in the paper at hand, it is assumed that sFST were evoked by cognitive load. Recent work reported that performing either a memory task or presenting auditory distractors did not evoke an increased frequency of sFST, but the combination did (Grunwald et al., 2014). The aim of the present analysis was to examine EEG-based connectivity to test the hypotheses, whether sFST affect brain network interactions differently than aFST and whether brain network interactions differ between the respective pre- and post-phases of sFST and aFST.

During the experiment, the participants had the task to explore haptic stimuli, maintaining the shapes of the stimuli in memory during a 14-min retention interval, and drawing the shapes after the retention

interval (see Fig. 1). The present work examined multivariate, directional, and weighted connectivity to analyze network interactions between brain areas over the course of spontaneous and active facial self-touches in intra-individual comparisons.

4.1. Do sFST affect cortical mechanisms that are relevant for other than sensorimotor processes? (Hypothesis 1)

Comparing b-sFST vs. a-sFST revealed differences with regard to connectivity measures, which were not observed comparing b-aFST vs. a-aFST. Increased connectivity was prominently observed in the phase b-sFST in slower frequencies (delta, theta, alpha) from the right ventrolateral prefrontal cortex (rVLPFC) and from the left medial temporal gyrus (lGTM) to the vertical midline (frontocentral, centrocentral, parieto-central).

The rVLPFC is associated with processes of memory content maintenance (D'Esposito et al., 1999), handling distractor processing (Weintraub-Brevda and Chua, 2019), top-down processes, inhibition (Blinowska et al., 2010; Levy and Wagner, 2011; Long, 2021) and long-term memory formation (Machizawa et al., 2010). Increased activity of the rVLPFC has also been observed in the context of stress-inducing situations (Al-Shargie et al., 2017). Trambaiolli et al. (2022) propose two possible functions of the rVLPFC, on the one hand the prediction of possible outcomes associated with salient stimuli and on the other hand preparing appropriate behavioral responses later selected by the dorsal anterior cingulate gyrus. This is in line with our results, pointing towards increased connectivity between the rVLPFC and medial structures in the phase b-sFST. Since all of the aforementioned processes with which the rVLPFC is associated are potentially relevant to the paradigm at hand, it can only be speculated about the causes of the connectivity differences from the rVLPFC to other brain areas.

The lGTM is associated with memory storage and retrieval (Clark, 2018; Opitz, 2014). More specifically, hippocampal delta and theta oscillations are associated with memory processes (Axmacher et al., 2008; Mitchell et al., 2008; Nuñez and Buño, 2021). The increased connectivity from bilateral to medial electrodes may indicate a hippocampal-cortical information exchange in which medial structures, such as the anterior cingulate gyrus or medial septum, play a mediating role (Nuñez and Buño, 2021; Onton et al., 2005; Rolls, 2019).

Fronto-frontal increased delta connectivity has been observed during maintenance of memory content compared to the resting condition (Tóth et al., 2012). During the maintenance of information in working memory, concentration and sustained attention increased delta activity was observed in frontal areas (Fernandez et al., 2002; Harmony, 2013; Spille et al., 2022a). Hence, connectivity differences between the phases b-sFST and a-sFST indicate dynamics regarding memory processes, which were not found for aFST.

Oscillations in the theta frequency band are associated with memory storage and retrieval and cognitive control functions (Cavanagh and Frank, 2014; Grunwald et al., 1999, 2001, 2014; Hasselmo and Stern, 2014; Herweg et al., 2020; Hsieh and Ranganath, 2014; Karakaş, 2020; Nuñez and Buño, 2021). Colgin (2013) argue that theta rhythms allow for long synaptic delays due to their slow time scale and therefore can maintain coupling between distributed brain regions. The assumption of theta-oscillatory information exchange from the hippocampus to neocortical areas is consistent with properties of glutamatergic *N*-methyl-D-aspartate (NMDA) receptors, which are abundant in the hippocampus and follow a theta rhythm (Jensen and Lisman, 1996). A positive relationship has been observed between hippocampal glutamate concentration and frontal theta oscillations during the execution of cognitive processes (Gallinat et al., 2006). Furthermore, studies observed a positive relationship between network-interactions of the hippocampus and the frontal cortex and successful retrieval of memory content (Jones and Wilson, 2005; Hyman et al., 2010). The frontal midline theta is associated with proactive control, response initiation and response inhibition processes (Hsieh and Ranganath, 2014; Messel et al., 2021; Onton et al., 2005). Increased theta connectivity in the phase b-sFST might point to memory or executive function processes, which are affected by sFST, but not aFST.

