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Research article

Enhanced amygdala–cortical functional connectivity in meditators

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HIGHLIGHTS

- Functional connectivity in meditation experts during emotion processing was studied.
- Enhanced neural connectivity in meditators during affective processing.
- The enhanced neural connectivity may relate to the mental training of meditation.
- Amygdala involves in meditation-related affective neuroplasticity.

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ABSTRACT

Previous studies have demonstrated that meditation is associated with neuroplastic changes in the brain regions including amygdala, anterior cingulate cortex (ACC), and temporal–parietal junction. Extended from these previous works, this study examined the functional connectivity of the amygdala in meditation experts during affective processing and observed that these experts had significantly stronger left amygdala (LA) connectivity with the dorsal ACC (dACC), premotor, and primary somatosensory cortices (PSC) while viewing affectively positive stimuli when compared to the novices. The current findings have implications for further understanding of affective neuroplastic changes associated with meditation in the amygdala.

1. Introduction

Loving-kindness meditation is a mental practice of the cultivation of unconditionally positive feelings toward the self and others [1]. Meditation practitioners usually commence their practice in forms that train attention or mindfulness and then move on to other forms of practice such as loving-kindness meditation. The initial attention practice is thought to be complementary to the subsequent compassion practice, which in turn provides a calm and peaceful state for one to enter an attentive state. The practice of meditation is associated with a reduction in anxiety and negative affect [2–4].

Lutz et al. [5] observed that practice of compassion meditation is associated with a significantly higher level of neural activity in the amygdala, right temporo–parietal junction, and right posterior superior temporal sulcus. Lee et al. [6] have demonstrated that experts of loving-kindness meditation showed significant activity in the ventral anterior cingulate cortex (ACC) and inferior frontal gyrus while viewing happy pictures and that in the caudate and middle frontal gyrus while viewing sad pictures. These regions are

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important for identifying the emotional value of stimuli, generation of affective states, and regulation of emotional responses [7].

Amygdala is a prime neural correlate of the limbic system essential for emotion processing [8]. Altered amygdala activity toward emotional stimuli has been consistently observed in patients with depression, anxiety, bipolar disorder, or post-traumatic stress disorder [9]. Stein et al. [10] reported that the amygdala is functionally connected with an extended cortical–subcortical network consisting of the anterior and posterior cingulate, insular, prefrontal, and parahippocampal cortices during the perception of angry and fearful faces. Specifically, the amygdala is strongly inhibited by the supragenual ACC when processing fearful/angry stimuli. Such inhibition of the amygdala is important for the down-regulation of the fear response [11]. Failure to engage the pregenual ACC to down-regulate the amygdalar response relates to difficulty in resolving emotional conflict in patients with generalized anxiety disorder [12]. Activity of the amygdala is also strongly inhibited by the activity of the posterior cingulate when processing fearful/angry stimuli [10].

A recent study which found that eight weeks of compassion training increased the activity of the right amygdala (RA) in response to negative images at trend-level in a group of meditation novices, and such increase correlates with a decrease in depression scores [13]. Change of functional synchrony of the amygdala with other brain regions during affective processing after long-term meditation practice remains unanswered. Taken together, because of the importance of the neural synchrony between the amygdala and its connected regions in emotion processing and initial evidence of meditation-related affective plasticity in the amygdala, this study explored, for the first time, the impact of long-term meditation practice on the amygdalar functional connectivity during emotion processing. A passive viewing paradigm was employed to probe the basic process of emotion perception in the absence of other cognitive demands. The hypothesis that meditation experts would exhibit a different pattern of amygdalar connectivity in regions involved in affective and reward processing such as the nucleus accumbens, ACC, and OFC compared to novices during emotion processing was verified in this study.

