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Inter-individual differences in the experience of negative emotion predict variations in functional brain architecture☆

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ABSTRACT

Current evidence suggests that two spatially distinct neuroanatomical networks, the dorsal attention network (DAN) and the default mode network (DMN), support externally and internally oriented cognition, respectively, and are functionally regulated by a third, frontoparietal control network (FPC). Interactions among these networks contribute to normal variations in cognitive functioning and to the aberrant affective profiles present in certain clinical conditions, such as major depression. Nevertheless, their links to non-clinical variations in affective functioning are still poorly understood. To address this issue, we used fMRI to measure the intrinsic functional interactions among these networks in a sample of predominantly younger women (N = 162) from the Human Connectome Project. Consistent with the previously documented dichotomous motivational orientations (i.e., withdrawal versus approach) associated with sadness versus anger, we hypothesized that greater sadness would predict greater DMN (rather than DAN) functional dominance, whereas greater anger would predict the opposite. Overall, there was evidence of greater DAN (rather than DMN) functional dominance, but this pattern was modulated by current experience of specific negative emotions, as well as subclinical depressive and anxiety symptoms. Thus, greater levels of currently experienced sadness and subclinical depression independently predicted weaker DAN functional dominance (i.e., weaker DAN–FPC functional connectivity), likely reflecting reduced goal-directed attention towards the external perceptual environment. Complementarily, greater levels of currently experienced anger and subclinical anxiety predicted greater DAN functional dominance (i.e., greater DAN–FPC functional connectivity and, for anxiety only, also weaker DMN–FPC coupling). Our findings suggest that distinct affective states and subclinical mood symptoms have dissociable neural signatures, reflective of the symbiotic relationship between cognitive processes and emotional states.

Introduction

Negative mood states foster internally oriented attention and perceptual decoupling from the here-and-now (Smallwood et al., 2007; Smallwood et al., 2009). Nevertheless, the neural signature and unique contribution of distinct negative emotions to this effect of mood on engagement with the external world have not been identified despite their significance to both normal and pathological variations in emotional functioning. To address this issue, the present research capitalized on existing evidence that the human brain is organized into dissociable anatomical networks (Fox & Raichle, 2007), which provide a latent functional architecture that is readily recruited during goal-directed cognition (Laird et al., 2011; Smith et al., 2009). Importantly, recent investigations have documented the key role that these intrinsic functional networks play in supporting not only cognitive, but also affective processes (i.e., emotion experience and perception, cf. Touroutoglou et al. (in press)), including those observed during experimentally induced variations in mood states (e.g., sadness, Harrison et al., 2008) and those underlying individual differences in emotion-relevant traits (e.g., emotional reactivity, Touroutoglou et al., 2014; trait anger, Fulwiler et al., 2012).

Of the intrinsic functional networks identified to date (e.g., van den Heuvel and Sporns, 2013), most relevant to the present investigation are two networks with activity that tends to be anti-correlated both at rest and during task. These two networks, the dorsal attention

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network (DAN) and the default mode network (DMN), have garnered considerable attention in the literature, and are thought to support externally and internally oriented cognition, respectively (Andrews-Hanna et al., 2014; Corbetta & Shulman, 2002; Fox et al., 2005). The two are spatially distinct, with the DAN encompassing the dorsolateral prefrontal cortex (PFC), frontal eye fields, middle temporal motion complex, and superior parietal lobule, and the DMN incorporating the medial PFC, posterior cingulate cortex, superior frontal gyri, medial temporal lobes, and the angular gyri (Spreng et al., 2013). A third network, the frontoparietal control network (FPC), encompassing the lateral PFC, the anterior part of the inferior parietal lobule (IPL), medial superior PFC, and the anterior insula, has been recently identified as the "adjudicator" of the DAN–DMN functional competition, based on its flexible, task-driven coupling with either the DMN or the DAN (Cole et al., 2013; Spreng et al., 2010).

Individual differences in the functional architecture underlying the DMN, DAN and FPC carry significant implications for both normal and pathological variations in cognitive functioning across the lifespan (e.g., Andrews-Hanna et al., 2007; Spreng & Schacter, 2012). Moreover, they also play a role in the maladaptive affective profiles that characterize certain clinical conditions (e.g., major depression, Andrews-Hanna et al., 2014; Belleau et al., 2014; Hyett et al., 2015; Kaiser et al., 2015; Sambataro et al., 2013; van Wingen et al., 2013). For example, in a recent meta-analysis of resting state functional connectivity studies with major depression disorder (MDD) patients and healthy controls (Kaiser et al., 2015), MDD was reportedly linked to a pattern of hypoconnectivity between the DAN and the FPC and a complementary pattern of hyperconnectivity between the DMN and the FPC. In light of behavioral studies, linking negative, predominantly sad, mood states to greater internally oriented attention and perceptual decoupling from the here-and-now (Smallwood et al., 2007, 2009), Kaiser et al.'s findings raise the intriguing possibility that individual differences in DAN–FPC versus DMN–FPC connectivity patterns, suggestive of reduced attentional allocation to the external environment, relative to the inner milieu, would be related to affect in the general population and also may be a premorbid neural marker of depression.

