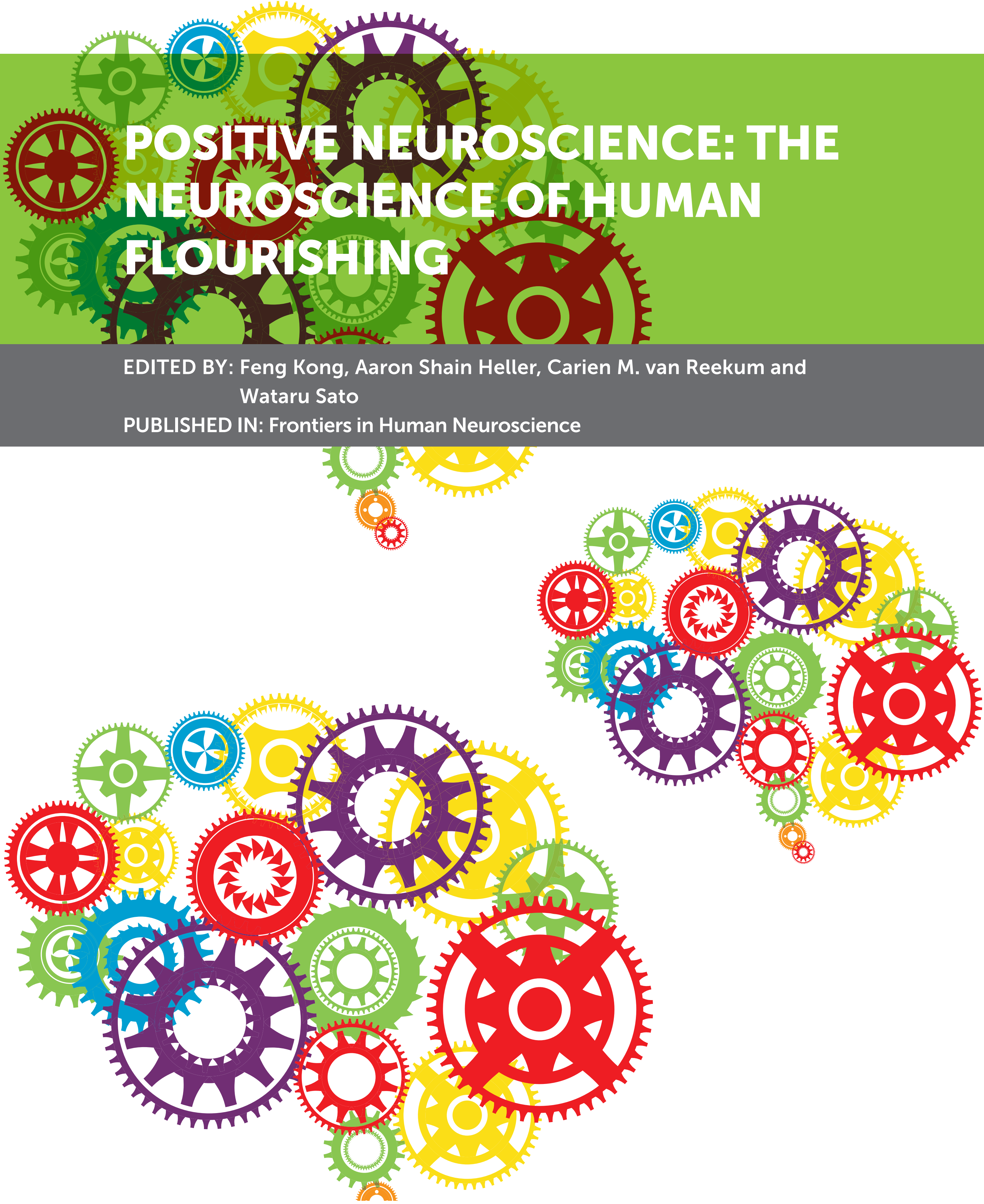

POSITIVE NEUROSCIENCE: THE NEUROSCIENCE OF HUMAN FLOURISHING

EDITED BY: Feng Kong, Aaron Shain Heller, Carien M. van Reekum and
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PUBLISHED IN: Frontiers in Human Neuroscience

frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88963-642-6
DOI 10.3389/978-2-88963-642-6

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POSITIVE NEUROSCIENCE: THE NEUROSCIENCE OF HUMAN FLOURISHING

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Citation: Kong, F., Heller, A. S., van Reekum, C. M., Sato, W., eds. (2020). Positive Neuroscience: The Neuroscience of Human Flourishing. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-88963-642-6

Table of Contents

frontiers
in Human Neuroscience

EDITORIAL
published: 28 February 2020
doi: 10.3389/fnhum.2020.00047

Editorial: Positive Neuroscience: the Neuroscience of Human Flourishing

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Keywords: positive neuroscience, flourishing, well-being, character strengths, neuroimaging

OPEN ACCESS

Edited and reviewed by:
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Specialty section:
This article was submitted to
Cognitive Neuroscience,
a section of the journal
Frontiers in Human Neuroscience

Received: *12 December 2019*
Accepted: *03 February 2020*
Published: *28 February 2020*

Citation:
Kong F, Heller AS, van Reekum CM and Sato W (2020) Editorial: Positive Neuroscience: the Neuroscience of Human Flourishing.
Front. Hum. Neurosci. 14:47.
doi: 10.3389/fnhum.2020.00047

Editorial on the Research Topic

Positive Neuroscience: the Neuroscience of Human Flourishing

The burgeoning subfield of neuroscience focused on salubrious attributes of the human condition has begun to illuminate the complex biological basis of human functioning and flourishing. This has been referred to as positive neuroscience. Instead of focusing on pathology, research on positive neuroscience directs its attention on the neural mechanisms supporting flourishing, psychological well-being, resilience, and promotion of health. Previous studies have investigated the structural and functional neural basis underlying positive human functioning such as well-being (e.g., Van Reekum et al., 2007; Heller et al., 2013; Kong et al., 2015a; Sato et al., 2015), meditation (e.g., Cahn and Polich, 2006; Sperduti et al., 2012), optimism (e.g., De Pascalis et al., 2013), resilience (e.g., Kong et al., 2015b, 2018), and creativity (e.g., Fink et al., 2009), based on experimental and self-reported measures. However, this emerging literature is just the tip of the iceberg on the quest to identify the complex mechanisms of brain structure and function supporting human behavior. The Research Topic "Positive neuroscience: the neuroscience of human flourishing" provides an outlet for novel work in this domain and to advance our understanding of the underlying mechanisms of aspects of human flourishing.

Kress and Aue begin this topic with a behavioral study on the effect of attention bias modification on optimism bias—that is, being overly optimistic—for future positive events. They found that extensive training in which subjects were required to direct attention to positive social information could enhance comparative optimism bias for future positive events, over, and above trait optimism.

Wang et al. used an activation likelihood estimation (ALE) meta-analysis of functional magnetic resonance imaging (fMRI) studies to investigate whether neural systems involved in prosocial behaviors and reward demonstrated overlapping or distinct neural signatures. They found that prosocial behaviors specifically activated the insula, temporal lobe, and superior temporal gyrus (STG), whereas reward specifically activated the lentiform nucleus, thalamus, caudate nucleus, parahippocampal gyrus (PHG), and anterior cingulate cortex (ACC). Relatedly, Tunison et al. more specifically report on an event-related potential (ERP) component associated with reward processing, the reward-related positivity (RewP). The RewP is a positive deflection ERP component observed between 250 and 350 ms after reward feedback over fronto-central electrode sites, and its amplitude has been related to internalizing psychopathology. However, the RewP has been examined almost exclusively in response to financial rewards, and whether this ERP component is a general feature of reward processing remains uncertain. To address this, Tunison et al. used a point-based system of reward and found that RewP amplitudes were indeed larger for rewarded trials vs. non-rewarded trials. These data add to a growing literature that there are general properties of incentives regardless of the reward type.

Three studies in this issue focused on the neural basis of positive emotion and well-being. First, Hu et al. used functional near-infrared spectroscopy (fNIRS) to examine the brain's hemodynamic responses to different positive emotions. They found 10 typical kinds of positive emotions (joy, gratitude, serenity, interest, hope, pride, amusement, inspiration, awe, and love) could be divided into three distinct clusters (i.e., playfulness, encouragement, and harmony) and hemodynamic responses to these three clusters showed distinct patterns. Second, using fMRI, Hong et al. explored the neural basis of a specific and rarely examined positive emotion type—professional pride. They found that professional pride may be associated with multiple brain networks including the right ventrolateral prefrontal cortex (VLPFC), left dorsolateral prefrontal cortex (DLPFC), left middle and inferior temporal gyri, left posterior superior temporal sulcus, right temporoparietal junction, left lingual gyrus, left calcarine cortex, right insula, left caudate, and right putamen. Third, Goldbeck et al. used resting state fNIRS to investigate neural basis of well-being. Performing a voxelwise regression, they found that the networks linked to individual differences in well-being included areas of the posterior default mode network. Interestingly, they found specific divergence in neural circuits linked to eudaimonic well-being, defined as a sense of meaning and purpose, positive social relationships, mastery, autonomy, virtues, and subjective well-being, a more general term referring to the various types of subjective evaluations of one's life, including both cognitive evaluations, and affective feelings (Diener et al., 2018). Specifically, they found that while the left middle temporal/fusiform gyrus was a hub node of a network associated with eudemonic well-being, the left primary/secondary somatosensory cortex was a hub node of the network associated with subjective well-being. Continued work exploring whether eudaimonic and subjective well-being are linked to distinct neural circuits and relevant health outcomes will be essential to characterizing the specific neural systems associated with eudaimonia versus subjective well-being.

Furthermore, several papers in this issue centered upon the neural basis of positive personal characteristics such as trait mindfulness, creativity, and emotional intelligence. For example, Parkinson et al. found that trait mindfulness and its facets was associated with increased functional connectivity (FC) in regions linked to attentional control, interoception, and executive function, and decreased FC in regions linked to self-referential processing and mind wandering. In another study, Arkin et al. demonstrated that musical creativity was negatively associated with gray matter volume in the right inferior temporal gyrus and bilateral hippocampus. Motivated by Thayer et al.'s Neurovisceral Integration model (e.g., Thayer and Lane, 2009; Smith et al., 2017) which proposes a key role for brain networks supporting cognitive and affective flexibility in cardiac vagal control, Vanuk et al. assessed the association between emotional intelligence and cardiac vagal control. The authors found that ability emotional intelligence, but not mixed emotional intelligence, was positively associated with cardiac vagal control.

Beyond positive personal characteristics, four studies explored the effect of mindfulness/meditation training on the brain and psychological functions. First, using a two-stage mindfulness training over eight weeks, Zhang et al. examined whether the effects of different components of mindfulness meditation training differentially affected anxiety, depression, and rumination. They found that the first 4-weeks of focused attention (FA) meditation could improve self-reported levels of mindfulness and reduce levels of anxiety and depression, while the subsequent 4-weeks open monitoring (OM) meditation could further improve the level of mindfulness and maintain a positive mood. Second, Kwak et al. explored the neural mechanisms underlying the effect of a 4-days meditation intervention on stress resilience using resting state fMRI FC. They found that increased resting-state FC between the left rostral ACC and the dorsomedial prefrontal cortex (dmPFC) was linked to neural basis of the effect of the meditation intervention on stress resilience that was assessed via the Resilience Quotient Test (RQT). Third, Tang et al. reviewed key components and potential brain-body mechanisms related to well-being and proposed mindfulness training as a promising method to improve well-being. Finally, Reddy and Roy further reviewed the role of one's motivation to engage in meditation practices. They proposed that while practicing meditation one may benefit from traditional assistance and ethical/moral teachings in addition to meditation training in isolation.

Interestingly, several papers in this issue also report on the neural components linked to other positive activities (e.g., expressive writing, martial arts, attention training) that can promote positive human functioning. For example, DiMenichi et al. investigated the effect of expressive writing on neural processing during learning. A large literature finds that expressive writing is linked to healthy psychological function (e.g., Pennebaker and Chung, 2007). Here, they found that writing about a past failure led to increased activation in the mid-cingulate cortex (MCC) during the learning task. In addition, Fujiwara et al. investigated the effect of a form of martial arts, "Kendo," on the motivation network during attention processing. They found that Kendo players (KPs) exhibited a lower FC between the nucleus accumbens and frontal eye field (FEF) within the motivation network and a higher FC between intraparietal sulcus (IPS) and precentral gyrus (PCG) within the motivation network than non-KPs. Song et al. reviewed the underlying psychological and neural mechanisms that may underlie positive illusions and proposed that increasing positive illusions may be a promising way to improve relationships. Lastly, Zhu et al. used real-time fMRI neurofeedback (rtfMRI-NF) to investigate the capacity to self-regulate hippocampal activity. They found that hippocampal activity and amygdala–hippocampus connectivity can be regulated using rtfMRI-NF.

Finally, Takeuchi et al. investigated the effects of family socioeconomic status (SES) on brain structure. They partly replicated previously observed main effects of family SES on regional gray matter volume and fractional anisotropy. They also observed a significant interaction between sex and family SES in white matter tracts between areas such as the thalamus, corpus callosum, ACC and lateral PFC. The precise pathways by which these effects may manifest are open to debate.

In summary, the articles presented in this Research Topic provide a valuable insight into understanding the biological bases of positive human functioning and flourishing, and highlight new and exciting directions for the field of positive neuroscience.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

ACKNOWLEDGMENTS

We thanks all the authors for their contributions to this special issue.

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Conflict of 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.

frontiers
in Human Neuroscience

MINI REVIEW
published: 11 January 2019
doi: 10.3389/fnhum.2018.00526

Improving Relationships by Elevating Positive Illusion and the Underlying Psychological and Neural Mechanisms

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Romantic relationships are difficult to maintain novel and exciting for long periods of time, and individuals in love are known to engage in a variety of efforts to protect and maintain their romantic relationship. How to protect and maintain these relationships more effectively has, however, plagued people, psychologists, and therapists. Intimate partners typically perceive their relationship and their partners in a positive light or bias, a phenomenon called positive illusion. Interestingly, higher levels of positive illusion between partners have been associated with a decreased risk for relationship dissolution, as well as higher satisfaction, and less conflict or doubt in relationships. These findings indicate that elevating positive illusion amongst romantic partners may be of benefit and improve romantic relationships. In the present article, we discuss solving the paradox of positive illusion. As positive illusion may have relationship-enhancing attributes, we discuss the psychological and neural mechanisms that may underlie positive illusion. By elucidating the mechanisms underlying positive illusion, we shine a spotlight on potential future directions for research that aims to improve positive illusion and thus enhance the satisfaction and longevity of romantic relationships.

