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Fmri study of changes in large-scale brain networks during affective touch

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Abstract The importance of touch in human social development and interpersonal interactions is widely recognized, yet the underlying neurological processes remain relatively unexplored. To better understand these mechanisms, we analyzed functional magnetic resonance imaging (fMRI) data to investigate how affective touch influences brain activity. Our study employed independent component analysis (ICA) and cluster analysis to identify brain components that exhibit significant changes following tactile stimulation. These components were then mapped to large-scale brain networks, focusing on those with the most pronounced spatial intensity differences. Our findings highlight the crucial role of distinct brain networks in processing tactile sensations. Notably, we observed significant changes in the default mode network (DMN) activity, particularly in the control group, after the touch experiment. Additionally, specific alterations were detected in the amygdala, cuneus, and orbitofrontal cortex. This study sheds light on the neurological foundations of tactile experiences and their potential impact on behavior and emotional states. Understanding these processes could inform the development of therapeutic strategies that leverage touch to alleviate stress and enhance mental health.

1 Introduction

Affective touch, characterized by gentle, comforting, and empathetic physical contact, plays a significant role in shaping our emotional experiences, social bonds, and overall well-being. This unique form of touch has been associated with reduced stress, enhanced trust, and improved mental health outcomes [1]. However, the neural mechanisms underlying its profound emotional impact are still only partially understood [2–4]. Functional magnetic resonance imaging (fMRI) provides a vital tool for exploring these mechanisms. It offers a non-invasive, high-resolution means to reveal the dynamic interactions between brain regions, neurotransmitters, and subjective experiences related to affective touch [5–7].

By uncovering the neural processes involved in affective touch, fMRI research has the potential to inform the development of new interventions for individuals with touch-related disorders or impairments [8]. For instance, understanding the neural basis of reduced sensitivity to affective touch in conditions such as chronic pain or sensory processing disorders could lead to the creation of targeted therapies. These therapies would aim to restore normal touch processing and, in turn, improve emotional well-being [9, 10].

Currently, there is some understanding of how affective touch influences the activation of specific brain areas and their functional connectivity [11–14]. However, the impact of affective touch on large-scale brain networks remains underexplored. This is a critical gap, because these networks are fundamental to describing brain activity,

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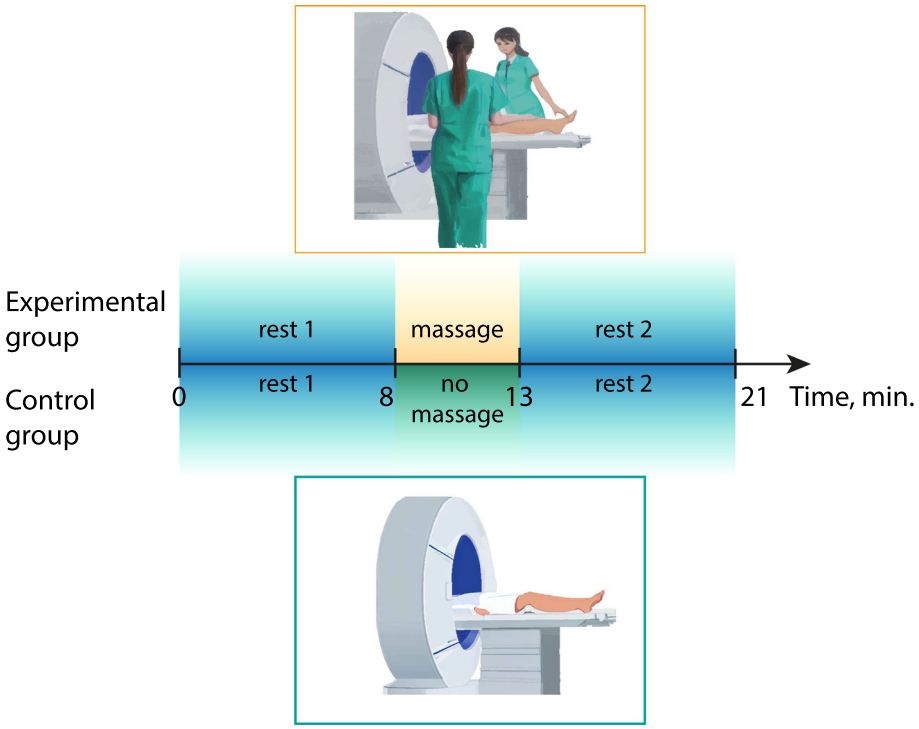