Alpha-band activity in general (Bonnefond and Jensen, 2012; Haegens et al., 2011; Klimesch et al., 2007; Hanslmayr et al., 2012; Jensen and Mazaheri, 2010) and increased fronto-parietal alpha connectivity in particular (Tian et al., 2021) are associated with the suppression of task-irrelevant content, such as distractors. Suppression of distractors is necessary to maintain items in memory (Burgess et al., 2011; Gazzaley et al., 2005; Gray et al., 2003; McCollough et al., 2007; Vogel and Machizawa, 2004; Wiley et al., 2011). One study observed a positive relationship between parieto-medial to temporal left alpha connectivity and the number of items to be maintained in memory (Payne and Kounios, 2009). Since sFST were more frequently performed during the presentation of distractors, the increased alpha connectivity observed in the phase b-sFST suggests inhibiting processes of distractors.

In contrast to the slower frequencies, in faster frequencies (beta, gamma) increased connectivity from medial to globally distributed areas was observed in the phase a-sFST. In line with Grunwald et al. (2014), in the present study increased centro-parietal beta connectivity was observed in the phase a-sFST relative to the phase b-sFST. Grunwald et al. interpreted the before-after difference in the beta band as sensorimotor activity. However, for the comparison b-aFST vs. a-aFST this difference was neither observed in terms of spectral EEG power (Grunwald et al., 2014) nor in the present work in terms of connectivity. Kus et al. (2004) observed increased beta connectivity after a movement starting from central areas as a so-called rebound effect. However, it is questionable why this rebound effect was not observed for aFST. Hence, the results suggest that sFST affect beta-band network interactions, which are relevant for other than sensorimotor processes.

Gamma-band activity is associated with the maintenance of memory content (Bastos et al., 2018; Honkanen et al., 2015; Howard et al., 2003; Roux et al., 2012; Roux and Uhlhaas, 2014; Spille et al., 2022a). A positive relationship has been observed between gamma band activity and the number of items held in working memory (Howard et al., 2003; Kornblith et al., 2016; Roux et al., 2012). Other studies observed increased fronto-parietal gamma synchronization during memory processes such as information retrieval and integration (Kaminski et al., 2019; Salazar et al., 2012). In a neuromodulatory study, a positive association between transcranial magnetic stimulation (TMS)-induced increase in gamma connectivity between frontal and parietal areas and improvement in cognitive abilities was observed (Liu et al., 2021). The increased gamma connectivity observed in phase a-sFST may indicate sFST-induced network reactivation and thus promotion of cognitive processes (Başar, 2013; Fries, 2009). However, gamma-band-responses at centro-central regions were observed during the presentation of auditory stimuli (Leicht et al., 2021; Mulert et al., 2007, 2010). In the study at hand significantly more sFST were observed in the presence of auditory distractors than in the absence of auditory distractors. Therefore, it cannot be ruled out that observed gamma-band-connectivity differences are influenced by auditory processing.

Taken together, increased connectivity from lateral to medial areas is prominent in the slower frequencies in phase b-sFST relative to phase a-sFST, whereas increased connectivity from medial to lateral areas is prominent in the faster frequencies in phase a-sFST. Both the frequencies and the areas in which differences were observed between phases b-sFST and a-sFST, which were not observed comparing b-aFST vs. a-aFST, support the hypothesis that sFST affect cortical network mechanisms that are relevant for other than sensorimotor processes.

4.2. Which network states precede and follow sFST? (Hypothesis 2)

In order to approach the understanding of the neurophysiological state before and after sFST, the phases b-sFST and b-aFST and a-sFST and a-aFST phases were compared in terms of connectivity, respectively. The results reveal that brain network interactions differ between the before

phases as well as between the after phases of spontaneous and active facial self-touches. The differences between the before and after comparisons were prominently observed in the delta, alpha, and gamma bands.