Keywords: positive illusion, romantic love, relationships, commitment, relationship satisfaction

OPEN ACCESS

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Received: *05 August 2018*
Accepted: *12 December 2018*
Published: *11 January 2019*

Citation:
Song H, Zhang Y, Zuo L, Chen X, Cao G, d'Oleire Uquillas F and Zhang X (2019) Improving Relationships by Elevating Positive Illusion and the Underlying Psychological and Neural Mechanisms.
Front. Hum. Neurosci. 12:526.
doi: 10.3389/fnhum.2018.00526

INTRODUCTION

As one of the most captivating affective states, romantic love has edified some of the loftiest achievements of mankind throughout the ages (Bartels and Zeki, 2000). Early research on love and relationships focused primarily on the description, interpretation, and development of romantic relationships (Le et al., 2010). In the past 20 years, research has gradually shifted towards studying the stability of these romantic relationships.

Will love fade as time goes by? In the initial stage of love, the loving partners indubitably hope to spend the rest of their lives together. However, studies suggest that love may not last forever (Fisher et al., 2016; Zou et al., 2016). For example, scores from lovers on the Passionate Love Scale have been found to decrease over time (Hatfield et al., 2008; McNulty et al., 2017). While many experience gradual decreases in their perception of romantic love towards their partners, it may not all be doom and gloom for everybody. For example, a study conducted by Acevedo et al. (2012) revealed that individuals in long-term relationships (marriages lasting an average of 21.4 years) showed similar brain activation patterns while viewing facial images of their partners as individuals reporting to have recently fallen in love (length of time in love about 3–18 months). This begs the question of what factors influence the maintenance of romantic relationships. Le et al. (2010) believe that a construct called "positive illusion" is the best predictor for the maintenance of subjective feelings of romantic love (Cohen's d: -0.991), in comparison to other relationship-related variables such as commitment, love, and satisfaction. This finding highlights that cognitive processing and biases play a significant role in stay-leave decisions regarding romantic relationships (Le et al., 2010), and offer a potentially promising avenue for the study and intervention of romantic relationship maintenance.

In recent years, researchers have posited that a positive illusion about their partner may be closely related to relationship satisfaction and relationship persistence (Miller et al., 2006; Barelds and Dijkstra, 2011; Abbasi, 2017; Ogolsky et al., 2017). Positive illusion is usually defined as a tendency to perceive one's own relationship as having higher positive characteristics and lesser negative characteristics than other people's relationships (Murray et al., 1996a), or a tendency to view one's own romantic partner more favorably than their partner views themself (Neff and Karney, 2002). Additionally, a higher positive illusion level during the initial stages of a relationship may predict a subsequent slower decline in relationship satisfaction over time, as well as a greater likelihood of relationship persistence (Murray and Holmes, 1997; Murray et al., 2011; Finkel et al., 2013; Dijkstra et al., 2014). While previous studies suggest that an elevated positive illusion regarding their partner might benefit and improve the length of romantic relationships, researchers have yet to discover ways of enhancing this predictive marker of romantic love. In the present article, we discuss solving the paradox of positive illusion that may have a relationship-enhancing function. Furthermore, we discuss the potential psychological and neural mechanisms behind positive illusion. Based on the discussion regarding the potential mechanisms that may underlie positive illusion, we assert several potential directions for future research on this topic, specifically, how to improve positive illusion in romantic relationships.

SOLVING THE PARADOX OF POSITIVE ILLUSION

Social psychology researchers have studied positive illusion in relationships for decades now, and have debated whether positive illusion is a key feature that defines the well-being of an enduring relationship, as well as whether a lack thereof can leave people vulnerable toward disillusionment and regretful decision-making (Fletcher, 2015; Abbasi, 2017). While some argue that positive illusion is crucial for dating and marital relationship satisfaction (Martz et al., 1998), others view positive illusion as an unpropitious mental disorder akin to addiction (Brickman et al., 1987). However, there is significant evidence supporting the former view. For example, individuals with higher positive illusions of their relationship enjoy higher relationship satisfaction, less conflicts and doubts, and decreased risk for relationship discontinuation (Barelds and Dijkstra, 2009, 2011; Le et al., 2010; Abbasi, 2017). From an evolutionary perspective, romantic love is often seen as a commitment mechanism that promotes the nurture of offspring by encouraging couples to engage in a substantial investment (Fletcher et al., 2015). The ultimate realization of long-term love commitments requires a leap of faith that manifests as positive illusion to quell doubt and produce a sense of security (Murray and Holmes, 1997). However, the Darwinian perspective suggests that mate-selection criteria for any species has evolved based on natural and sexual selection (Darwin, 1888). According to this view, human mate-selection must rest on reasonably accurate judgments about physical attractiveness, and the status of potential partners (Fletcher, 2015). Thus, these differing arguments produce a paradox in that individuals commit to long-term relationships based on both objective and subjective judgments.

To attempt to reconcile this paradox, researchers have conducted a series of experiments. Rusbult et al. (2000) for example, decreased, to some extent, individuals' positive illusion about their partner by manipulating the experimental instructions by which participants were required to describe their own relationship as honestly and accurately as possible. Although in the accurate instructions condition, positive illusion was slightly reduced rather than completely eliminated, this was the first attempt to separate illusion from reality, and the first tentative solution to the evolutionary paradox. Positive illusion, thus, does not seem to be more blind than prescient (Murray et al., 1996b), and Gagné and Lydon (2004) believe that one can be both biased (holding positive illusions) and accurate at the same time, as accuracy and positive illusion may coexist in people's evaluations of their relationships. Positive illusion can provide a constant sense of security, regulate feelings regarding a relationship, and help maintain faith that a relationship is worth pursuing (Murray and Holmes, 1999). On the other hand, accuracy helps avoid future disillusionment and regretful decision making (Gagné and Lydon, 2004; Fletcher, 2015).

Overall, positive illusion motivates individuals to perceive their partners or relationships in a realistic positive light. It influences individuals to interpret the shortcomings of their partner in a kind and generous manner rather than to directly ignore those shortcomings. Importantly, people with positive illusion do not tend to attribute false desirable characteristics to their partners (Luo et al., 2010). In summary, as time goes by, positive illusion is associated with greater relationship satisfaction, care, trust, and lasting intimacy—hallmarks of healthy relationships.

RELATIONSHIP-ENHANCING FUNCTION OF POSITIVE ILLUSION

Relationships are not all smooth-sailing, and we are often confronted by a variety of unavoidable issues that constantly challenge the stability of our relationships. Sometimes we overcome these issues with an optimistic mentality; while at other times we confront such challenges in a negative manner. Compared with a pessimistic mentality, optimism is more likely to yield beneficial results (Miller and Turnbull, 1986). As a defined pattern of optimistic belief, how does positive illusion help confront threats to relationships and address challenges?

Positive illusion can help with facing inevitable threats to relationships. Most relationships are inevitably threatened by conflicts of interest or seductive alternatives, and solving such problems often requires a departure from one's own direct interests. For example, when a partner behaves badly, accommodation rather than revenge are more conducive to the stability of the relationship (Rusbult et al., 1991; Van Lange et al., 1997). Further, when partners' preferences are inconsistent, it is beneficial to sacrifice one's own interests for the partner's interests. Overall, positive belief systems motivate us to find available solutions to dilemmas found across relationships (Murray et al., 1996a). Such systems promote persistence, by increasing pro-social motivation, and facilitating a willingness to investment oneself in a relationship (Miller et al., 2006; Le et al., 2010). Thus, it is plausible that positive illusion may serve to enhance the health of relationships.

Positive illusion may also help sustain faith in relationships when there is uncertainty or doubt. Even the most idyllic relationships suffer from difficult periods that evoke feelings of discontent or suspicion. It is believed, however, that positive illusion may reduce suspicion or uncertainty from potentially confounding information (Niehuis et al., 2011).

Positive illusion may also maintain a relationship by improving self-esteem, and has been shown to be associated with self-fulfillment. For example, the idealization between partners can promote self-fulfillment that immunizes intimates against the detrimental effects of early suspicion and conflict, thereby enhancing later satisfaction (Murray et al., 1996b; Fletcher, 2015; Erol and Orth, 2016). From this perspective, individuals that hold positive beliefs about their relationship will often feel greater satisfaction about themselves, and this has been shown to make it more likely for their relationship to persist (Boyes and Fletcher, 2007; Barelds and Dijkstra, 2009; Erol and Orth, 2014).

In summary, positive illusion has a relationship-enhancing function that can buffer conflicts and doubts, enhance the maintenance of relationships, increase the level of relationship satisfaction through the application of coping mechanisms to inevitable challenges, and foster an improvement in a partner's self-esteem.

PSYCHOLOGICAL MECHANISMS OF POSITIVE ILLUSION

In previous sections, we discussed the relationship-enhancing function of positive illusion. For such an important phenomenon, we will next discuss how it may be generated and maintained from the perspective of psychological mechanisms.

As to the generation of positive illusion, previous studies have raised two points of view: (1) Murray et al. (1996a) suggested that in close relationships, people may project their own virtues and their ideal partners' virtues onto their current partners; and (2) Commitment is a motivator of positive illusion. When individuals invest a higher level of commitment in their relationship, they also take a more favorable view towards their relationship (Gagné and Lydon, 2004). Although some empirical studies partially support these views, many questions remain unclear. With regard to the first view, researchers have used cross-sectional data to study the causal link among individuals' self-images, ideals, and the impressions of their partners (Murray et al., 1996a), and their results suggested that the impressions of their partners were a mirror of individuals' self-images and ideals. However, the characteristics of a current partner may confound that individual's criteria of their ideal partner, and thus, measuring the development of positive illusion via cross-sectional data is quite limited and requires further longitudinal research. With regard to the second view, Rusbult et al. (2000) used threatening instructions to manipulate the level of commitment, in an attempt to study the motivator of positive illusion. Their results suggested that manipulating commitment leads to only a partial change rather than a complete elimination of positive illusion. This result, thus, did not provide direct evidence in support of a causal link between commitment and positive illusion. An association between commitment and positive illusion might fit into a model of cyclical growth in which variables represented as "later effects" feed back into and influence "earlier causes." Therefore, the researchers ultimately did not seem to agree on how positive illusion arises, and this requires additional studies to further clarify their results.

Why does positive illusion persist, even in the face of conflicting information? Compared to the development of positive illusion, the maintenance of positive illusion is even more essential. Indeed, some individuals' positive perceptions about their partners do not disappear, but instead, become more prominent as time goes by Miller et al. (2006). Researchers have suggested that social comparison includes dimensional comparison (selectively focusing on advantaged dimensions of one's own relationship), downward comparison (comparing others' relationships that are worse off), avoidance of comparison (ignoring information that is detrimental to one's own relationship), and the manipulation of surrounding dimensions (selectively focusing on information that derogate others' relationship), all crucial for developing and maintaining positive illusion (Wood and Taylor, 1991). Furthermore, Murray et al. (1996a) believed that self-images play an important role in structuring the images of others, and found that more positive self-images contribute to the maintenance of positive perceptions of partners. Although the above-mentioned studies have tried to assess how positive illusion is maintained, thus far, there is still no empirical research that has been able to study the mechanisms that underlie the maintenance of positive illusion.

NEURAL MECHANISM OF POSITIVE ILLUSION

With the advent of magnetic resonance imaging (MRI) technology, researchers have become increasingly interested in investigating the underlying neural mechanisms of positive illusion. Recent functional MRI (fMRI) research has revealed the following brain regions as being associated with positive illusion (see **Figure 1**): (a) the caudate nucleus; (b) the dorsal anterior cingulate cortex (dACC); (c) the ventral anterior cingulate cortex (vACC); (d) the orbitofrontal cortex (OFC); (e) the ventrolateral prefrontal cortical regions (vLPFC); and (f) the dorsal medial prefrontal cortex (dMPFC; Meyer et al., 2011; Hughes and Beer, 2012). Interestingly, these areas play important roles in the processing of reward (the caudate nucleus; Aron et al., 2005), subjective valuation (OFC; De Martino et al., 2006; Fellows, 2007), conflict detection (dACC; Botvinick et al., 2004; Kawamoto et al., 2012), and emotional control (vACC, vLPFC, and dMPFC; Meyer et al., 2011).

The caudate nucleus is a dopaminergic brain area associated with goal-directed motivation and reward, and is usually considered as one of the neurobiological correlates of romantic love (Aron et al., 2005). Activity found here has been associated with the perception of a romantic partner (i.e., this region activates upon looking at a photograph of a romantic partner) as compared with familiar friends (Bartels and Zeki, 2000; Aron et al., 2005; Xu et al., 2011). Importantly, the caudate nucleus is connected to the ventral tegmental area (VTA) and nucleus accumbens (NAC) by dopaminergic neurons, and is associated with the processing of love-related reward signals that drive individuals to approach a romantic love target (Lauwereyns, 2006). It is believed that the activation of the caudate nucleus lends salience to the positive characteristics of a romantic partner over negative characteristics or other social comparisons (Hughes and Beer, 2012).

The dACC has been associated with error detection, monitoring of conflict, and social exclusion (Botvinick et al., 2004; Kawamoto et al., 2012). Participants in experiments display significantly elevated activation of the dACC when experiencing negative social evaluation and social exclusion (Eisenberger et al., 2011; Kross et al., 2011). Therefore, a reduction of dACC activation in response to partner-related negative information may represent an adaptive response to a partner's imperfections.

The vACC has been shown to play a key role in emotion conflict regulation and emotion control (Etkin et al., 2011). Increased activation of the vACC could enhance the differentiation of desirable social characteristics between intimate and non-intimate individuals (Hughes and Beer, 2012).

The OFC has been associated with the encoding of subjective value and the weighing of information (positive or negative) in decision-making (De Martino et al., 2006; Fellows, 2007). Social perception of ordinary individuals (i.e., the average peer), represents the integration of both desirable and undesirable information about an evaluation target. In social comparisons, the positive information about a potential partner becomes available and is integrated into the target personality characteristics of a partner (Kunda, 1990; Rusbult et al., 2000). In theory, the OFC may modulate priority integration of positive

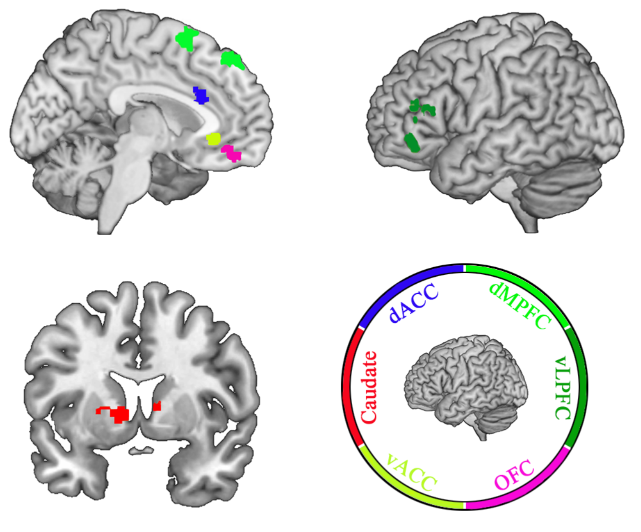

FIGURE 1 | Brain areas related to positive illusion. This image is an original schematic diagram, and the brain areas referred to previous studies (Meyer et al., 2011; Hughes and Beer, 2012). Definitions: dACC, dorsal anterior cingulate cortex; dMPFC, dorsal medial prefrontal cortex; vLPFC, ventrolateral prefrontal cortical regions; OFC, the orbitofrontal cortex; vACC, ventral anterior cingulate cortex.