Fig. 1 Flowchart of the experiment

diagnosing disorders, and assessing therapeutic effects. One key framework for understanding these large-scale networks is the triple network model, which includes the default mode network (DMN), salience network (SN), and central executive network (CEN). This model is crucial for understanding how different networks interact to support cognitive and emotional functions [15–18].

Independent component analysis (ICA) is particularly effective for studying the large-scale brain networks, because it allows for the decomposition of complex brain signals into independent components, facilitating the identification of distinct networks and their interactions. In our work, we aim to bridge the existing gap by applying ICA to examine the activity within the large-scale brain networks. Specifically, our fMRI study investigates the functional changes in brain activity in response to the aftereffects of lower limb massage. Through this research, we seek to enhance our understanding of how tactile sensations can influence behavior and emotional states.

2 Materials and methods

2.1 Subjects and design

Twenty-seven healthy study participants (EX: 13 males, 14 females) and eleven healthy controls (HC: 5 males, 6 females) were recruited for the study. To be included, participants had to meet certain criteria, such as age between 20 and 40 years (difference is insignificant at $p > 0.5$), right-handedness, no history of neurological or psychiatric diseases, and no drug use prior to the study. All study participants were required to abstain from alcohol consumption for at least 48 h prior to the study, avoid tobacco or caffeine consumption for at least 2 h before the study began, and refrain from using any psychoactive substances. All subjects underwent a clinical examination and a functional MRI scan while in a resting state.

In the experimental group, the experiment consisted of a 5-min foot massage, followed by two resting periods—one before and one after the massage session. This setup allowed us to analyze two periods of interest for each participant: Rest1 and Rest2. The control group included participants who lay down in the scanner for 5 min instead of receiving a massage. Each subject participated in two resting-state fMRI sessions, with each session lasting 8 min (see Fig. 1).

2.2 Data registration and preprocessing

Functional and structural images were obtained using a Philips Achieva 3.0-T scanner (Koninklijke Philips NV, Amsterdam, The Netherlands) equipped with a 20-channel head coil. For each functional run, 360 images were

acquired using T2×-weighted echoplanar imaging (EPI) with slice thickness of 4 mm and no interslice gap. The imaging parameters were as follows: 2 mm in-plane voxel size, covering the entire brain volume; TR of 2.0 s; TE of 30 ms; and a matrix size of 76×74 pixels.

The data obtained were analyzed using the SPM12 [19] statistical processing package, running on the MATLAB platform (version 2019b). The preprocessing process incorporated motion correction, co-registration, segmentation of the structural data, and normalization to the Montreal Neurological Institute (MNI) standard space, according to standard procedures.

2.3 ICA and cluster analysis

Independent component analysis (ICA) is a mathematical technique used to separate different component signals from a composite signal. The goal is to decompose the complex and mixed brain signals into unique and independent components that can then be interpreted as distinct neural activities. ICA helps to identify and isolate specific brain networks or regions involved in particular cognitive functions or tasks. In our study, group ICA was performed to identify brain networks that were activated. ICA was performed on the BOLD fMRI scans using GIFT [20]. We decomposed the complex fMRI data into 20 different components. The analysis was performed to discover the functional brain networks in the data that emerged from the statistical processing without any prior assumptions. The number of components selected was 20 to balance the possibility of multiple brain networks with the limited number of subjects in the study.

The components were further analyzed to find differences in the spatial structure of the averaged time courses between groups. The resulting values were analyzed by two-sample voxel-wise t test across subjects (in the MANCOVAN module [21]) to identify significant effects at the $p < 0.0025$ level to accommodate Bonferroni correction (0.05/20). Only significantly changed parts of the significantly different components were used for clustering analysis. We used MRICRON [22] to identify clusters ($T > 2.3$, Size$\geq$100 voxels). The clusters we found were mapped to the Yeo-7 atlas (7 parcellations, these networks are sets of brain regions that show synchronized activity at rest or during task performance) [23] and the AAL3 atlas (166 parcellations that allow understanding of small-scale structures) [24], as well as their average dynamics were tested for Pearsonś correlation with the RSN-28 resting-state network atlas (14 resting-state networks divided into left and right hemispheres) using the GIFT labeler tool.