In the delta frequency band, increased connectivity starting from the lMTG was observed in the phase b-sFST relative to the comparison phases (a-sFST and b-aFST), which might point to memory processes in the phase b-sFST. As opposed to the before-comparison, in the after-comparison few differences were observed with respect to delta. This observation suggests that the before phases differ from each other regarding delta-associated processes, while the after states differ less. The increased delta connectivity emanating from fronto-central and left temporal areas in phase b-sFST is in line with a previous study, which observed increased intra-regionally and inter-regionally delta connectivity during memory maintenance (Tóth et al., 2012. In another study, a negative relation was observed between frontal delta connectivity and semantic memory retrieval (Hanouneh et al., 2018). Knyazev (2012) concludes that the delta-oscillatory mode increases when more advanced systems (e.g., gamma band) lose their priority for unknown reasons, such as in states of early development, sleep, and various pathologies. Furthermore, the author describes that functional delta oscillations influence the synchronization of brain activity in autonomic functions, reward- and defense-associated motivational processes, and cognitive processes such as attention and recognition of motivationally salient stimuli in the environment (Knyazev, 2012). The increased delta connectivity observed in phase b-sFST relative to phases a-sFST and b-aFST may indicate that sFST influence memory-related network interactions. However, clinical studies suggests that excess as well as reduced connectivity between brain areas can occur in diseases that alter cognition (Bartolomei et al., 2014; Englot et al., 2017, 2018; Murias et al., 2007). Hence, increased connectivity in the phase b-sFST could also represent dysfunctional states, which prevent cognitive processes.

In the before-comparison, increased theta connectivity was observed for sFST from the lGTM to frontal and temporal areas, which might indicate hippocampal theta-activity due to the maintenance of the shapes (Jones and Wilson, 2005; Hyman et al., 2010). In the after-comparison, these differences were not observed anymore, which points to an sFST-induced brain network alignment.

In the alpha band, few connectivity differences were observed when comparing the before phases. In the after comparison, increased connectivity was observed in the phase a-aFST starting from frontal, central, and parietal areas. Since the majority of sFST were performed during the presentation of distractors, increased alpha connectivity in the phase b-sFST, representing suppression of task-irrelevant content (Tian et al., 2021), was expected.

Instead, increased alpha connectivity was observed in the phase a-aFST relative to the phase a-sFST. These observations might be explained by alpha desynchronization in the phase a-sFST (see fig. S1), which was positively related to the richness of information (Hanslmayr et al., 2012). Hence, sFST might facilitate the richness of information processing.

No differences were observed in the beta band between the before and after comparisons in terms of the number of connectivity differences. However, the beta connectivity differences found for each comparison, might indicate planning and post-processing of a planned motor activities (Zaepffel et al., 2013). Increased connectivity in the phases b-aFST and a-aFST compared to the respective sFST-phases could indicate instruction-induced planning and post-processing of a planned motor activity during aFST. Since sFST are not planned the way aFST are planned, possibly increased beta connectivity was observed for the before and after phase of aFST.

Globally decreased gamma connectivity in the phase b-sFST relative to phase b-aFST might indicate the different execution of cognitive processes (Bosman et al., 2014; Fell and Axmacher, 2011; Hanouneh et al., 2018; Liu et al., 2021; von Lautz et al., 2017). The differences observed in the before comparison in terms of gamma connectivity, were less observed in the after comparison. This observation suggests that sFST activate gamma networks, not activated by aFST, which in turn might indicate that sFST serve a regulatory function. However, in contrast to the majority of sFST, no auditory stimuli were present during the performance of aFST. Therefore, it cannot be excluded that the observed gamma-band differences between sFST and aFST were influenced by auditory processing (Leicht et al., 2021; Mulert et al., 2007, 2010).