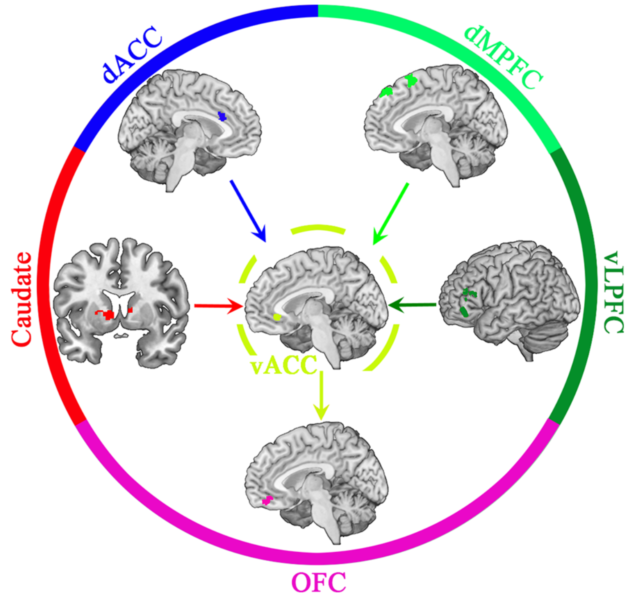

FIGURE 2 | Theoretical schematic diagram of signal processing during generation of positive illusions.

information (Hughes and Beer, 2012). The vLPFC and dMPFC are part of a brain network responsible for deliberate emotion regulation (i.e., top-down control of emotional responses; Ochsner et al., 2009). The activation of the vLPFC and dMPFC may benefit the suppression of affective responses that help attract or derogate alternatives (Meyer et al., 2011).

Importantly, these brain areas do not function independently, but rather interact with one other, a mechanism suggested by functional connectivity among these areas (i.e., synchronous activation between these distal brain regions; Cohen et al., 2005; Turner et al., 2006; Greicius et al., 2007; Zald et al., 2012; Song et al., 2015). Taken into context, the comparison between partners and non-close others may be facilitated and made more prominent by the processing of a partner's positive characteristics by the caudate nucleus, while the dACC suppresses the perception of a partner's negative features. At the same time, the vLPFC and dMPFC could be reducing the salience of attractive alternatives. Subsequently, these brain areas transmit signals to the vACC that may help differentiate information from potential partners over non-close others. Finally, as information is passed onto the OFC, the weighing of positive and negative information of a partner is redistributed, cementing biased subjective values (e.g., positive illusion) about the partner (see **Figure 2**).

SUMMARY AND FUTURE DIRECTIONS

In this article, we discussed solving the paradox of positive illusion. We then reviewed how positive illusion can enhance relationship satisfaction, and longevity. Lastly, we discussed the psychological and neural mechanisms that may underlie positive illusion. While these discussions have deepened our understanding of positive illusion, some questions still remain unresolved.

First, although previous studies have discussed the development of positive illusion, researchers have yet not reached a consensus on this process. As previous studies were unable to provide direct causal evidence, future studies using longitudinal data and strict laboratory experimental manipulations are in need to help elucidate this process.

Second, a better understanding of how individuals maintain positive illusions about their partners when confronted with information inconsistent with previous impressions is essential, as it may help explain the apparent contradiction between reinforcement and environmental fitness (e.g., the evolutionary paradox). Furthermore, this avenue of research may help design interventions that improve positive illusion, as well as help inform future experiment designs that simulate the maintenance of positive illusion and thus reveal potential mechanisms underlying positive illusion maintenance.

Third, while preliminary studies on the neural mechanisms of positive illusion indicate brain activation patterns associated with positive illusion toward romantic partners, studies have yet to explore the neural mechanisms associated with the generation and maintenance of positive illusion. In particular, fMRI experiments investigating how individuals maintain positive illusions of their partner when confronted with information that is inconsistent with previous impressions, remain to be performed. Even further, based on previous knowledge on associated brain areas and networks involved in positive illusion, future research may wish to use non-invasive neural intervention techniques, such as transcranial direct current stimulation (tDCS) or transcranial magnetic stimulation (TMS), to intervene in the generation and maintenance of positive perceptions amongst romantic partners. These techniques manipulate signal processing and brain mechanisms, and are thus elegant ways of investigating causal associations regarding positive illusion and other factors of relationships such as relationship satisfaction, commitment, and conflict resolution.

AUTHOR CONTRIBUTIONS

HS and XZ conceived and wrote the frame design. HS wrote the manuscript. HS, XZ, YZ, LZ, FU, XC and GC revised the manuscript, and all authors contributed to the final version.

FUNDING

This work was supported by grants from The National Key Basic Research Program (2016YFA0400900 and 2018YFC0831101), The National Natural Science Foundation of China (31471071, 31771221, 61773360, and 71874170), The Fundamental Research Funds for the Central Universities of China.

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Conflict of Interest Statement: 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.

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in Human Neuroscience

ORIGINAL RESEARCH
published: 14 January 2019
doi: 10.3389/fnhum.2018.00540

The Positive Brain – Resting State Functional Connectivity in Highly Vital and Flourishing Individuals

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The World Health Organization has defined health as "complete physical, mental and social well-being and not merely the absence of disease or infirmity" (World Health Organization, 1948). An increasing number of studies have therefore started to investigate "the good life." However, the underlying variation in brain activity has rarely been examined. The goal of this study was to assess differences in resting state functional connectivity (RSFC) between regular healthy individuals and healthy individuals with a high occurrence of flourishing and subjective vitality. Together, flourishing, a broad measure of psycho-social functioning and subjective vitality, an organismic marker of subjective well-being comprise the phenomenological opposite of a major depressive disorder. Out of a group of 43 participants, 20 high-flourishing (highFl) and 18 high-vital (highSV) individuals underwent a 7-min resting state period, where cortical activity in posterior brain areas was assessed using functional near-infrared spectroscopy (fNIRS). Network-based statistics (NBS) of FC yielded significantly different FC patterns for the highFl and highSV individuals compared to their healthy comparison group. The networks converged at areas of the posterior default mode network and differed in hub nodes in the left middle temporal/fusiform gyrus (flourishing) and the left primary/secondary somatosensory cortex (subjective vitality). The attained networks are discussed with regard to recent neuroscientific findings for other well-being measures and potential mechanisms of action based on social information processing and body-related self-perception.

Keywords: flourishing, subjective vitality, functional near-infrared spectroscopy (fNIRS), network-based statistics (NBS), default mode network (DMN), resting state functional connectivity (RSFC)

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Received: *30 September 2018*
Accepted: *27 December 2018*
Published: *14 January 2019*

Citation:
Goldbeck F, Haipt A, Rosenbaum D, Rohe T, Fallgatter AJ, Hautzinger M and Ehlis A-C (2019) The Positive Brain – Resting State Functional Connectivity in Highly Vital and Flourishing Individuals. Front. Hum. Neurosci. 12:540. doi: 10.3389/fnhum.2018.00540

Abbreviations: Ang, angular gyrus; DMN, default mode network; FC, functional connectivity; Fl, flourishing; fNIRS, functional near-infrared spectroscopy; FusG, fusiform gyrus; highFl, high-flourishing; highSV, high-vital; IPL/AG, inferior parietal lobe/angular gyrus; MPFC, medial prefrontal cortex; MTC, medial temporal lobe; MTG, middle temporal gyrus; NBS, network-based statistics; OTP, open-thought protocol; PCC/Rsp, posterior cingulate/retrosplenial cortex; PSC, primary somatosensory cortex; regFl, regular-flourishing; regSV, regular-vital; RRS, ruminative response scale; RSFC, resting state functional connectivity; SAC, somatosensory association cortex; SC, subcentral area/secondary somatosensory cortex; SuG, supramarginal gyrus; SV, subjective vitality; V3, visual area; VAS, visual analog scale.

INTRODUCTION

We know a lot more about the things that can go wrong in life than about the good life (Seligman and Csikszentmihalyi, 2000). For the field of human neuroscience, despite major contributions over the last years (Burgdorf and Panksepp, 2006; Van Reekum et al., 2007; Heller et al., 2009, 2013; Kringelbach and Berridge, 2009; Berridge and Kringelbach, 2015; Kong et al., 2015a,b,c, 2016; Sato et al., 2015; Greene and Seligman, 2016), this is still true. As in the case of psychological disorders, the good life consists of and is being measured in multiple aspects (Ryan and Deci, 2001; Peterson et al., 2005). Two widely used concepts, whose neurophysiological signatures are still unknown, are the constructs of flourishing (Keyes, 2002; Diener et al., 2010; Seligman, 2012) and subjective vitality (Ryan and Frederick, 1997). The term flourishing (Fl) has been used to describe a broad array of distinct dimensions of positive psycho-social functioning (Keyes, 2002; Fredrickson and Losada, 2005; Diener et al., 2010; Seligman, 2012; VanderWeele, 2017) whereas subjective vitality (SV) was introduced as a narrow construct to measure a person's perception of energy, available for mental and physical action (Ryan and Deci, 2008). In combination, the two concepts mirror the positive opposites of the main non-somatic criteria present in a major depressive episode (Huppert and So, 2013): Feeling competent and engaged, perceiving life as meaningful and being optimistic, experiencing positive emotions, having satisfying relationships and feeling alive and energetic. A healthy person who scores high on these dimensions compared to a healthy person with low scores shows fewer missed days of work, a lower risk for cardiovascular and chronical physical disease and fewer health limitations in daily life activities with age (Pressman and Cohen, 2005; Keyes, 2007). However, despite these findings concerning health and daily life behavior, the differences in human brain activity underlying different levels of Fl and SV have only scarcely been examined. This paper aims at contributing to fill this gap by looking at the neural correlates of flourishing and SV in the brain at rest. We did so via the comparison of highFl and highSV individuals with a group of healthy but regular-flourishing/regular-vital (regFl/regSV) subjects. Flourishing and SV were measured using validated self-report measures (Ryan and Frederick, 1997; Diener et al., 2010). Median split groups were derived for the purpose of group comparison. Both measures, Fl and SV, contain aspects of the "good life" and will be referred to as concepts belonging to the broader area of well-being measures.

Psychological disorders have been studied extensively from a neuroscientific perspective. Hence, we used associated methods and corresponding theories as a starting point for the design and hypotheses in this project. In depression research, recently much attention has been given to changes in RSFC (Wang et al., 2012; Mulders et al., 2015), changes in the temporal correlations of spontaneous brain activity in spatially remote areas in the resting brain (Friston et al., 1993). Some first studies in the field of well-being research also found significant changes in FC associated with happiness (Luo et al., 2015), eudaimonic and hedonic well-being (Luo et al., 2017). The majority of changes thereby occurred in areas of the DMN (Greicius et al., 2003). The DMN anatomically consists of precuneus, adjacent PCC/Rsp, the MPFC, the IPL/AG and the MTC (Horn et al., 2014) as well as parts of the lateral temporal and lateral frontal cortex (Yeo et al., 2011). It is assumed to play a major role in self-referential thought processes (Buckner et al., 2008; Davey et al., 2016). Hence, these processes, in particular rumination, a reoccurring, rather abstract style of thinking about the past or shortcomings of the self, have been highlighted as a potential mechanism for the aberrant FC patterns within the DMN in depression (Rosenbaum et al., 2017). In their study on happiness Luo et al. (2015) found higher resting state FC in the anterior and posterior DMN correlated with an inclination to ruminate and unhappiness. However, in a more recent study, the authors found increased as well as decreased DMN FC, depending on which measure of well-being was applied (Luo et al., 2017). Matching heterogeneity regarding increased and decreased DMN-activity has also been found in the literature on depression (Wang et al., 2012; Mulders et al., 2015; Rosenbaum et al., 2017). Based on these findings of DMN FC variations at rest, we decided to apply a resting state paradigm and measure cortical FC at temporal/parietal areas of the brain with the help of functional near-infrared spectroscopy (fNIRS). As part of an on-going project to study positive human neuroscience in more naturalistic contexts, we used fNIRS because the method combines relatively high temporal resolution, mobile application, insensitivity to movement artifacts, low costs and easy assessment (Ehlis et al., 2014). NBS were used to detect significant network differences in FC between the groups. As the tendency to ruminate has shown to be relevant for differences in DMN FC, we included a trait and state measure to account for this. Furthermore, to also cover mental activity at the other side of the spectrum, we assessed the feeling of free flowing thoughts (mind-wandering) during the measurement. Mind-wandering in this sense, has been proposed as opposite mental state to rumination (Rosenbaum et al., 2017). To control for general subjective experiences during the measurement, participants filled out an OTP afterward which consisted of a blank page to freely report all personal subjective experiences occurring during the measurement. To place findings within the broader context of clinical research we included a measure of depressive symptomatology The overall goal of this study was to explore FC correlates of trait-like group differences in flourishing and SV with a focus on DMN activity and the mental processes of mind-wandering and rumination as potential explanatory variables.