3 Results

No significant differences were identified between groups in the independent component analysis performed in the Rest1 condition. When analyzing the Rest2 condition, three statistically significant (Control group > Experimental group) independent components were identified, with corresponding cluster findings in components 3, 6, and 7 (see Fig. 2). The detailed information is provided in Table 1. For both components 3 and 6, only one cluster was identified within the Cerebellum, and this cluster was located beyond the parcellation boundaries defined in the Yeo atlas. The component 7 was found to belong to the default mode network (DMN), as identified by the Yeo atlas, and has 5 large significant clusters (see Fig. 3). Component labeller of the GIFT found that the networks were mostly correlated to the components (r denotes Pearsonś correlation between the component and corresponding RSN atlas area):

- Component 3—DMN ($r = 0.4561$);
- Component 6—Attention network ($r = 0.3721$);
- Component 7—Frontal parietal network ($r = -0.1419$).

Besides clusters presented in the Table 1, Component 7 includes parts of Vermis, Anterior Cingulate Cortex, Insula R, Calcarine R, and Thalamus ventral anterior nucleus (see Fig. 2 green highlights). These areas were represented by a set of small sites, with no large clusters, so were not included in the table.

4 Discussion

Our study offers valuable information about the spatial patterns associated with affective touch, specifically examining how foot massage impacts localized sensory information processing networks. The findings indicate that the control group displayed a higher degree of activity in the parts of the default mode network compared to

