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Neural correlates of the happy life: The amplitude of spontaneous low frequency fluctuations predicts subjective well-being

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ABSTRACT

Subjective well-being is assumed to be distributed in the hedonic hotspots of subcortical and cortical structures. However, the precise neural correlates underlying this construct, especially how it is maintained during the resting state, are still largely unknown. Here, we explored the neural basis of subjective well-being by correlating the regional fractional amplitude of low frequency fluctuations (fALFF) with the self-reported subjective well-being of healthy individuals. Behaviorally, we demonstrated that subjective well-being contained two related but distinct components: cognitive and affective well-being. Neurally, we showed that the fALFF in the bilateral posterior superior temporal gyrus (pSTG), right posterior mid-cingulate cortex (pMCC), right thalamus, left postcentral gyrus (PCG), right lingual gyrus, and left planum temporale (PT) positively predicted cognitive well-being, whereas the fALFF in the bilateral superior frontal gyrus (SFG), right orbitofrontal cortex (OFC), and left inferior temporal gyrus (ITG) negatively predicted cognitive well-being. In contrast, only the fALFF in the right amygdala reliably predicted affective well-being. Furthermore, emotional intelligence partially mediated the effects of the right pSTG and thalamus on cognitive well-being, as well as the effect of the right amygdala on affective well-being. In summary, we provide the first evidence that spontaneous brain activity in multiple regions associated with sensation, social perception, cognition, and emotion contributes to cognitive well-being, whereas the spontaneous brain activity in only one emotion-related region contributes to affective well-being, suggesting that the spontaneous activity of the human brain reflect the efficiency of subjective well-being.

Introduction

Over the decades, increasing attention has been devoted to subjective well-being, which reflects positive emotional functioning (Diener et al., 2003). Subjective well-being focuses on the hedonic aspect of well-being; thus, is also known as hedonic well-being (Diener, 1994; Ryan and Deci, 2001). Generally, subjective well-being is assumed to include a cognitive and an affective component (Diener, 1994; Diener et al., 1985, 2003; Lucas et al., 1996; Pavot and Diener, 1993; Ryan and Deci, 2001). The cognitive component of subjective well-being refers to life satisfaction that reflects an individual's general cognitive evaluations of his or her life (Diener, 1994; Pavot and Diener, 1993). The affective component of subjective well-being refers to affect balance or level, indicating having more pleasant than unpleasant emotional states in one's emotional life. In many studies, the two components of subjective well-being have been shown to be interrelated but distinct constructs (Diener, 1994). Although subjective well-being has drawn a lot of attention from researchers (e.g., Diener et al., 2003), the precise neural correlates underlying this construct are still largely unknown.

A growing body of evidence from electrophysiological or task-based functional magnetic resonance imaging (fMRI) studies has shown that the code for hedonic evaluations including anticipation, appraisal, experience, and memory of affective (pleasurable or unpleasurable) stimuli through objective measures of affect implicates multiple cortical and subcortical regions. The cortical regions mainly reside in the prefrontal cortex. They include the orbitofrontal cortex (OFC), insula, medial prefrontal, and anterior cingulate cortices (Amodio and Frith, 2006; Beckmann et al., 2009; Craig, 2002; Kringelbach, 2005; Kringelbach and Berridge, 2009). The subcortical regions are the nucleus accumbens, ventral pallidum, brainstem, thalamus, and amygdala (Amodio and Frith, 2006; Cardinal et al., 2002; Everitt and Robbins, 2005; Kringelbach, 2005; Kringelbach, 2005). However, as its name suggests, subjective well-being is subjective, which resides within the experience of an individual, and thus the best measure of subjective well-being may rely on self-report assessment (Diener, 1994; Pavot and Diener, 1993). To our knowledge, there is just one study that employed this approach (i.e., self-report assessment) to explore the neural basis of subjective well-being via measuring electroencephalography (EEG) activity at

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rest, which presumably reflects neuronal oscillations and variability in behavior (Niedermeyer and Lopes Da Silva, 2005; Putman, 2011; Schutter and Knyazev, 2012). This study revealed that greater left over right alpha activity in the superior prefrontal cortex was associated with higher levels of cognitive and affective well-being (Urry et al., 2004). Although no fMRI study has been conducted to directly investigate its neural correlates, a recent study has explored regional gray matter correlates of health-related quality of life, which is moderately correlated with subjective well-being (Abdel-Khalek, 2010). The gray matter volume (GMV) of multiple prefrontal areas including the superior frontal gyrus (SFG), mid-cingulate cortex (MCC) and anterior cingulate cortex (ACC) was associated with quality of life (Takeuchi et al., 2014). Because EEG has poor spatial resolution, the current study used resting-state fMRI (rs-fMRI) to examine where and how subjective well-being, especially its two components, is maintained by spontaneous brain activity in the absence of explicit, task-directed behaviors.