MATERIALS AND METHODS

Participants

Subjects were recruited using posters, flyers and the staff email distributor list of the University Hospital Tübingen. Among average healthy people the recruitment information explicitly asked for participants who felt a lot of energy or a high degree of well-being in their daily life. Additionally, data from 12 healthy subjects, who were part of the control group of a clinical intervention trial (NCT02375308) on depression with a similar experimental procedure, were used in this study. This study was carried out in accordance with the recommendations of 'Ethical guidelines, Ethics Committee at the University Hospital and University of Tübingen' with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the 'Ethics Committee at the University Hospital and University of Tübingen.' Only healthy subjects without acute or chronical coronary heart disease (e.g., hypertonia), diabetes or a diagnosed psychological or neurological disorder were included. Using an online questionnaire, 62 individuals were prescreened with regard to the exclusion criteria and their level of Fl and SV. Forty-three attended the laboratory session and provided data for the following analysis. Initially we planned on using "agreed" or "strongly agreed" on all items of one or both scales ($\geq$48 for flourishing, $\geq$36 for SV) as classification criteria for "high" in the respective outcome (Hone et al., 2014). However, over the recruiting process it proved more difficult to find participants meeting this criterion for SV compared to flourishing ($n_{\mathrm{SV}} = 18$ vs. $n_{\mathrm{Fl}} = 28$). To keep group sizes equal and since we were interested in exploring extreme group effects without hypothesis on the effect of a clear cut-off value we used a median split approach (Farrington and Loeber, 2000) and assigned individuals with a score above the median ($m_{\mathrm{fl}} > 48$; $m_{\mathrm{sv}} > 35$) to the respective "high" group. 25 individuals were grouped as regSV and 18 as highSV, 23 as regFl and 20 as highFl. Twelve of the highSV subjects (i.e., 66%) also belonged to the highFl group. The group characteristics are displayed in **Table 1**. In the overall sample, 14% of the participants held a middle school degree, 83.7% a high-school diploma (German Abitur) and 2.3% a university degree. 69.8% were currently enrolled as students, 27.9% indicated to work full-time. 65% of the participants were female. Both high score subgroups did not differ from their low score counterparts with regard to age (for SV $t_{41} = 0.99$, $p > 0.1$; for Fl $t_{41} = 0.95$, $p > 0.1$), sex ratio (for SV $\chi^2{}_1 = 0.22$, $p > 0.1$; for Fl $\chi^2{}_1 = 0$, $p > 0.1$) and level of education (for SV $\chi^2{}_2 = 0.99$, $p > 0.1$; for Fl $\chi^2{}_2 = 0.91$ $p > 0.1$).

fNIRS

Hemodynamic changes were measured via fNIRS, an optical imaging method using light in the near-infrared spectrum to measure concentration changes of oxygenated and deoxygenated hemoglobin. The penetration depth and therefore spatial measurement depth of fNIRS is approximately 2–3 cm (Haeussinger et al., 2014). Importantly, fNIRS has been shown to be a useful and reliable device to measure FC (Lu et al., 2010; Mesquita et al., 2010; Zhang et al., 2010; Deppermann et al., 2016; Rosenbaum et al., 2016). We used a continuous wave, multichannel NIRS system (ETG-4000 Optical Topography System; Hitachi Medical Co., Japan) with a temporal resolution of 10 Hz. The distance between channels was 3 cm. To measure parts of the DMN, we placed the probe set in the form of a rectangle over parietal areas covering the precuneus (Horn et al., 2014) with reference points Pz (Channel 16), T3 (Channel 43) and T4 (Channel 52), according to the 10-20 system (Jasper, 1958). The system consisted of 52 channels (**Supplementary Figure 1**). Channel positions with regard to Brodmann areas were located using a neuro-navigation system on a volunteer's head (**Figure 1**).

Procedure

The resting state measurement was part of a larger study (NCT02375308) on the cortical correlates of depression and well-being. Results regarding the depressive subsample are reported elsewhere (Rosenbaum et al., 2017). For the purpose of this study, data was assessed during a 7-min resting phase in which participants were asked to sit still with eyes closed, think of nothing in particular and let their thoughts flow. Since the participants had to complete other tasks as part of the overall study and RSFC has shown to be measurable reliably in short periods of time (Sakakibara et al., 2016; Zhao et al., 2016) we chose a 7-min resting-state

TABLE 1 | Sample and subgroup characteristics.

	Normal-vital		**High-vital**			**Normal-flourishing**		**High-flourishing**		
	Mean	**SD**	**Mean**	**SD**	t/χ^2	**Mean**	**SD**	**Mean**	**SD**	t/χ^2
Scale	31.61	2.83	38.67	2.25		44.96	3.18	51.85	2.08	
Age (years)	27.5	6.55	30.72	12.46	$t_{(41)} = 0.99$ $p > 0.1$	31.00	11.36	27.96	9.56	$t_{(41)} = 0.95$ $p > 0.1$
Sex (f/m)	61.1%		68%		$\chi^2{}_{(1)} = 0.22$ $p > 0.1$	65%		65.2%		
N_{subgroup}	25		18			23		20		
N_{highFl}	8		12		N_{highSV}	6		12		
N_{normFl}	17		6		N_{normSV}	17		8		

Overall sample (n = 43)	**Mean**	**SD**	**Range**	**Kurtosis**	**Skewness**	**Cronbach α**	**Retest**
Flourishing Scale	48.16	4.402	38–56	−0.407	−0.402	0.782	$r_{(35)} = 0.84$
Subjective Vitality Scale	34.58	4.349	25–42	−0.487	−0.128	0.785	$r_{(36)} = 0.87$

Subgroups were derived using a median split (>48 for high-flourishing, >35 for high-vital subjects). Participants with median value were assigned to the lower subgroup to balance group size.

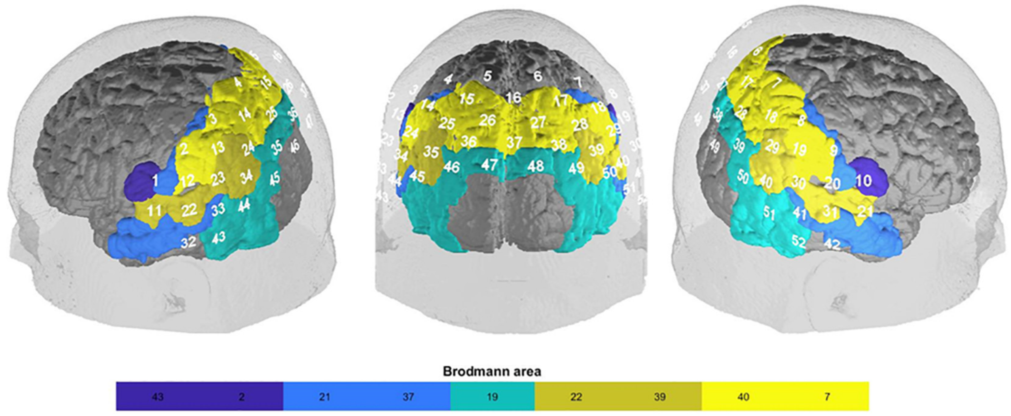

FIGURE 1 | fNIRS-channel brain mapping (Brodmann area) based on a neuro-navigational measurement in an exemplary volunteer: somatosensory association cortex (BA 7; SAC; channel 4, 5, 6, 7, 15, 16, 17, 25, 26, 27, 28, 35, 36, 37), supramarginal gyrus (BA 40; SupG; channel 2, 3, 8, 9, 12, 13, 18, 19, 23, 30), angular gyrus (part of Wernicke's area; BA 39; AngG; channel 14,24, 29, 34, 39, 40, 45, 50), superior temporal gyrus (BA 22; STG; channel 11, 21, 22, 31, 33, 41), visual area 3 (BA 19; V3; channel 38, 46, 47, 48, 49), fusiform gyrus (BA37; FusG; channel 43, 44, 51, 52), middle temporal gyrus (BA 21; MTG; channel 32, 42), primary somatosensory cortex (BA 2; PSC; channel 1, 20), subcentral area (BA43; SC; channel 10, 11).

measurement as a trade-off between data quality and economic demands.

Mind-Activity Measures

To assess thought processes and experiences during the measurement, directly after completion the subjects reported what they had done and experienced during measurement using (1) visual analog scales (VAS) and (2) a blank page for a written OTP (Rosenbaum et al., 2017). For the VAS, subjects were asked to approximately rate on a scale from 0 to 100% how much time they had spent on ten different activities (Rosenbaum et al., 2017). The scales of mind-wandering and rumination during the measurement were analyzed for this study. The free written OTP was screened and categorized by two independent raters to assess qualitative measures of the process during resting state according to qualitative methods: The forms were first analyzed and categories of experiential content were set and defined until saturation was reached. Second, the most common categories were used to categorize self-report forms by two independent raters. Also, the raters evaluated the emotional tone (positive, negative, mixed, neutral) and level of arousal (calm, aroused) of the thought protocol. For the final analysis, the ratings of the two independent raters for each OTP were discussed if deviating and integrated in a final single rating.

Trait Measures

Subjects were categorized based on their self-rating on scales of SV (Ryan and Frederick, 1997) and flourishing (Diener et al., 2010; Esch et al., 2012). Both scales where phrased to be answered with regard to life in general using a Likert scale format (strongly disagree – strongly agree). The SV scale consists of six items to assess a person's self-perceived level of energy (e.g., Item 1: "I feel alive and vital"; Item 3: "I have energy and spirit") and alertness (e.g., Item 5: "I nearly always feel alert and awake") in daily life. Diener et al. (2010) proposed eight items to determine a person's level of flourishing. The scale covers aspects of self-perceived meaning and purpose (Item 1: "I lead a purposeful and meaningful life"), engagement (Item 3: "I am engaged and interested in my daily activities"), competence (Item 5: "I am competent and capable in the activities that are important to me"), self-esteem (Item 6: "I am a good person and live a good life"), optimism (Item 7: "I am optimistic about my future") and quality in relationships (Items 2, 4, 8 e.g., "My social relationships are supportive and rewarding"). Trait rumination was assessed using the subscale rumination of the ruminative response scale (RRS; Nolen-Hoeksema and Morrow, 1991). To control for associations with depressive symptomatology we included the depression module of the Patient Health Questionnaire (PHQ-9; Kroenke et al., 2001).

Data Preprocessing

The data was processed and analyzed using MATLAB R2017b (MathWorks Inc., Natick, MA, United States, RRID:SCR_001622). After preprocessing, the MATLAB *NBS toolbox* (Zalesky et al., 2010; RRID:SCR_002454), *Wavelab850 toolbox*[1] and *BrainNetViewer toolbox*[2] (Xia et al., 2013; RRID:SCR_009446) were used for analyzing and plotting results. Furthermore, SPSS (Version 24; RRID:SCR_002865) was used for data analysis. fNIRS data preprocessing included: bandpass filtering (0.1–0.01 Hz, FC differences were expected in this spectrum) to minimize high- and low-frequency noise, movement artifact reduction by correlation-based signal improvement (Cui et al., 2010; Brigadoi et al., 2014), as well as component-based removal of bite artifacts (ICA). For the resting state subjects were instructed to keep their heads as still as possible and refrain from clenching their teeth. Afterward, all signals were visually inspected which revealed noisy channels after the described preprocessing in seven subjects. In these

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[1] http://statweb.stanford.edu/~wavelab/

[2] http://www.nitrc.org/projects/bnv

cases, channels were interpolated from surrounding channels. Three (one subject) or one channel (six subjects) had to be interpolated. Since FC can be significantly influenced by global signal changes, e.g., low frequency blood pressure oscillations (Mesquita et al., 2010), a global signal reduction was performed with a spatial Gaussian Kernel filter (Zhang et al., 2016) with a standard deviation of $\sigma = 50$. No short distance channels were used. After preprocessing, FC-coefficients were computed for each participant using pairwise correlation between all channel's signal time courses. The values were then transformed via Fishers r-to-z-transformation (Silver and Dunlap, 1987).

Network-Based Statistics (NBS)

Subsequent FC-differences between the flourishing and the SV subgroups were investigated with NBS (Zalesky et al., 2010). NBS is a statistical method that uses massive univariate testing of a contrast on connectivity matrices, and clusters connections that exceed a significance threshold using a breadth first search. The significance of the extracted cluster is then tested using permutation tests. The resulting p-values represent the likelihood to attain a cluster, similar or larger in the number of connected edges under the assumption of random group assignment of the individual scores in the sample at hand. Settings for NBS were set as follows: statistical threshold for massive univariate testing was set at $t = 3.1$, significance level for permutation tests $\alpha = 0.05$, permutations = 5000, component size = "extent." We estimated confidence intervals for the computed p-values of the permutation tests parametrically following Zalesky et al. (2010).

Analysis Procedure

The following analysis was performed on the data: After the computation of FC measures, NBS were used to identify network-differences in FC between the highFl (score > 48) and the regFl group as well as between the highSV (score > 35) and the regSV group. Group differences were calculated using independent t-tests and chi-squared tests for the VAS, trait rumination, the OTP and depressive symptomatology. Whenever stated, significance levels for these tests were adjusted for multiple comparisons using the Bonferroni correction method. Significant group differences in mind-wandering, rumination and depressive symptomatology were used as covariates in the NBS models to test their role as explanatory variables for differences in FC patterns. In case of a significant influence of the covariate on the NBS its influence was further explored via the examination of correlations between the covariate and the significant network connections. To further explore the relation between SV and flourishing, we calculated NBS for one variable using the other as covariate and calculated correlations between the covariate and the significant network connections of the hub nodes in each network. Eventually, hub nodes ($\geq$3 edges) of the significant networks were used as seed regions and the group comparisons in network connectivity strength were plotted. The fNIRS raw data as well as the respective code script and SPSS file are available under https://doi.org/10.17026/dans-zym-vewk.

RESULTS

Flourishing

The NBS yielded a single more strongly connected network for the highFl group, comprising 11 functional connections at threshold $t = 3.1$ ($p = 0.036 \pm 0.0053$). The derived network consisted of 10 nodes with 11 edges (**Table 2**). Nodes were classified as hub nodes if they had more than **three edges**. The network centered around two hub nodes in the left middle temporal (MTG) and the left FusG, spreading onto bilateral parietal areas of the DMN (**Figure 2A**), bilateral parts of the SAC and visual area (V3). The right angular (AnG) and SuG were part of the network in the right hemisphere. Further analysis revealed that flourishing correlated significantly positively with all except two connections in the network ($p < 0.1$). All correlations are displayed in **Table 3**. The differences in FC between regFl and highFl participants are displayed in **Figure 3** using the two hub nodes left MTG (A) and left FusG (B) as seed channels.

Subjective Vitality

In the comparison of the highSV and the regSV group, the NBS analysis yielded a significantly more strongly connected network for the highSV group comprising 10 functional connections at threshold $t = 3.1$ ($p = 0.046 \pm 0.0059$). The network consisted

TABLE 2 | Degrees of the significant network differences between high-flourishing and regular-flourishing subjects ($t = 3.1$) and high-and regular-vital subjects ($t = 3.1$).

Channel	Region	Flourishing (t = 3.1) Degree	Sub. Vitality (t = 3.1) Degree
1	PSC (left)		**3**
11	SC/STG (left)		**5**
12	SupG (left)		2
18	SupG (right)	1	
23	SupG (left)		1
24	AngG (left)		2
25	SAC (left)		2
28	SAC (right)	1	1
29	AngG (right)		1
32	MTG (left)	**6**	
35	SAC (left)		1
36	SAC (left)	1	1
39	AngG (right)	1	1
43	FusG (left)	**5**	
46	V3 (left)	2	
47	V3 (left)	1	
48	V3 (right)	2	
50	AngG (right)	2	
Nodes		10	11
Edges		11	10
p-value		0.036 ± 0.0053	p = 0.046 ± 0.0059

Only channels of the significant networks are presented. PSC, primary somatosensory cortex; SC, subcentral area/secondary somatosensory cortex; SupG, supramarginal gyrus; AnG, angular gyrus; SAC, somatosensory association cortex; MTG, middle temporal gyrus; FusG, fusiform gyrus; V3, visual area. Hub nodes marked in bold.