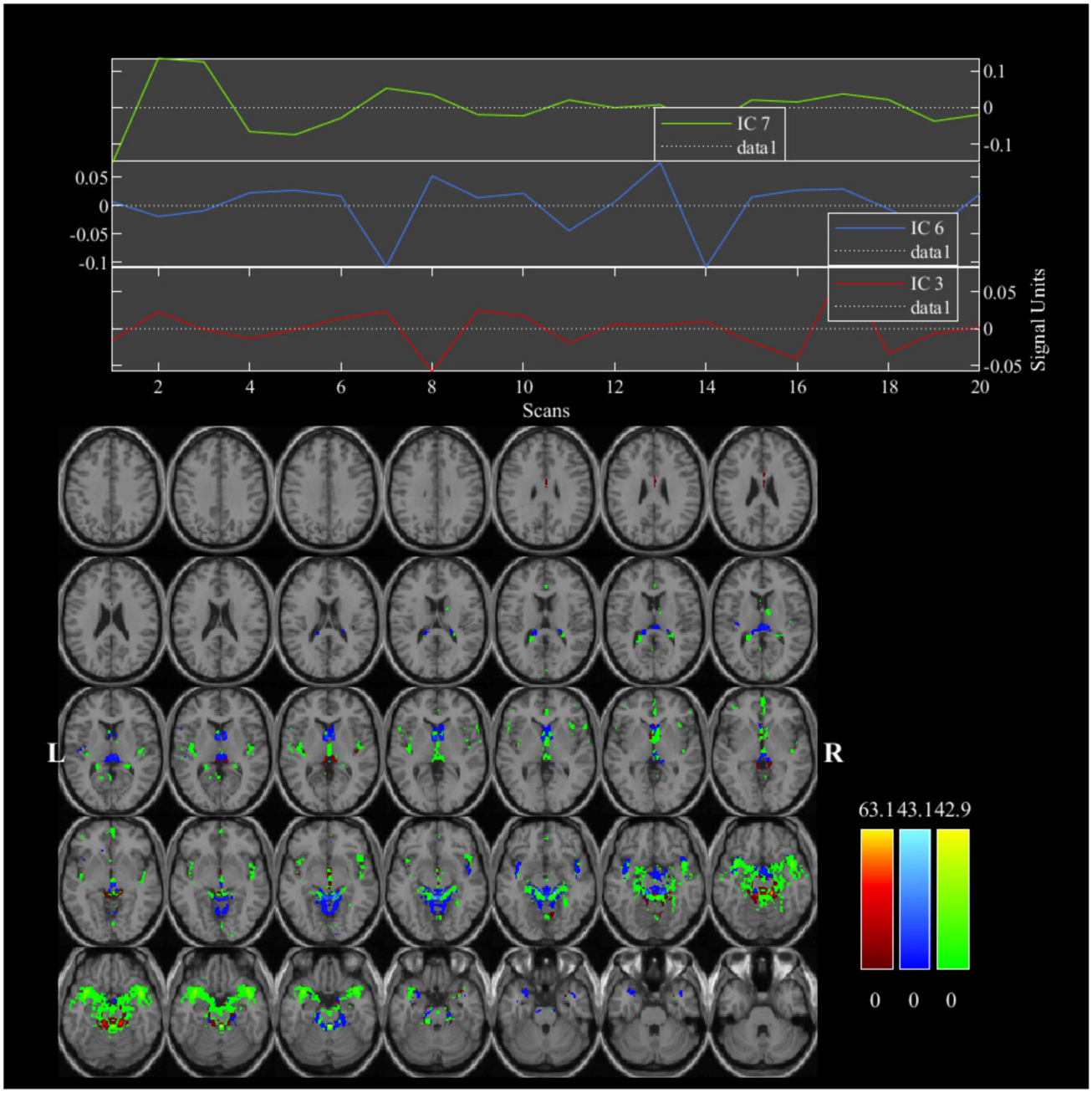

Fig. 2 Time courses and distributions of the components 3 (red), 6 (blue), and 7 (green)

the experimental group. It is known that affective touch has also been shown to decrease activity in the DMN, particularly in the dorsal medial prefrontal cortex, during tasks that require external attention [25–27].

The absence of a statistically significant effect in Rest1 condition indicates that there were no differences between the groups prior to the massage. The focus of the study is on the most significant areas and their potential influence on the outcomes of the experiment.

4.1 Amygdala

The amygdala, a part of the brain's limbic system, is primarily known for its role in processing emotions, memory, and fear responses [28]. However, its involvement in processing touch information is indirect and complex, often related to emotional or social contexts [29, 30]. The touch processing pathway begins with the activation of sensory receptors in the skin, which transmit signals to the spinal cord and eventually to the brain. The primary

Table 1 Clusters of significant changes in activity found for the components. X, Y, and Z denote coordinates of the center of mass (com) corresponding to the cluster in MNI coordinates; cluster size is denoted in voxels, intensity in t values, area number, and name according to the AAL3 atlas

Component	# Cluster	Xcom	Ycom	Zcom	Size	Intensity	Area	Area Name
3	1	0	− 34	− 16	233	12.12719	101	Cerebellum_4_5_L
6	1	0	− 38	− 10	287	10.68835	100	Cerebellum_3_R
7	1	22	− 12	− 16	308	8.07183	46	Amygdala_R
7	2	− 30	− 2	− 18	516	7.983779	45	Amygdala_L
7	3	− 26	− 76	− 10	294	5.04806	51	Lingual_L
7	4	4	52	− 6	133	4.681133	21	Frontal_Med_Orb_L
7	5	− 14	− 82	14	108	5.475353	49	Cuneus_L

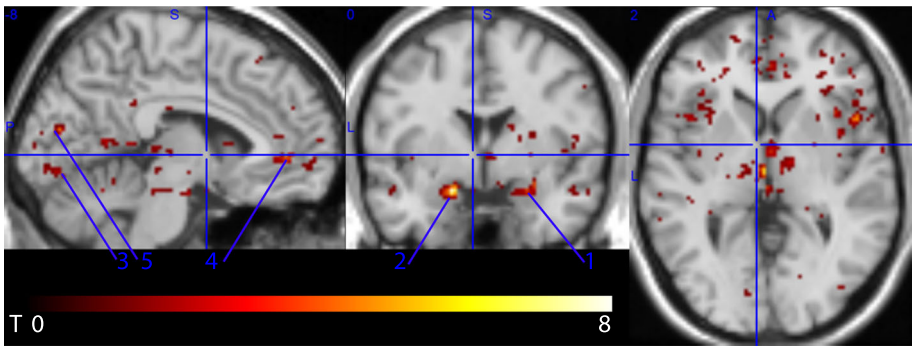

Fig. 3 Significant activity areas obtained with the T test for the component 7 in sagittal, coronal, and axial projections. Colormap denotes T-map intensity for the areas. Numbers show significant clusters from Table 1