To test this hypothesis, we assessed resting state functional interactions among the DAN, DMN, and FPC in a large sample of younger women who were part of the Human Connectome project (HCP). To shed light on the unique link between sadness and its associated functional connectivity patterns, we used participants' reports regarding their current experience of three negative emotions (i.e., sadness, fear, and anger), which had been identified as basic constituents of affective experience (Shaver et al., 1987) and pivotal determinants of variations in optimal emotional functioning (Schimmack, 2003).

Our main goal was to elucidate whether participants who were currently experiencing greater levels of sadness would demonstrate greater DMN–FPC and weaker DAN–FPC coupling, suggestive of greater attention to the internal milieu and reduced goal-directed engagement with the external environment (cf. Spreng et al. (2010)). To disentangle the effects of normal versus more pathological variations in sad mood states, we also assessed whether the aforementioned internetwork connectivity patterns would be more strongly expressed among participants who were experiencing subclinical depressive symptoms. Such a constellation of results would be broadly consistent with our proposal that variations in DAN–FPC versus DMN–FPC connectivity may be a premorbid marker of depression.

As a secondary goal, we tested whether participants who were currently experiencing greater levels of anger would evidence a pattern of DAN–FPC connectivity opposite to the one predicted for sadness. This hypothesis was based on previous findings that anger is linked to greater approach motivation (for reviews, see Carver & Harmon-Jones (2009); Harmon-Jones et al. (2010)), and, thus, arguably, associated with greater goal-directed attention towards the external perceptual environment, which, in turn, is manifest neurally as greater DAN–FPC coupling (cf. Spreng et al. (2010)). We did not have any specific hypotheses regarding the effect of anger on DMN–FPC connectivity because, although rumination helps maintain angry mood states (Ray et al., 2008), the extent to which it makes a unique contribution to anger experiences beyond its broad contribution to negative affect is unclear. Thus, it is possible that, as predicted, anger would exert a strong positive effect on DAN–FPC coupling and a weaker, but still a positive effect on DMN–FPC coupling (cf. Ray et al. (2008)).

The extant literature suggested opposing hypotheses regarding the link between individual differences in fear/anxiety and functional brain architecture. Specifically, there is evidence that fear/anxiety is associated with a *motivation* to withdraw (from potential environmental threats, cf. Carver & Harmon-Jones (2009)), as well as greater attentional engagement with the external environment (to scrutinize for potential threats, e.g., Baas et al., 2006; Cornwell et al., 2007). Thus, although we could not formulate any specific hypotheses regarding their associated internetwork connectivity patterns, we reasoned that it would be important to also include measures of normal and subclinical variations in fear/anxiety. Not only is fear foundational to emotional experience (Shaver et al., 1987), but, in the clinical domain, anxiety and depression often co-occur (Brown et al., 2001; Joorman et al., 2005; Kessler et al., 1999; Sanderson et al., 1990) and the severity of co-occurring anxiety has been found to influence brain function in depression (Engels et al., 2007; Heller, 1993; Heller & Nitschke, 1998; Heller et al., 1997; Keller et al., 2000; Nitschke et al., 1999).

Method

Participants

The present study included a sample of 162 younger women (27 between 22 and 25, 77 between 26 and 30 and 58 between 31 and 36 years of age, see Van Essen et al. (2012) for the rationale behind this age reporting strategy in HCP data releases) from the Human Connectome Project (HCP). We used the data from these 162 participants because this sample represents the largest number of HCP female participants with available resting state fMRI and emotion data who are unrelated to each other. We opted to focus exclusively on women due to evidence of significant sex differences in both emotional experience and functional brain anatomy (Caeyenberghs & Leemans, 2014; Tomasi & Volkow, 2012; Wager et al., 2003), which could have thus interfered with the detection of our predicted effects.

The majority of participants (N = 147) were right-handed[1]. All participants were screened for a history of neurological and psychiatric conditions and use of psychotropic drugs, as well as for physical conditions or bodily implants that may render their participation unsafe. Diagnosis with a mental health disorder and structural abnormalities, as revealed by the MRI structural scans, were also exclusion criteria. Participants provided informed consent in accordance with the HCP research ethics board.

Measures

Participants completed the measures described below on the day of their Session 1 fMRI appointment. Scores on all the variables were provided in the latest HCP data release.

[1] The HCP uses a continuous measure of handedness, with scores ranging from −100 (completely left-handed) to 100 (completely right-handed). Negative scores indicate that the participant is more left-handed than right-handed. Positive scores indicate that the participant is more right-handed than left-handed. In our sample, 147 of the 162 participants had handedness scores of 10 or greater, indicating that they were more right- than left-handed. Eliminating the 15 mostly left-handed participants or introducing handedness as a covariate in our analyses did not change any of the reported results. Consequently, for the sake of simplicity, we report the analyses in which handedness scores are not introduced as a covariate.