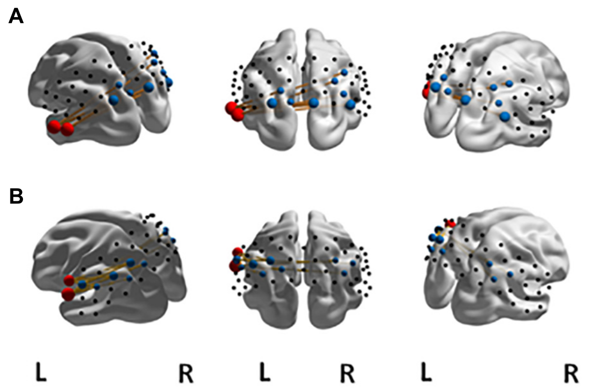

FIGURE 2 | Significant NBS network at $t = 3.1$ for FC in the **(A)** high-flourishing group compared to the regular-flourishing group with hub nodes (red) at left MTG and left FusG, other network nodes (blue) and edges (yellow). The significant NBS network at $t = 3.1$ for FC in the high-vital group compared to the regular-vital group with hub nodes (red) at left sub central area and left primary somatosensory cortex is displayed in **(B)**.

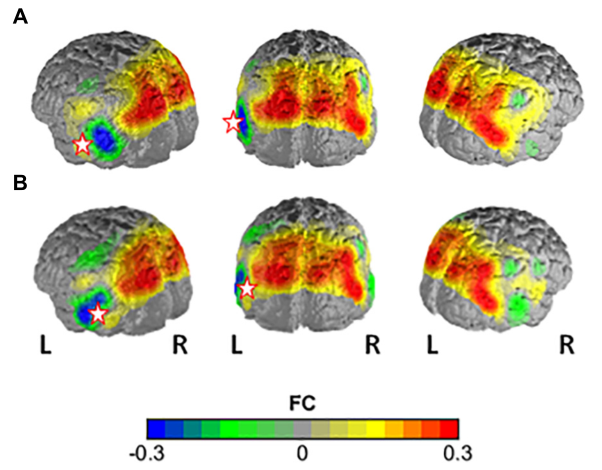

FIGURE 3 | Difference in FC between the high-flourishing and regular-flourishing group with **(A)** channel 32 (lMTG) and **(B)** channel 43 (lFusG) as seed regions. Warm colors indicate higher FC with seed in high-flourishers vs. low-flourishers.

of 11 nodes and 10 edges (**Table 2**). The major hub node was located in an overlapping area of the left subcentral area (SC) and superior temporal gyrus, connecting to nodes in the bilateral SAC and the bilateral AnG. The second most connected node within the PSC stretched to left SupG, left AnG and left SAC (**Figure 2B**). The network did not reach significance ($p < 0.05$) at any other threshold, however, different thresholds returned p-values close to the level of significance ($t = 2.8$, $p = 0.0721$, $t = 3.0$, $p = 0.0546$; $t = 3.2$, $p = 0.0618$; $t = 3.3$, $p = 0.0552$). In depth analysis revealed that SV correlated positively with all except one connection in the network ($p < 0.05$; **Table 4**). The differences in FC between regSV and highSV participants are displayed in **Figure 4** using the two hub nodes left PSC and left SC as seed channels.

Covariate Networks and the Relation Between Flourishing and Subjective Vitality

Subjective vitality was positively correlated with flourishing ($r = 0.63$, $p < 0.001$). When using SV as a covariate in the NBS procedure for flourishing, the significant network difference between the flourishing groups dissolved. However, in depth analysis of the correlations between SV and the network connections in the flourishing network yielded only one marginally significant correlation with the connection between lFusG and lAngG ($r = 0.26$, $p = 0.086$). All correlations are displayed in **Table 3**. Entering flourishing as a covariate into

TABLE 3 | *P*-Values of the significantly stronger connected network channels in the flourishing network and correlations with flourishing, subjective vitality, mind-wandering, trait rumination, and depression.

Hub nodes (seed)		$t = 3.1$	Flourishing		Subjective vitality		Mind-wandering		Trait rumination		Depression	
		***p*-value**	***r***	***p***	***r***	***p***	***r***	***p***	***r***	***p***	***r***	***p***
Flourishing network												
lMTG (Ch 32)	rSupG (Ch 18)	0.002	0.39*	0.01	0.13	0.387	0.30	0.05	−0.20	0.204	−0.31*	0.041
	lSAC (Ch 36)	0.001	0.26	0.095	0.21	0.172	0.29	0.058	−0.28	0.071	−0.36*	0.018
	lV3 (Ch 46)	0.001	0.26	0.096	0.16	0.303	0.35*	0.023	−0.33*	0.029	−0.20	0.203
	lV3 (Ch 47)	0.002	0.22	0.158	0.18	0.252	0.39*	0.009	−0.30	0.05	−0.27	0.077
	rV3 (Ch 48)	0.002	0.29	0.062	0.18	0.241	0.44*	0.003	−0.32*	0.036	−0.31*	0.04
	rAngG (Ch 50)	0.003	0.21	0.174	0.20	0.195	0.26	0.096	−0.26	0.089	−0.21	0.166
lFusG (Ch 43)	rSAC (Ch 28)	0.003	0.36*	0.018	0.17	0.284	0.22	0.146	−0.35*	0.021	−0.38*	0.012
	rAngG (Ch 39)	0.002	0.31*	0.04	0.12	0.451	0.19	0.231	−0.28	0.065	−0.34*	0.028
	lV3 (Ch 46)	0.002	0.29	0.06	0.17	0.278	0.30	0.051	−0.42*	0.005	−0.30*	0.047
	rV3 (Ch 48)	0.001	0.30	0.053	0.15	0.34	0.43*	0.004	−0.37*	0.014	−0.35*	0.021
	rAngG (Ch 50)	0.003	0.26	0.086	0.26	0.086	0.16	0.305	−0.33*	0.032	−0.27	0.074

*All variables were used as covariates in a follow-up NBS analysis of flourishing. *p < 0.05; the p-value corrected for multiple comparison was p < 0.0045.*

TABLE 4 | *P*-Values of the significantly stronger connected network channels in the subjective vitality network and correlations with flourishing, subjective vitality, mind-wandering, trait rumination, and depression.

Hub nodes (seed)		***t* = 3.1**	**Flourishing**		**Subjective vitality**		**Mind-wandering**		**Trait rumination**		**Depression**	
		***p*-value**	***r***	***p***	***r***	***p***	***r***	***p***	***R***	***p***	***r***	***p***
Subjective vitality network												
lSC/STG (Ch 11)	lAngG (Ch24)	0.002	0.17	0.261	0.33*	0.033	−0.03	0.856	0.02	0.916	−0.16	0.30
	rSAC (Ch 28)	0.001	0.24	0.124	0.33*	0.031	−0.02	0.916	0.06	0.682	−0.02	0.873
	lSAC (Ch35)	0.003	0.24	0.120	0.36*	0.018	0.13	0.387	0.05	0.77	−0.03	0.826
	lSAC (Ch36)	0.001	0.14	0.366	0.41*	0.006	−0.06	0.678	0.17	0.277	−0.04	0.811
	rAngG (Ch39)	0.003	0.20	0.199	0.33*	0.03	−0.095	0.546	0.11	0.497	0.05	0.735
lPSC (Ch 1)	lSupG (Ch23)	0.001	0.20	0.19	0.35*	0.023	−0.17	0.277	−0.10	0.52	−0.11	0.491
	lAngG (Ch24)	< 0.001	0.15	0.345	0.34*	0.026	−0.21	0.17	−0.09	0.553	−0.08	0.63
	lSAC (Ch25)	0.002	0.18	0.258	0.40*	0.008	−0.18	0.234	−0.05	0.743	−0.03	0.848
SupG (Ch 12)	lSAC (Ch 25)	0.003	0.08	0.623	0.34*	0.027	−0.25	0.102	0.06	0.719	0.08	0.588
	rAngG (Ch 29)	0.006	0.24	0.121	0.18	0.241	−0.21	0.183	−0.17	0.261	−0.05	0.741

*All variables were used as covariates in a follow-up NBS analysis of flourishing. *p < 0.05; the p-value corrected for multiple comparison was p < 0.0045.*

the NBS analysis of SV, yielded a significant network comprising 11 nodes and 11 edges at $t = 3.1$ ($p = 0.044 \pm 0.0058$). In contrast to the original vitality network, this network remained significant at different thresholds. At $t = 2.3$ a significant network resulted comprising 29 nodes and 67 edges ($p = 0.040 \pm 0.0055$). At $t = 2.7$ the network decreased to 21 nodes and 35 edges ($p = 0.028 \pm 0.0047$). Flourishing showed no significant correlations with any of the connections of the SV network (all $p > 0.1$; **Table 4**).

Rumination, Mind-Wandering, the OTP and Depressive Symptomatology

HighFl participants reported significantly more mind-wandering than regFl participants ($t_{32.2} = 4.34$, $p < 0.001$ $d = 1.30$), significantly less trait rumination ($t_{41} = 3.20$, $p = 0.003$, $d = 0.99$) and significantly less depressive symptomatology ($t_{34.5} = 2.52$, $p = 0.017$, $d = 0.75$); no significant difference between groups was found for state-rumination. The highSV and the regSV group did not differ significantly on mind-wandering, depressive symptomatology, state or trait rumination. Both high-score groups did not differ from their regular counter parts with respect to any category of the OTP. The categories derived for the OTP and content classification percentages are presented in the **Supplementary Table 1**. The only exception was the extent of thinking about the measurement for the flourishing groups (25% of regFl vs. 5% of highFl; $\chi^2_1 = 7.26$, $p < 0.004$ corrected for multiple comparison, OR = 8.25). Also, no group differences were found for emotional tone and experienced arousal.

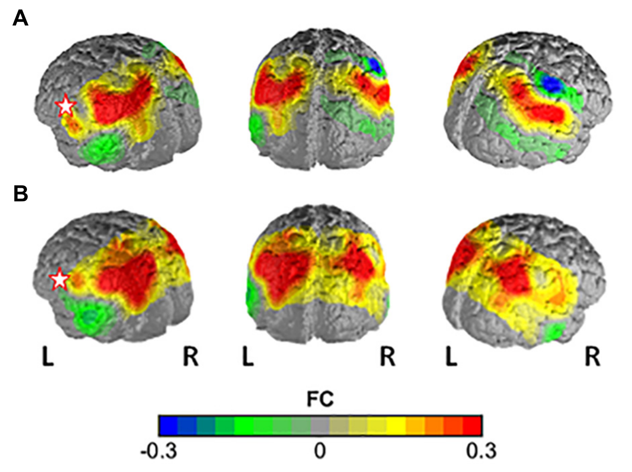

FIGURE 4 | Difference in FC between the high-vital and the regular-vital group with **(A)** channel 1 (PSC) and **(B)** channel 11 (lSC) as seed regions. Warm colors indicate higher FC with seed in high-vital vs. regular-vital participants.

Rumination, Mind-Wandering, and Depressive Symptomatology as Covariates in the NBS

Because trait rumination, mind-wandering and depressive symptomatology differed significantly between the highFl and the regFl group we conducted further analysis and used all three variables as covariates in a repeated NBS analysis of flourishing. Using the degree of mind-wandering in the NBS for the flourishing groups as a covariate rendered the network insignificant. A closer examination of the relation between mind-wandering and FC within the flourishing network, when using the hub node in the left MTG as a seed region, revealed significantly positive correlations for six network connections ($p < 0.1$). However, only the relation with the right visual area remained significant after correction for multiple comparisons ($r_{43} = 0.44$, $p < 0.0045$). Using the second hub node within left FusG as a seed yielded positive correlations for the connection with the left visual area ($r = 0.30$, $p = 0.051$) and right visual area ($r = 0.43$, $p = 0.004$). The latter remained significant after correction for multiple comparisons ($r = 0.43$, $p < 0.0045$). All correlations are displayed in **Table 3**.

When trait rumination was entered as a covariate, also no significant network resulted as a difference between groups. Further analysis revealed FC within the flourishing network to be negatively correlated with trait rumination. When using the left MTG as a seed, significant negative correlations were found for FC with left ($r = -0.33$, $p = 0.029$) and right visual area ($r = -0.32$, $p = 0.036$). The associations with left SAC ($r = -0.28$, $p = 0.071$) and right angular gyrus ($r = -0.26$, $p = 0.089$) pointed toward a significant correlation. No correlation survived correction for multiple comparisons ($p > 0.0045$). When taking the left FusG as a seed region correlations between trait rumination and FC with bilateral visual area ($-0.42 < r < -0.37$, $0.005 < p < 0.01$), right AnG ($r = -0.33$, $p = 0.032$) and rSAC ($r = -0.35$, $p = 0.021$) turned out significant. No correlation remained significant after correction for multiple comparisons. All correlations are displayed in **Table 3**.

Using depressive symptomatology as a covariate in the NBS yielded no significant connectivity network difference between the highFl and the regFl group. Further correlational analysis revealed negative correlations between depression and the connectivity strength between lMTG and rSupG ($r = -0.31$, $p = 0.041$), lSAC ($r = -0.36$, $p = 0.018$) and rV3 ($r = -0.31$, $p = 0.041$). Furthermore, depressive symptomatology correlated negatively with the connectivity strength between lFusG and rSAC ($r = -0.38$, $p = 0.012$), rAngG ($r = -0.34$, $p = 0.028$), lV3 ($r = -0.30$, $p = 0.047$) and rV3 ($r = -0.35$, $p = 0.021$). No correlation survived correction for multiple comparison ($p < 0.0045$).

In case of the NBS for subject vitality, mind-wandering as a covariate led to a decrease of the original network comprising seven nodes with six edges at $t = 3.2$ ($p = 0.047 \pm 0.0060$). The original network remained stable when trait rumination was added as a covariate in the NBS ($p = 0.049 \pm 0.0061$). Adding symptoms of depression as covariate lead to no significant group differences in connectivity strength at threshold of $t = 3.1$. However, a marginally significant difference resulted at threshold $t = 2.9$ ($p = 0.0902 \pm 0.0081$). All correlations of the covariates with the SV network are displayed in **Table 4**.