5. Limitations and future directions

One limitation is the research object itself, since the occurrence of *spontaneous* facial self-touches and thus the number of analyzable events can only be manipulated to a limited extent. A longer duration of the experiment would maximize the number of events to be analyzed, but for reasons of good scientific practice, an experiment should not exceed a certain duration. In a simulation study Brovelli (2012) revealed that a limited amount of single trial (here: events) granger causality spectra can increase the type II error (accepting a false null hypothesis) and in turn decrease the statistical power. Hence, the present results should be interpreted carefully. To increase the number of sFST in future experiments, increasing the sample size and the cognitive load, e.g. by combining a sustained attention with distractors, might be efficient.

The examination of sFST compared to other kinds of touch is just beginning and the question of the function of sFST cannot be answered in the study at hand. To approach this question, further studies are needed that, for example, predict task performance by neurophysiological differences between b-sFST and a-sFST or classify neurophysiological states according to behavioral conditions (e.g., b-sFST, a-aFST) by machine learning algorithms. To predict task performance, future studies should conduct quantifiable and operationalizable tasks.

In the present study, neither target stimuli nor distractors were manipulated for emotionality. However, several studies observed increased rVLPFC and frontal midline activity during emotion processing (Mitchell et al., 2008; Nguyen et al., 2019; Strawn et al., 2012; Townsend and Altshuler, 2012). A positive relationship has been observed between emotional processing and sFST frequency (Carrillo-Díaz et al., 2021a; Harrigan, 1985; Reiter et al., 2022). To differentiate the hypothesized cognitive and emotional regulatory functions of sFST, future studies should manipulate and compare experimental situations in terms of emotionality (e.g., target stimuli, distractors) and compare phases of distractor presentation with phases of distractor absence. The majority of sFST were performed in the presence of auditory distractors. Hence, auditory processing might have confounded the revealed differences between b-sFST and a-sFST, especially in the gamma-frequency band. The amount of sFST, performed in the absence of auditory distractors, was not appropriate to calculate statistical tests. Furthermore, in contrast to the majority of sFST, aFST were not accompanied by auditory input. Therefore, it cannot be ruled to out that auditory processing influenced the comparisons of sFST and aFST.

In the study at hand, both the spatial (19 electrodes) and the temporal (256 Hz) resolution are too low to apply certain analysis methods, such as source reconstruction techniques (according to Michel and Brunet, 2019: at least 64 electrodes) and short-time directed transfer function (Korzeniewska et al., 2008). In order to draw more precise conclusions about spatial and temporal dynamics in the course of sFST, future studies should increase the spatial and temporal resolution.

Since the control condition aFST differs from the experimental condition sFST with regard to the task demands, the comparability of both conditions is limited. Some might argue that the observed differences between sFST and aFST are explained by the haptic memory task demands during sFST, which did not take place during aFST. However, this argument does not explain the observed differences between the phases b-sFST and a-sFST, given that memory content was to maintain during both phases. Furthermore, some might argue that processing of the

instruction before and during aFST has an impact on the comparability of the control and experimental conditions. However, if perceptual processes of the instruction had an influence on the comparability of the two conditions, we would expect connectivity differences between the before and after phases of aFST, which were not observed.

6. Conclusion

To approach the question whether and which regulatory mechanisms underlie sFST, we know only one neurophysiological comparison of sFST and aFST (Grunwald et al., 2014). The present work enhances the work of Grunwald et al. (2014) by including a larger sample, employing multivariate network-based analyses, and including delta oscillations to the analysis. The results support the assumption that spontaneous facial self-touches affect cortical network mechanisms that are relevant for other than sensorimotor processes. Both before and after facial self-touch, spontaneous versus instructed executions of this behavior differ in terms of brain network interactions. Our hypothesis that brain network interactions are more similar in the after phases of sFST and aFST than in the before phases was underpinned. Although sFST research is in its infancy, the present analysis suggests that sFST serve regulatory functions.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of University of Leipzig Medical Faculty.

CRediT authorship contribution statement

KHGB performed the analysis and wrote the manuscript. MG, SMM, JLS and SM supervised the work in technical and statistical respects and contributed ideas to how the analysis should be performed and how the results should be presented. SMM performed the data acquisition. KHGB performed data preprocessing. MG, SMM and SM conceptualized and planned the study.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

The raw data (EEG) used to support the findings of this study are available from the corresponding author upon request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpsycho.2022.12.004.

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