Non-invasive rs-fMRI is a promising tool for measuring brain activity at rest that can be used to uncover the neural basis of inter-individual differences in behavior (e.g., personality characteristics) (Biswal, 2012; Fox and Raichle, 2007; Raichle, 2010). Here, we focused on the low frequency fluctuations (LFFs, 0.01–0.10 Hz) in the blood oxygen level-dependent (BOLD) signal at rest, which are related to spontaneous neuronal activity (Logothetis et al., 2001). Slow neuronal oscillations are believed to reflect excitatory neuron activity and allow for better "communication" between the regions that are spatially more distant from one another (Buzsaki, 2006; Schroeder et al., 2008). Here, we employed an increasingly popular measure of low frequency BOLD oscillations: fractional amplitude of low frequency fluctuations (fALFF, Zou et al., 2008), which reflects regional properties of intrinsic brain dynamics. Previous investigation of regional ALFFs have shown that ALFFs reflect physiological signals and are behaviorally relevant (Biswal, 2012; Fox and Raichle, 2007; Raichle, 2010). Individuals with cognitive-affective brain disorders, such as depression, mild cognitive impairment and schizophrenia, exhibit abnormal fALFF in the regions that are involved in the corresponding cognitive-affective processes (Han et al., 2011; Hoptman et al., 2010; Liu et al., 2013a). In addition, several recent studies have shown healthy individuals' fALFFs are associated with individual differences in working memory (Zou et al., 2013), response inhibition (Hu et al., 2014; Mennes et al., 2011), delay discounting (Schmaal et al., 2012), empathy (Cox et al., 2012), and personality traits (Wei et al., 2014). These findings indicate that fALFF can effectively reflect the neural mechanisms underlying cognitive and emotional functions. Therefore, here we attempted to employ fALFF to explore the neural correlates of subjective well-being of healthy individuals.

Previous studies on subjective well-being have generally considered emotional intelligence as one of the most effective predictors of subjective well-being (e.g., Bar-On, 2005; Diener and Lucas, 1999; Salovey et al., 1999). Emotional intelligence that reflects one's ability to perceive, use, understand and manage emotions in the self and others (Mayer and Salovey, 1997) has been conceptually linked to subjective well-being (Bar-On, 2005; Mayer and Salovey, 1997; Salovey et al., 1999). That is, individuals with higher emotional intelligence likely possess a better capacity of perceiving and reasoning emotions in the self and others, which facilitates a greater sense of subjective well-being (Mayer and Salovey, 1997; Salovey et al., 1999). A large body of research has empirically confirmed this relationship, with all reporting low to moderate correlations ranging from r = 0.11 to r = 0.55 (Bar-On, 1997; Bastian et al., Gannon and Ranzijn, 2005; Ciarrochi et al., Ciarrochi et al., 2000; Gallagher and Vella-Brodrick, 2008; Gannon and Ranzijn, 2005; Kong et al., 2012a,b; Kong and Zhao, 2013; Liu et al., 2013b; Palmer et al., 2002; Schutte and Malouff, 2011). Some researchers have further discovered that emotional intelligence accounts for unique variance in subjective well-being after controlling for covariates such as demographic characteristics, IQ, Big-Five personality, mindfulness, resilience, self-esteem and social support (e.g., Bastian et al., 2005; Extremera and Fernández-Berrocal, 2005; Gallagher and Vella-Brodrick, 2008; Gannon and Ranzijn, 2005; Kong et al., 2012a, bLiu et al., 2013a; Palmer et al., 2002; Schutte and Malouff, 2011). A recent study has also found that, with increased emotional functions through emotional intelligence training, individuals' subjective well-being also tends to increase (Nelis et al., 2011). Taken together, these findings suggest that emotional intelligence plays a critical role in cultivation of subjective well-being. Furthermore, given the conceptual distinction between the cognitive and affective components of subjective well-being, we speculated that individual differences in emotional intelligence should differentially mediate the association between fALFF and two components of subjective well-being.

To answer these questions, we firstly used the Satisfaction with Life Scale (SWLS, Diener et al., 1985) and the Positive and Negative Affect Schedule (PANAS, Watson et al., 1988) to assess the cognitive and affective components of subjective well-being of healthy individuals ($N = 294$), respectively. Then, a confirmatory factor analysis (CFA) was performed to replicate the two-factor structure of subjective well-being. Third, we conducted a correlation analysis of the relationship between the participants' self-reported subjective well-being score and their regional fALFF to identify the brain regions that could explain individual differences in subjective well-being, especially its two components. Finally, we conducted mediation analyses to examine whether and how emotional intelligence mediates the association between fALFF and two components of subjective well-being.

Methods

Participants

Two hundred and ninety-four healthy university students (158 females; mean age = 21.56 years, standard deviation (SD) = 1.00) with no history of neurological or psychiatric disorders were recruited from Beijing Normal University as paid participants. Both behavioral and fMRI protocols were approved by the Institutional Review Board of Beijing Normal University. Written informed consent was obtained from all participants prior to the study.

Behavioral tests

The cognitive component of subjective well-being was assessed using the Satisfaction with Life Scale (SWLS, Diener et al., 1985). The SWLS consists of five statements such as, "I am satisfied with my life" and "In most ways my life is close to my ideal." Respondents are instructed to indicate the extent to which they agree or disagree with each statement using a 7-point Likert scale. Higher scores indicate higher levels of life satisfaction. The scale has been shown to have high internal consistency and convergent/discriminant validity with related constructs such as negative affect, optimism, gratitude, mindfulness, psychological stress, positive affect, self-esteem, anxiety, and depression (Kong and You, 2013; Kong et al., 2012a,b, 2014a,b; Lucas et al., 1996; Pavot and Diener, 1993). The Chinese version of the SWLS has been demonstrated to be a reliable and valid measurement used to assess the cognitive well-being of Chinese adults (e.g., Kong and Zhao, 2013; Kong et al., 2012a,b). In this study, the SWLS exhibited adequate reliability (Cronbach's $\alpha = 0.82$).

The affective component of subjective well-being was assessed using the Positive and Negative Affect Schedule (PANAS, Watson et al., 1988). The PANAS consists of a word list describing two different affect states (10 positive and 10 negative words) (e.g., "active," "afraid"). Respondents are instructed to indicate the extent to which they generally feel each affective state using a 5-point Likert scale. According to Thompson (2007), some of the words in the full 20-item PANAS are ambiguous in "international" English. Consequently, we analyzed our data according to the brief version of the international Positive and Negative Affect Schedule (I-PANAS-SF, Thompson, 2007), which originated from the PANAS developed by Watson et al. (1988). Positive and negative

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