DISCUSSION

The goal of this study was to investigate associations of cortical FC at rest with two widely used indicators of well-being – flourishing and SV. For people high in flourishing, we found significantly increased FC within a network comprising parts of the DMN (right angular gyrus, right SuG, left MTG), bilateral somatosensory and visual cortex and left FusG. For highSV participants, we found a network of significantly increased FC related to the DMN (bilateral angular gyrus, left SuG, left superior temporal gyrus) and nodes in bilateral somatosensory, left primary and secondary somatosensory cortex. The inclusion of either mind-wandering, trait rumination or depression as covariate in the NBS nullified the difference in FC between the flourishing groups. In comparison, the vitality network remained, when including mind-wandering or trait rumination as a covariate in the NBS. Depressive symptomatology as covariate led to a marginally significant difference at a lower threshold.

DMN

Our results add to prior findings of the association between changes in DMN FC and trait indicators of well-being (Luo et al., 2015, 2017). However, depending on the measure of well-being and the specific area of the DMN, the authors reported heterogeneous findings regarding the increase and decrease of FC. In our study, which was limited to parietal and temporal cortex areas, we observed increased FC for areas that included the bilateral inferior parietal lobe (AnG/SuG) and left lateral temporal areas.

Flourishing

The network of increased FC within the highFl group centered around two hub nodes in the left MTG and the left FusG. As part of the DMN, the MTG has been associated with the provision of memory content in the process of spontaneous thought generation (Smallwood et al., 2016), but also social information processing in general (Alcalá-López et al., 2017). Behavioral research shows that the DMN related activity of mind-wandering is crucial for the navigation of the social world (Poerio and Smallwood, 2016) and in turn, social day-dreaming is being associated with increased feelings of love, connectedness and happiness (Poerio et al., 2015). We believe this is a potential dynamic behind the results in this study as a major factor in the selection of individuals as highFl was the reported quality of their social relationships. HighFl participants showed higher ratings of social commitment for others and perceived support and respect in their relationships (three out of seven items). Our findings of increased FC in social- and DMN-related brain areas in highFl individuals and the role of mind-wandering indicate a link between three different lines of research: The "social brain" (Tan et al., 2014; Alcalá-López et al., 2017), DMN-related spontaneous thought activity (Smallwood et al., 2016) and the importance of social factors for well-being (Diener and Seligman, 2002; Kafetsios and Sideridis, 2006; Sánchez-Álvarez et al., 2016). The FusG as second hub node in the flourishing network and its' role in face recognition (Kanwisher and Yovel, 2006) with relevance for social cognition and emotional intelligence (Takeuchi et al., 2011, 2013) lent further support to this hypothesis. The co-appearance of left MTG and FusG in our findings is also in line with a PET study by Volkow et al. (2011) which found positive emotionality, a construct composed of well-being, achievement/motivation, social potency and social closeness, to be positively associated with glucose metabolism in the left MTG and FusG. Overall, our results for flourishing and brain activity are consistent with studies that suggest a link between the processing of social cues, DMN activity and increased levels of well-being. At the same time they provide support for a mechanism underlying the prominent broaden-and built theory of positive emotion (Fredrickson, 2001). Multiple behavioral studies have supported the claim that positive emotions broaden our scope of attention and foster a state of learning (Fredrickson, 2013); our findings indicate an extension to the neurophysiological level via the link of differences in DMN related FC, mind-wandering and trait levels of flourishing.

Subjective Vitality

The two hub nodes in the vitality network were located in the left primary and secondary somatosensory cortex (Eickhoff et al., 2006) overlapping with posterior left superior temporal gyrus. Individuals high in trait SV report prolonged feelings of increased aliveness and energy, which is in line with findings of a connection between PSC and arousal and attention related areas of the brain (Gobbelé et al., 2000; Jang et al., 2014). A higher level of perceived energy can also be achieved via anodal transcranial direct current stimulation (tDCS) of the bilateral PSC (Tecchio et al., 2014). The posterior superior temporal gyrus has been linked to DMN activity (Wang et al., 2015) whereas secondary somatosensory cortex has been associated with the unconscious representation of feelings and peripheral physiological activity (Anders et al., 2004a,b). The frequent experience of elated, positive states associated with physiological arousal in highSV individuals (Ryan and Bernstein, 2004) is in line with these findings. On a higher level, PSC and somato-associative cortex play a role in the feeling of ownership and identification with one's own body (Aspell et al., 2012; Blanke, 2012). This form of body-connection, in turn, is positively associated with physical activity (Babic et al., 2014). Results from this study sample (reported elsewhere) suggest that the highSV group (M = 8.34, SD = 4.23) spends significantly more hours on physical activity per week (t_{32} = 3.54, p = 0.001) than the regSV group (M = 3.72, SD = 3.37). However, this difference does not exist for highFl and regFl individuals (t_{32} = 0.28, p = 0.781). The assumption that highSV individuals may be more prone to body-related self-processing relates to the DMN literature as Treserras et al. (2009) found that sensorimotor networks become coupled with DMN networks when preparing for movement or activity; a state which, according to the authors, can last over longer periods of time and may be one explanation for the findings regarding SV in this study. In contrast to flourishing, entering mind-wandering as covariate only decreased the size of the FC network difference between highSV and regSV participants. This is consistent with the fact that part of the vitality network shows DMN overlap whereas the major hub nodes in the primary and secondary somatosensory cortex are not considered part of the DMN.

Flourishing and Subjective Vitality

Despite the conceptual overlap of SV and flourishing, the body as a stage for subjective experience (Damasio et al., 2000) may be more prominent in highSV individuals. HighFl individuals on the other hand, are a selection of people with strong positive cognitive evaluations of life (e.g., the self, social relationships, the future). In their joint NBS analysis, flourishing as a covariate stabilized the vitality network, whereas SV as a covariate dissolved the flourishing network. We speculate that adding cognitive DMN related components of flourishing on top of a body-related vitality core component increases the network, whereas taking the body-related core away removes variance of a more fundamental component that is nevertheless central to flourishing. Adding to the argument of a different role of cognition in the two well-being measures is the finding that habitual (rumination) and spontaneous (mind-wandering) thought processes explained main shares of variance in FC between the flourishing but not the SV groups. State rumination did not significantly differ between groups and was not used further as covariate in the analysis. On the one hand, a mere resting state procedure may not be an adequate measure to assess healthy people's spontaneous tendency to ruminate (Rosenbaum et al., 2017); on the other hand, the experience of spontaneously flowing thoughts may just be of higher discriminative power regarding the extent of well-being in non-clinical samples. Overall, we speculate the high correlation between flourishing and SV and their distinct relation to states of mind indicate essential overlap between the two constructs with potential differences in higher order brain processes (Kringelbach and Berridge, 2017).

Flourishing, Subjective Vitality, and Symptoms of Depression

Of further interest is the fact that in this study we found depressive symptomatology to be negatively correlated with flourishing on a behavioral and neurophysiological level. The findings support the notion of an anti-relation between flourishing and mental illness (Huppert and So, 2013). For SV, the inclusion of depressive symptoms in the NBS analysis weakened the group differences on a neurophysiological level and no relation was found on a behavioral level. Depression showed no significant correlation with any of the significant network relations in the SV network which speaks to the fact that the NBS result may be more of a power problem. If so, the findings are in line with research that shows well-being/positive valence as a distinct phenomenon which goes beyond the mere opposite of malicious states (Keyes, 2002; Cuthbert and Insel, 2013). Among a more differentiated diagnostic, these findings may be relevant for the creation and effect of interventions where improvement and prevention of states of illness may demand different foci. Further research on the neurophysiology of positive states and traits could help to illuminate what is needed for each segment.

Limitations

One major limitation of this study was the restriction on parietal cortical areas of the DMN. Due to its usability and robustness against artifacts, fNIRS is a promising method to study brain activity and spontaneous thought processes in naturalistic contexts. However, this comes at the cost of limited insight into the activity of deeper-lying brain structures and whole brain activity. In case of this study, no conclusions can be drawn about medial and frontal subcomponents of the DMN. Secondly, we used NBS to identify significant differences in brain activation between groups. This approach allows for an interpretation on a network-level; conclusions on the role of single nodes have to be taken with care. Differences in DMN activity during rest have been related to group differences as well as various types of self-generated thought. However, due to the lack of experimental control during the resting state, the interpretability of on-going mind and brain processes within the participant is limited. We tried to control for this via the collection of OTP data from each participant after the measurement. However, we did not find any significant difference with regard to the content and emotional tone reported by the participants in the different groups. Meyer et al. (2015) reported changes in brain activity following imagined relieve of physical pain which did not display in the self-report of participants following their measurement. This adds to our findings, as the role of subconscious processes and lack of information about the on-going experience of the participant are two major limitations that need to be considered in the interpretation of our results. A further constraint in this study was the limitation of statistical power to detect medium and small effect sizes due to the modest sample size. In the case of the NBS for SV and the in-depth analysis of covariates a number of results were significant only at the level of $\alpha = 0.10$ and often did not survive correction for multiple comparison. One major strength of NBS is the increase in statistical power (Zalesky et al., 2010) that comes at the cost of limited interpretational power of single network connections. We therefore believe, the results of this study should be considered a starting ground that needs to be tested and extended in future studies.

CONCLUSION

In the well-being literature, conceptual distinctions have been made between eudaimonic and hedonic components of well-being (Ryan and Deci, 2001; Peterson et al., 2005). Others have separated cognitive from affective or global from specific aspects of subjective well-being (Diener, 1984; Diener et al., 1999). Flourishing has evolved as a complex construct in response to the diversity in symptomatology of psychological disorders. SV on the other hand specifically addresses the link between the subjective experience and organismic processes rooted in the human body. Hence, both constructs are distinct from other constructs used in the existing well-being literature. A neurophysiological framework to integrate the different concepts is still lacking. Our results add to the existing literature by showing distinct cortical FC correlates of flourishing and SV in the brain at rest. This may serve the purpose of further unraveling the neurophysiological correlates of the good life.

DATA AVAILABILITY STATEMENT

The fNIRS raw data as well as the respective code script and SPSS file can be found in the EASY DANS repository under https://doi.org/10.17026/dans-zym-vewk.

AUTHOR CONTRIBUTIONS

FG did the primary drafting, interpretation of the data and data analysis. DR contributed to the analysis of the data. AH contributed to the drafting of the experimental design and acquisition of the data. TR, MH, AF, and A-CE contributed to the design and the acquisition of the work and revised it critically for important intellectual content.

FUNDING

AH was partly supported by the "Milton Erickson Gesellschaft für klinische Hypnose e.V." A-CE was partly supported by IZKF Tübingen (Junior Research Group 2115-0-0). FG was supported by the "Stiftung der deutschen Wirtschaft (sdw) GmbH."

ACKNOWLEDGMENTS

The authors would like to thank Ramona Taeglich, Betti Schopp, Hannah Renner, and Hendrik Laicher for their excellent work and their valuable support with the measurements.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2018.00540/full#supplementary-material

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

ORIGINAL RESEARCH
published: 18 January 2019
doi: 10.3389/fnhum.2018.00543

The Effects of Family Socioeconomic Status on Psychological and Neural Mechanisms as Well as Their Sex Differences

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Received: *04 July 2018*
Accepted: *31 December 2018*
Published: *18 January 2019*

Citation:
Takeuchi H, Taki Y, Nouchi R, Yokoyama R, Kotozaki Y, Nakagawa S, Sekiguchi A, Iizuka K, Yamamoto Y, Hanawa S, Araki T, Miyauchi CM, Sakaki K, Nozawa T, Ikeda S, Yokota S, Magistro D, Sassa Y and Kawashima R (2019) The Effects of Family Socioeconomic Status on Psychological and Neural Mechanisms as Well as Their Sex Differences. Front. Hum. Neurosci. 12:543. doi: 10.3389/fnhum.2018.00543

Family socioeconomic status (SES) is an important factor that affects an individual's neural and cognitive development. The two novel aims of this study were to reveal (a) the effects of family SES on mean diffusivity (MD) using diffusion tensor imaging given the characteristic property of MD to reflect neural plasticity and development and (b) the sex differences in SES effects. In a study cohort of 1,216 normal young adults, we failed to find significant main effects of family SES on MD; however, previously observed main effects of family SES on regional gray matter volume and fractional anisotropy (FA) were partly replicated. We found a significant effect of the interaction between sex and family income on MD in the thalamus as well as significant effects of the interaction between sex and parents' educational qualification (year's of education) on MD and FA in the body of the corpus callosum as well as white matter areas between the anterior cingulate cortex and lateral prefrontal cortex. These results suggest the sex-specific associations of family SES with neural and/or cognitive mechanisms particularly in neural tissues in brain areas that play key roles in basic information processing and higher-order cognitive processes in a way females with greater family SES level show imaging outcome measures that have been associated with more neural tissues (such as greater FA and lower MD) and males showed opposite.

Keywords: family social economic status, voxel-based morphometry, diffusion tensor imaging, sex difference, family income, parents' highest educational qualification

INTRODUCTION

Family socioeconomic status (SES, particularly, family income and parents' educational qualifications) is an important factor that affects an individual's neural and cognitive development (Hair et al., 2015; Noble et al., 2015). For example, in young individuals, higher family SES is associated with better cognitive and memory functions, including better working memory, executive function, language and literacy abilities, and memory functions (Bowey, 1995; Noble et al., 2007). Higher family SES is also associated with increased self-regulatory behaviors, academic performance, and sense of well-being and less impulsive decision making, learned helplessness, stress, and psychological distress in young individuals (Evans and English, 2002; Evans et al., 2005; Sirin, 2005; Sweitzer et al., 2008).

Although many previous studies have focused on the effects of SES on these cognitive measures across sexes (e.g., Evans and English, 2002; Evans et al., 2005; Sweitzer et al., 2008), some studies have focused on the sex differences of effects of SES on health measures as described below. It is revealed that higher educational qualification of parents leads to low blood pressure during the developmental phase only in women (Janicki-Deverts et al., 2012). Several studies have shown that the associations between higher childhood SES and lower cardiovascular disease morbidity and mortality in later life are stronger in women than in men (Claussen et al., 2003; Hamil-Luker and Angela, 2007; Næss et al., 2007). In addition, while the effects of family SES on cognitive mechanisms are largely assumed to be mediated by the associations between increased stress and low family SES (Evans and English, 2002; Evans and Schamberg, 2009; Ursache and Noble, 2016a), previous animal studies have shown that females and males show opposite neural changes in response to stressors (Shors et al., 2001). For example, Shors et al. (2001) showed in response to stress event, spine density was enhanced in the male hippocampus but reduced in the female hippocampus. Notably, women tend to have more stressors, particularly socially, and these stressors tend to cause more depressive symptoms (Hankin et al., 2007).

Previous neuroimaging studies have investigated brain functions and brain volume correlates of family SES in young subjects of both sexes. Functional imaging studies have investigated the associations between family SES and a wide range of cognitive tasks. Based on these studies, SES is suggested to effect areas of cognitive control and regulation (prefrontal cortex), social emotional processing (amygdala), and memory (hippocampus) as well as the left hemisphere language network for language-related processing (Noble et al., 2006; Gianaros et al., 2008; Kishiyama et al., 2009; Hanson et al., 2011; Ursache and Noble, 2016a).