2. Materials and methods

2.1. Participants

This study was approved by the Institutional Review Board of the University of Hong Kong and the Hospital Authority (Hong Kong West Cluster). There were altogether 24 right-handed Chinese men participated in this study. The right-handedness was confirmed with the Edinburgh Handedness Inventory [14]. They were free of any medical or psychiatric conditions that could confound the results at the time of recruitment. There were 10 meditation experts who have practiced meditation following the *Theravada* tradition for at least five years, which include the practice of attention and loving-kindness meditation. The 14 matched novices did not have long-term meditation experience but were interested in meditation and had undergone seven hours of home-based basic meditation practice (to control for motivation of meditation practice between the two groups). Both groups were matched in ages [$t(22) = 0.651$, $p > 0.5$] and years of education [$t(22) = -1.683$, $p > 0.1$]. All participants gave their written informed consent before the study began.

2.2. Self-report measures

The 20-item Chinese Affect Scale [15] was used to assess positive affect (PA) and negative affect (NA). It is culturally adapted to be equivalent to the Positive and Negative Affect Schedule [16]. Participants rated the frequency of 10 positive and 10 negative affective states in the previous two weeks on a 5-point scale. Separate summation scores were calculated for PA and NA.

2.3. Emotion processing task

The task included 20 affectively positive (happy), negative (sad), and neutral (neutral) pictures each from the International Affective Picture System (IAPS) with the highest valence and arousal ratings [17]. Each emotion valence had equal proportions of pictures with human and nonhuman images. All stimuli appeared once on a dark background randomly in two 30-trial runs. Each picture was displayed for 3000 milliseconds (ms), separated by a white central fixation cross with varying ISI: 500 ms, 1000 ms, 1500 ms, 2000 ms, and 2500 ms. The experimental conditions were the trials viewing happy and sad pictures whereas the trials viewing neutral pictures represented the control condition (see the Supplementary Result and Fig. S1 in the Supplemental Material for further details of validation of the task using the novices' data). The duration of each run was about 155 s, and there were two runs. So the total duration of the fMRI scan was about 310 s. Participants also rated the valence from 1 (very negative) to 9 (very positive) and arousal from 1 (not arousing) to 9 (very arousing) for each happy and sad picture outside the scanner after scanning.

2.4. Image acquisition

Whole-brain axial scanning was performed with a 3.0 Tesla Philips Medical Systems Achieva scanner equipped with an 8-channel SENSE head coil. Thirty-two functional slices were acquired using a T2*-weighted gradient echo planar imaging sequence [slice thickness = 4 mm, time to repetition (TR) = 1800 ms, time to echo (TE) = 30 ms, flip angle = 90°, matrix = 64×64, field of view (FOV) = $230 \times 230 \times 128$ mm, voxel size = $3.59 \times 3.59 \times 4$ mm^3]. The duration of each fMRI run was about 3 min, and there were two runs. So the total duration of the fMRI scan was about 6 min. The axial slices were adjusted to be parallel to the anterior commissure–posterior commissure (AC–PC) plane. The first six volumes were discarded to allow for T1 equilibration effects. A three-dimensional, T1-weighted, magnetization-prepared rapid-acquisition gradient-echo (MP-RAGE) sequence was used to acquire high-resolution anatomical images (164 contiguous sagittal slices, 1 mm thick, TR = 7 ms, TE = 3.2 ms, flip angle = 8°, FOV = 164 mm, matrix = 256×240 mm, voxel size = 1 mm^3).

2.5. fMRI data analysis

The fMRI data were preprocessed using SPM8 (Wellcome Department of Cognitive Neurology, London, UK) in MATLAB 7.7 (Mathworks Inc. Natick, MA, USA). The preprocessing steps included slice-timing correction, realignment, coregistration, segmentation, normalization, smoothing with an 8 mm full width half maximum (FWHM) kernel, and band-pass filtering ($0.009 < f < 0.08$ Hz) to reduce the effect of low-frequency drift and high-frequency noise. Functional connectivity analysis, using a seed-driven approach, was performed with the 'conn' toolbox v13.1 [18] [http://www.nitrc.org/projects/conn]. The toolbox computes the correlation coefficients between the fMRI signal in a seed region and each voxel in the brain separately to generate the parametric seed-voxel correlation map, which is one of the most common techniques for studying functional connectivity [19]. The left amygdala (LA) and RA were defined using the MarsBar toolbox (v0.42, http://marsbar.sourceforge.net/) [20] as the seed region-of-interest (ROI), based on the anatomical masks provided by the anatomical