somatosensory cortex (S1) is the first point of processing for touch information in the brain. From S1, the information is relayed to other areas, including the secondary somatosensory cortex (S2) and the insula [31]. Research has shown that the amygdala receives touch information from the S2 and the insula, particularly when the touch is emotionally salient or threatening [32]. The amygdala's involvement in touch processing is thought to be related to its role in detecting potential threats or dangers [33].

4.2 Lingual gyrus

The lingual gyrus receives input from various sensory systems, including touch, proprioception, and visual information. It integrates these inputs to create a comprehensive understanding of the environment [34, 35]. While not directly involved in touch processing, the lingual gyrus is interconnected with other brain areas, including those involved in multisensory integration. This means that visual information processed in the lingual gyrus can influence and be influenced by other sensory modalities, including touch [36, 37].

4.3 Medial orbitofrontal cortex

The Medial Orbitofrontal Cortex (mOFC) is a brain region involved in various functions, including emotion regulation, decision-making, and social cognition [38, 39]. While it is not traditionally considered a primary region for processing touch information, research has shown that the mOFC does play a role in the processing of touch, particularly in the context of emotional and social touch [40]. The mOFC is activated when we experience emotional touch, such as gentle stroking or caressing. This type of touch can elicit feelings of comfort, relaxation, and pleasure. The mOFC processes the emotional significance of touch, which can influence our emotional state and social behavior [41, 42]. The mOFC is also involved in processing social touch, such as holding hands, hugging, or kissing. Social touch can convey emotional support, comfort, and intimacy, and the mOFC helps to interpret these cues [43].

4.4 Cuneus

The Cuneus's role in affective touch is thought to be related to its involvement in the processing of slow, gentle touch, which is often associated with social and emotional connection [44, 45]. The Cuneus may be involved in the

extraction of emotional cues from touch, which can influence our emotional state and social behavior [46]. Some studies have suggested that the cuneus is involved in the emotional modulation of sensory processing [47]. For instance, its activity can be influenced by the emotional content of visual or tactile stimuli. This suggests that it might play a role in affective touch processing [35].

4.5 Global networks' interaction

When we see how the significant clusters for component 7 from Table 1 partly correspond to the DMN, the question arises why is there no correlation of activity with DMN? On the one hand, this is happening, because part of the component activity that accounts for the correlation with the frontal network occurs in small distributed areas, less than a threshold value [48, 49]. The strong correlation observed for the other components is due to their concentrated localisation, as each component consists mostly of a single cluster. Conversely, the seventh component has a broader distribution and the correlation is only partially captured in this case. Thus, overall contribution of the small distributed areas prevails over large clusters corresponding to the DMN. On the other hand, the mechanism of tactile processing provides for interaction between the DMN and the frontal parietal network, as a result of which the activity of DMN areas is modulated by the activity of the frontal parietal network[50].

Our findings highly correlate with the explanations provided in the work [42], particularly in the part here the anteroventral viscero-autonomic insula may be one link from the orbitofrontal cortex to autonomic output, the route from the orbitofrontal cortex and amygdala via the basal ganglia.

5 Conclusions

Our objective was to explore the differences in large-scale brain networks' activity between a group of healthy participants who underwent a lower limb massage and a group of healthy controls who did not receive any massage. We applied the use of functional magnetic resonance imaging to examine alterations in the activity between various brain regions after the massage session. Notably, we discovered that the default mode network, amygdala, and cuneus exhibited decreased activity after the massage.

From a practical perspective, our findings hold significant implications for the development of sensory stimulation techniques beneficial for individuals with prolonged disorders of consciousness, sensory loss, and autism spectrum disorders.

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Availability of data and materials The data presented in this study are available on request from the corresponding author.

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