A neuroimaging study with 1099 typically developing individuals aged between 3 and 20 years showed that parents' educational qualifications and the family income were positively correlated with the total brain surface area (Hurt and Betancourt, 2015). Another study involving 389 typically developing children showed an association between a higher family SES and a greater total gray matter volume (Hair et al., 2015). Although studies with smaller sample sizes have generated inconsistent results, they generally show a relation between low family SES and decreased brain volume (Hanson et al., 2011; Lawson et al., 2013; Luby et al., 2013). Another study involving a diverse sample of 1082 children and adolescents aged between 3 and 21 years showed that a higher family income is related to higher fractional anisotropy (FA) (which reflects the structural properties of white matter) in and near the hippocampus and frontal cortex (Ursache and Noble, 2016b).

Mean diffusivity (MD) is measured by diffusion tensor imaging (DTI) (Beaulieu, 2002) and used to measure the microstructural properties of gray and white matter. As we summarized previously (Takeuchi et al., 2016a), lower MD is sensitive to greater tissue density of the brain parenchyma (though is not strictly a measure of it). Tissue density increases with the increased presence of unspecific cellular structures (i.e., capillaries, synapses, spines, and macromolecular proteins); the properties of myelin, neuronal membranes, and axons; the shape of neurons and glia; and enhanced tissue organization (Beaulieu, 2002; Sagi et al., 2012). The majority of these tissue differences are thought to affect neural plasticity. Therefore, MD is supposed to provide characteristic information regarding neural plasticity (though, it is obviously not limited to be a measure of neural plasticity); indeed, MD measurements served as a characteristic and sensitive tool to study neural plasticity and development (Sagi et al., 2012; Takeuchi et al., 2015a, 2016a).

As described, family SES is an important factor that affects cognitive, socioemotional, neural, and health development. However, despite the characteristic importance of family SES in humans and studies investigating effects of family SES on cognitive and functional and structural neural mechanisms as described above, the following issues have not been investigated: (a) the effects of family SES on MD despite the characteristic property of MD to reflect neural plasticity and development and (b) the influence of sex on the effects of SES, particularly regarding neural mechanisms despite the extensive evidence on sex-specific SES effects on health (low SES levels tended to be associated with more health problems in females than in males as described above).

Therefore, the purpose of this study was to investigate these issues. To this end, we hypothesized that higher family SES is associated with lower MD in the brain areas, including the prefrontal cortex, hippocampus, amygdala, and the left hemisphere language network, and that higher family SES results in more neural tissue, as evidenced by associations with brain volume, FA, and MD more strongly in females.

We also investigated the effects of family SES on relevant psychological measures to reveal the nature of correlates of family SES. Based on abovementioned previous studies and theoretical background of family SES, these include diverse psychological measures of (a) basic cognitive functions, (b) traits related to affects, (c) stress, (d) traits related to cognition, and education. Family SES was separately measured using both family annual income and the parents' average highest educational qualifications.

MATERIALS AND METHODS

Subjects

The present study, which is a part of an ongoing project to investigate the association between brain imaging, cognitive function, and aging, included relevant SES measures and imaging data from 1216 healthy, right-handed individuals (702 men and 514 women). The mean age of the subjects was 20.7 years [standard deviation (SD), 1.8; age range: 18–27 years old]. For details of subjects' information, see **Supplemental Methods**. Written informed consent was obtained. All methods were performed in accordance with the Declaration of Helsinki (1991). This study was approved by the Ethics Committee of Medical Faculty of Tohoku University.

SES Measures

Data related to the socioeconomic status were collected in accordance with our previous study and mostly with the standard approach used by the Japanese government for evaluating socioeconomic status. Descriptions in this subsection were largely reproduced from our previous study that used similar methods (Takeuchi et al., 2014a). The measure of socioeconomic status consisted of three questions. One was an enquiry relating to family annual income (income of the family that the individual grew up in). Annual income data were collected using discrete variables: 1, annual income <2 million yen (the currency exchange rate is now approximately $1 USD = 120 yen); 2, annual income 2–4 million yen; 3, annual income 4–6 million yen; 4, annual income 6–8 million yen; 5, annual income 8–10 million yen; 6, annual income 10–12 million yen; 7, annual income ≥12 million yen. The values 1–7 were used in subsequent regression analyses. The other two questions related to the highest educational qualification of both parents. There were 8 options [1, elementary school graduate or below; 2, junior high school graduate; 3, graduate of a short term school completed after junior high school; 4, normal high school graduate; 5, graduate of a short term school completed after high school (such as a junior college); 6, university graduate; 7, Masters degree; and 8, Doctorate] and each choice was converted into the number of years taken to complete the qualification in the normal manner in the Japanese education system (1, 6 years; 2, 9 years; 3, 11 years; 4, 12 years; 5, 14 years; 6, 16 years; 7, 18 years; 8, 21 years). The average of the converted values for each parent was used in the analyses. Not all subjects had both parents' information and in such cases, one parent's information was used in the analysis. This protocol followed the standard approach used by the Japanese government for evaluating socioeconomic status, but the questions relating to the parents' highest educational qualifications were modified to increase the number of options available and thus also increased precision. Although, we have no way of knowing whether subjects answered questions sincerely, like in the cases of any other questionnaires, but subjects were explicitly instructed that they are allowed not to answer questions, if they don't like to. It should also be noted that while parents' highest educational qualifications may usually not change over time during the development of children, family income may change more or less as have been the cases of most of the studies of family SES.

Instead of composite scores, two SES measures were separately used because most (though not all) relevant previous studies either separated two psychological factors or used one of two measures. Moreover, the effects of two factors are often different in previous studies (Noble et al., 2012; Lawson et al., 2013; Hurt and Betancourt, 2015; Noble et al., 2015).

Psychological Measures

The following neuropsychological tests and questionnaires were administered to study participants: The references and additional details of these measures were provided in the **Supplemental Methods**. As described in the Introduction, based on nature of family SES, and previous studies, we investigated the effects of family SES on diverse psychological measures of (a) basic cognitive functions, (b) traits related to affects, (c) stress, (d) traits related to cognition, and education.

(A) Raven's Advanced Progressive Matrices (RAPM), a non-verbal reasoning task; (B) Tanaka B-type intelligence test (TBIT) type 3B, an intelligence test that does not require verbal knowledge; (C) a reading comprehension task; (D) the S-A creativity test, a measure of creativity measured by divergent thinking (CMDT); (E) computerized digit span task, a verbal (working memory) WM task; (F) SQ and EQ questionnaires, a measure of empathizing (drive to identify the mental status of other individuals) and systemizing (drive to analyze a system); (F) Emotional Intelligence Scale, a questionnaire measure of emotional intelligence; (G) General Health Questionnaire 30 (GHQ30), a measure of mental health; (H) WHOQOL-26, the Japanese version of the QOL Scale; (I) the scale for Critical Thinking Disposition, the measure for evaluating disposition toward critical thinking. (J) the cognitive reflectivity–impulsiveness questionnaire, a measure of individual differences in reflectivity and impulsivity; (K) the Japanese version of Need for Cognition Scale, a measure of the tendency for an individual to engage in and enjoy thinking; (L) the Japanese version of the Achievement Motivation Scale, a measure of two psychometrically derived achievement motivations, including self-fulfillment achievement motivation (SFAM: achievement motivation directed at pursuing goals evaluated by one's own standards of achievement, regardless of the values of others and the society) and competitive achievement motivation CAM: achievement motivation directed at seeking social prestige by defeating others and achieving better results than others; (M) the Japanese version of the Rosenberg Self-Esteem Scale (RSES), a measure of global trait self-esteem; (N) the National Identity Scale, a self-reported measure of individual nationalism and patriotism; (O) the Japanese version of the Optimism Scale, a questionnaire measure of individual optimism and pessimism; (P) the Japanese version of the General Self-Efficacy Scale, a measure of individual general self-efficacy (general self-efficacy is defined as individuals' perception of their ability to perform across various different situations); (Q) the Japanese version of the third version of the UCLA Loneliness Scale, a measure of social isolation and loneliness; (R) the Japanese version of the checklist individual strength (CIS) questionnaire, a measure of chronic fatigue; (S) the Japanese version of the Beck Depression Inventory, a measure of states of depression; (T) the Japanese version of State-Trait Anxiety Inventory (STAI), a measure of state and trait anxiety; (U) the shortened Japanese version of the Profile of Mood States (POMS) questionnaire, a measure of participants' mood in the preceding week [the total score (total mood disturbance) was used in this study]; (V) the Japanese version of the NEO Five-Factor Inventory (NEO-FFI), a measure of five basic personalities: neuroticism, extraversion, openness, agreeableness, and conscientiousness; (W) the Japanese version of Dispositional Envy Scale, a measure of proneness to envy; (X) the Preoccupation Scale, including the External-Preoccupation Scale, which measures the maintenance of external focus on a specific object, and the Self-Preoccupation Scale, which reflects the degree and duration of self-focusing; (Y) the Scale of Egalitarian Sex Role Attitudes-Short Form (SESRA-S), a self-report questionnaire used to measure an individual's sex-role egalitarianism (SRE), i.e., the belief that the sex of an individual should not influence the perception of his/her rights, abilities, obligations, and opportunities; and (Z) scale of life events in interpersonal and achievement domains, a measure of negative and positive events.

Behavioral Data Analysis

The behavioral data were analyzed using SPSS 22.0 statistical software (SPSS Inc., Chicago, IL, United States). Some of the descriptions in this subsection were mostly reproduced from our previous study (Takeuchi et al., 2015b).

Associations between SES measures and psychological variables were analyzed using analyses of covariance (ANCOVAs), with age and sex as covariates. To model these analyses, age and one SES measure (family annual income or the parents' average highest educational qualifications) were used as covariates, sex was a fixed factor, and the interaction between sex and each SES measure was included. Thus, we performed 78 ANCOVAs [number of SES measures (2) × number of psychological measures (39)]. In this study, we investigated the main effects of SES measures as well as the interaction effects of sex and SES measures on diverse neurocognitive mechanisms. Family, annual income and the parents' average highest educational qualifications were not included in the same model because they are highly correlated and conceptually overlap. This procedure of separate analyses for family income and parents' education levels has previously performed in this field (Noble et al., 2015).

In all ACNOVAs performed to analyze behavioral measures, results with a threshold of $P < 0.05$ were considered to be statistically significant, after correcting for the false discovery rate (FDR) using the graphically sharpened method (Benjamini and Hochberg, 2000). For the rationale and basic explanation of the FDR test, see **Supplemental Methods**.

Image Acquisition

The methods for MR image acquisition were described in our previous studies and reproduced below (Takeuchi et al., 2012; Takeuchi et al., 2016a). All MRI data acquisition was performed using a 3-T Philips Achieva scanner. High-resolution T1-weighted structural images (T1WIs: 240 × 240 matrix, TR = 6.5 ms, TE = 3 ms, FOV = 24 cm, slices = 162, slice thickness = 1.0 mm) were collected using a magnetization-prepared rapid gradient echo sequence from 1216 subjects. Diffusion-weighted data were acquired using a spin-echo EPI sequence (TR = 10293 ms, TE = 55 ms, FOV = 22.4 cm, $2 \times 2 \times 2$ mm^3 voxels, 60 slices, SENSE reduction factor = 2, number of acquisitions = 1) from 1205 subjects. The diffusion weighting was isotropically distributed along 32 directions (b-value = 1,000 s/mm^2). Additionally, three images with no diffusion weighting (b-value = 0 s/mm2) (b = 0 images) were acquired, (TR = 10293 ms, TE = 55 ms, FOV = 22.4 cm, $2 \times 2 \times 2$ mm^3 voxels, 60 slices). FA and MD maps were calculated from the collected images using a commercially available Philips' diffusion tensor analysis package on the MR console. Images with artifacts were removed after visual inspection and remaining data included images of 1205 subjects as described above. For more details, see **Supplemental Methods**.

Pre-processing of Structural Data

Preprocessing of the T1WIs data was performed using Statistical Parametric Mapping software (SPM12; Wellcome Department of Cognitive Neurology, London, United Kingdom) implemented in Matlab (Mathworks Inc., Natick, MA, United States). The methods for the preprocessing of T1WIs were described in our previous studies and reproduced below (Takeuchi et al., 2018). Using the new segmentation algorithm implemented in SPM12, T1-weighted structural images of each individual were segmented and normalized to the Montreal Neurological Institute (MNI) space to give images with $1.5 \times 1.5 \times 1.5$ mm^3 voxels using diffeomorphic anatomical registration through exponentiated lie algebra (DARTEL) registration process implemented in SPM12. In addition, we performed a volume change correction (modulation) (Ashburner and Friston, 2000). Subsequently, generated rGMV images were smoothed by convolving them with an isotropic Gaussian kernel of 8 mm full width at half maximum (FWHM). For full descriptions of these procedures, see **Supplemental Methods**.

Preprocessing and analysis of diffusion data were performed using Statistical Parametric Mapping (SPM) 8 implemented in

Matlab. SPM8 instead of SPM12 was used here, this is because our preprocessing procedure was optimized and the quality of preprocessed images was validated using SPM 8 (Takeuchi et al., 2018). The methods for the preprocessing of diffusion data were described in our previous study and reproduced below (Takeuchi et al., 2019). Basically, we normalized MD, FA, gray matter segment [regional gray matter density (rGMD) map], white matter segment [regional white matter density (rWMD) map], cerebrospinal fluid (CSF) segments [regional CSF density (rCSFD) map] of diffusion images of subjects with a previously validated, modified version of DARTEL-based registration process (Takeuchi et al., 2018) method to give images with 1.5 × 1.5 × 1.5 mm^3 voxel size. Then normalized MD images were masked by the custom mask image that is highly likely to be the gray or white matter (see **Supplemental Methods** for details), the normalized images were smoothed by Gaussian Kernel of 8-mm full width at half maximum (FWHM) and normalized FA images were masked by the custom mask image that is highly likely to be the white matter and then smoothed by Gaussian Kernel of 6-mm FWHM. For more details of preprocessing and how partial voluming effects were removed, see **Supplementary Methods**.

Whole-Brain Statistical Analysis

We assessed rGMV, rWMV, MD, and FA associated with individual differences in family annual income and parents' average highest educational qualifications as well as the effects of interactions between sex and family annual income and parents' average highest educational qualifications. Statistical analyses of imaging data were performed with SPM8 (SPM8 was used because of its compatibility with the software, and see the **Supplemental Methods** for details). We performed two whole-brain ANCOVAs and two separate ANCOVAs (one for family annual income and one for parents' average highest educational qualifications). This procedure of separate analyses of family income and parents' education levels is consistent with a similar previous study (Noble et al., 2015) and based on the conceptual overlap of the two socioeconomic status measures. In addition, we did not include numerous psychological correlates (traits, cognitive functions, and states) of SES as covariates because we regarded these covariates and brain imaging properties as parallel phenomena. And like researchers do not regress out the effects of muscle power when they try to investigate association between nutrition and muscle amount, we believe that not regressing out the effects of psychological correlates of SES is appropriate for these whole-brain analyses of SES.

Analyzed using analyses of covariance for rGMV and rWMV were performed with sex, age, and either family annual income or parents' average highest educational qualifications. ANCOVAs for MD and FA were performed with the same variables, with the exception that the total intracranial volume (TIV) that was calculated as described previously (Hashimoto et al., 2015) was added (TIV was not included as a covariate for volume analyses due to the previous studies' findings on global effects of family SES on volume measures, in such case inclusion of global measures as covariates are improper). For the discussion, regarding how the inclusion of the global effect as a covariate is improper when there are supposed to be wide spread effects as it erases the effective findings, see our previous study (Takeuchi et al., 2010b). Analyses for rGMV and rWMV were performed in voxels for all subjects that showed a signal intensity of >0.05. Analyses for MD and FA were performed within the aforementioned gray + white matter mask and white matter mask, respectively.

For all imaging analyses (i.e., rGMV, rWMV, MD, and FA), multiple comparison correction was performed using threshold-free cluster enhancement (TFCE) (Smith and Nichols, 2009) with randomized (5,000 permutations) non-parametric testing using the TFCE toolbox[1]. We applied a threshold of FWE corrected at $P < 0.05$. We used FDR approach in behavioral analyses due to its sensitivity but used FWE approach in permutation analyses as that is the standard analysis as has been performed in our previous studies (e.g., Takeuchi et al., 2016c).

Post hoc Analyses of the Associations Between the Significant Imaging Correlates and the Significant Psychological Correlates of the Family SES's Effects

Next, we extracted the mean values of the significant imaging correlates (clusters) of the family income's effects and investigated whether the significant psychological correlates of family income were associated with those values in the same way (directions). These associations were analyzed using ANCOVAs, with age and sex as covariates and each mean value of the family income's effects' significant imaging correlates (clusters) as a dependent variable. To model these analyses, both the age and one of the significant psychological correlates of family SES were used as covariates. Sex was a fixed factor, and the interaction between sex and one of the significant psychological correlates of the family SES was included. Then, we also performed the same analyses on the significant correlates of the parents' educational qualifications.

Here, because there were a number of significant clusters and psychological correlates of family SES (we applied $p < 0.01$, uncorrected, for the statistical threshold), only the results showing association with the imaging correlates of family SES in the same direction were noted. Moreover, these analyses present the difficulties of double dipping procedures (Kriegeskorte et al., 2009); therefore, all results are exploratory and supplemental.

RESULTS

Basic Data

The average (and SD) age, RAPM score, family annual income, and parents' average highest educational qualifications for men and women are shown in **Table 1**. The distributions of family annual income and parents' average highest educational qualifications are presented in **Figure 1**. Note the difference of the number of subjects in each sex would not bias the results

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[1] http://dbm.neuro.uni-jena.de/tfce/

TABLE 1 | Demographic variables of the study participants.

	Male (*N* = 702)		Female (*N* = 514)	
Measure	**Mean**	***SD***	**Mean**	***SD***
Age	20.80	1.89	20.60	1.60
RAPM	28.79	3.86	28.11	3.81
Family annual income*	4.19	1.58	4.04	1.55
Parents' average educational qualification	14.75	1.87	14.51	1.85

Family annual income was classified as follows: 1, annual income below 2 million yen; 2, 2–4 million yen; 3, 4–6 million yen; 4, 6–8 million yen; 5, 8–10 million yen; 6, 10–12 million yen; 7, >12 million yen.

of interaction analyses involving sex. And since our study deals with the sex interaction analysis (meaning the difference of the correlation between men and women), the subtle difference of age (i.e., 0.2 years) or other characteristics between sex are generally not supposed to substantially affect the results of interaction analyses as the most of the range of such characteristics overlap between sex and among such mostly overlapped range of various characteristics, we see the sex difference of the correlation between family SES and other variables.

Family annual income and parents' average highest educational qualifications showed a robust significant substantial correlation (simple correlation, $r = 0.412$, $P = 5.91 \times 10^{-51}$), supporting the by far the most standard separate modeling of family annual income and parents' average highest educational qualifications.

Psychological Analyses of Effects of Family Annual Income

The effects of family annual income on a wide range of psychological variables were investigated. After correcting for

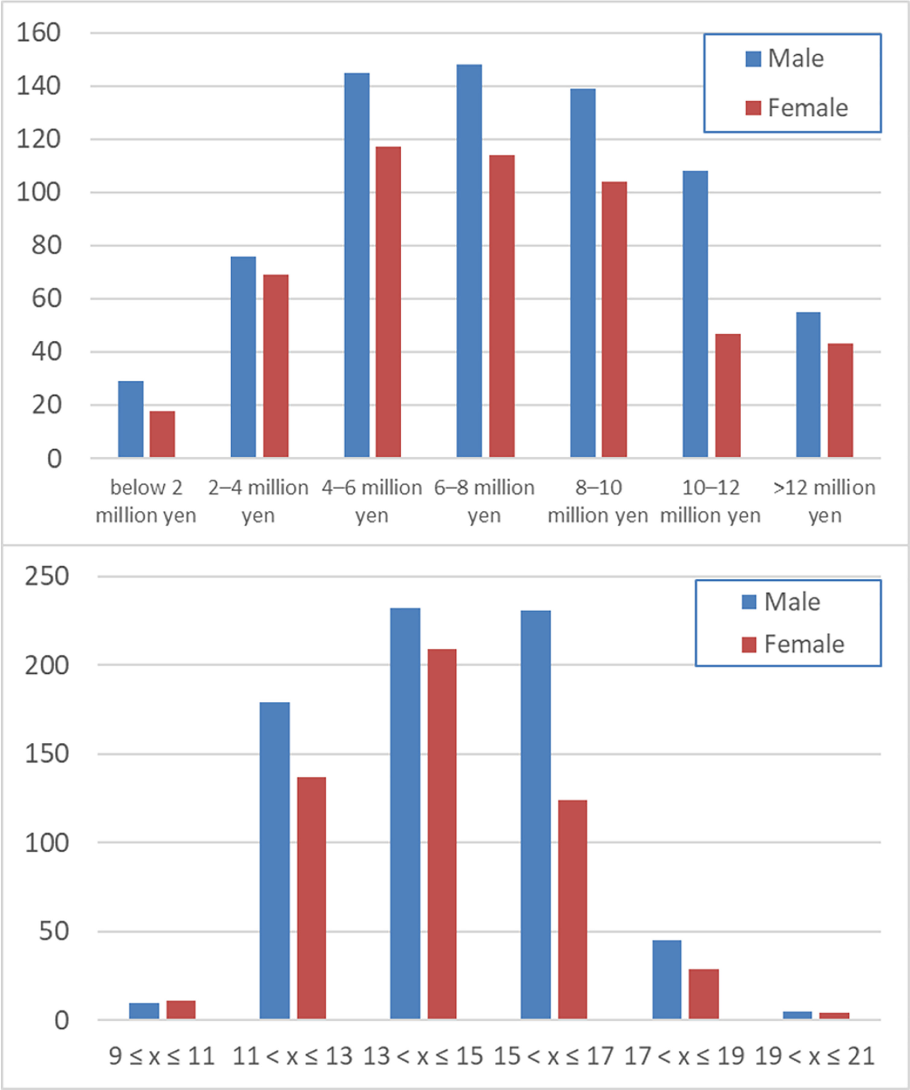

FIGURE 1 | Distribution of the family annual income (upper panel) and the average of the parents' highest educational qualifications (lower panel).

multiple comparisons, ANCOVAs revealed that there were significant main positive effects (regardless of sex) of family annual income on the total score of the Emotional Intelligence Scale, average score of WHOQOL, score of the competitive achievement motivation Scale, score of self-esteem, score of need for uniqueness, nationalism, extraversion, and positive life events as well as significant negative effects on the score of pessimism, score of the UCLA Loneliness Scale, and trait anxiety score of STAI. There was a significant effect of the interaction between sex and family annual income on the score of SESRA-S. This interaction had a negative effect on family annual income in males and a positive effect on family income in females. For statistical values, see **Table 2**.

Psychological Analyses of Effects of Parents' Average Highest Educational Qualifications

The effects of parents' average highest educational qualifications on a wide range of psychological variables were investigated. After correcting for multiple comparisons, ANCOVAs revealed that there were significant main positive effects (regardless of sex) of parents' average highest educational qualifications on the scores of intelligence tasks, including the speeded task (TBIT), S-A creativity test (creativity measured by divergent thinking), systemizing, WHOQOL26 (QOL measure), and the measure for the need for cognition and openness as well as significant main negative effects on the score of CIS (measure of chronic fatigue) and STAI's state and trait measures (measure of state and trait of anxiety). For statistical values, see **Table 3**.

Main Effects of Family Annual Income on Imaging Measures Regardless of Sex

Whole-brain ANCOVA revealed an overall positive main effect (regardless of sex) of family annual income on rGMV in the bilateral cerebellum, bilateral calcarine cortex, bilateral lingual gyrus, bilateral fusiform gyrus, bilateral medial temporal lobe areas (parahippocampal gyrus, hippocampus, and amygdala), bilateral perisylvian areas, left temporal pole, areas in the basal ganglia, insula and orbital frontal areas, and the subgenual cingulate gyrus (**Figure 2**). For complete information on brain areas and statistical values, see **Table 4**.

Whole-brain ANCOVAs revealed that there were no significant main effects of family income (regardless of sex) on rWMV, FA, and MD.

Effects of Interaction Between Sex and Family Annual Income on Imaging Measures

Whole-brain ANCOVA revealed effects of the interaction between sex and family annual income on MD in the thalamus [**Figure 3**, $x, y, z = 12, -30, 1.5$, TFCE value = 1012.64, $P = 0.042$, corrected and 174 voxels with the threshold of $P < 0.05$ corrected for multiple comparisons (permutation using TFCE values, FWE)]. Note the interaction is formed by both of tendencies of positive correlation in males and negative correlation in females as seen in **Figure 3**.

Whole-brain ANCOVAs revealed that there were no significant effects of interaction between sex and family annual income on rGMV, rWMV, and FA.

Main Effects of Parents' Average Highest Educational Qualifications on Imaging Measures Regardless of Sex

Whole-brain ANCOVA revealed an overall positive main effect (regardless of sex) of parents' average highest educational qualifications on FA in the white matter areas of the cerebral peduncle and internal capsule as well as white matter areas of the posterior brain, including part of the splenium of the corpus callosum and right posterior corona radiata (**Figure 4**). For complete information on brain areas and statistical values, see **Table 5**.

Whole-brain ANCOVAs revealed that there were no significant effects of parents' average highest educational qualifications on rGMV, rWMV, and MD.

Effects of Interaction Between Sex and Parents' Average Highest Educational Qualifications on Imaging Measures

Whole-brain ANCOVA revealed effects of interaction between sex and parents' average highest educational qualifications on FA in white matter areas of the genu and body of the corpus callosum and bilateral corona radiata (**Figure 5**). For complete information on brain areas and statistical values, see **Table 6**. Note the interaction is formed by both of tendencies of negative correlation in males and positive correlation in females as seen in **Figure 5**. The areas of significant interaction did not overlap with the areas of the main effects.

Whole-brain ANCOVA revealed effects of interaction between sex and parents' average highest educational qualifications on MD in the white matter areas of the body and genu of the corpus callosum as well as the bilateral corona radiata, caudate, prefrontal areas, and insula (**Figure 6**). For complete information on brain areas and statistical values, see **Table 7**. Note the interaction is formed by both of tendencies of positive correlation in males and negative correlation in females as seen in **Figure 6**.

Whole-brain ANCOVAs revealed that there were no significant effects of interaction between sex and parents' average highest educational qualifications on rGMV and rWMV.

Post hoc Analyses of the Associations Between the Significant Imaging Correlates and the Significant Psychological Correlates of Family SES's Main Effects

Regarding the *post hoc* analyses of family income, the *post hoc* analyses showed: (1) a significantly negative main effect of pessimism on the mean rGMV values of the significant cluster 1 (**Table 2**), which mainly involves the right calcarine cortex, right fusiform gyrus, right parahippocampal gyrus, and right cerebellum ($p = 0.006$); (2) a significantly negative main effect of pessimism on the mean rGMV values of the significant

TABLE 2 | Main effects of family annual income as well as effects of interaction between sex and family annual income on psychological measures.

	N male	N female	Correlation coefficient male	Correlation coefficient female	Main effect *F*-value	Main effect *P*-value, uncorrected	Main effect, *P*-value, FDR[1]	Interaction effect *F*-value	Interaction effect *P*-value uncorrected	Interaction effect *P*-value FDR
Cognitive functions										
RAPM[2](intelligence, non-verbal reasoning)	699	512	0.022	0.032	0.846	0.358	0.482	0.032	0.858	0.712
TBIT[3](intelligence)	632	457	0.038	0.036	1.33	0.249	0.372	0.005	0.942	0.727
Reading comprehension	608	422	−0.004	−0.006	0.014	0.907	0.719	0.001	0.974	0.736
S-A creativity test	700	512	0.069	−0.028	0.414	0.52	0.57	2.945	0.086	0.181
Digit span	697	509	−0.03	0.007	0.177	0.674	0.645	0.413	0.521	0.57
Traits and states										
Empathizing	700	512	0.039	0.099	5.08	0.024	0.085	0.954	0.329	0.461
Systemizing	700	512	0.02	0.126	5.188	0.023	0.084	2.473	0.116	0.226
Emotional Intelligence Scale	697	512	0.091	0.121	12.482	4.26×10^{-4}	0.005	0.142	0.706	0.655
GHQ30[4]	696	511	−0.068	−0.006	1.524	0.217	0.338	1.119	0.29	0.423
WHOQOL-26	697	512	0.148	0.126	21.719	4.00×10^{-6}	4.6×10^{-4}	0.271	0.603	0.596
Critical thinking disposition	698	512	4.62×10^{-4}	0.089	1.812	0.179	0.293	1.872	0.172	0.293
Cognitive reflectivity–Impulsiveness	697	512	0.007	−0.045	0.488	0.485	0.552	0.843	0.359	0.482
Need for Cognition	698	512	0.011	0.063	1.345	0.246	0.372	0.618	0.432	0.54
Self-fulfillment Achievement Motivation	698	512	0.012	0.033	0.506	0.477	0.552	0.102	0.75	0.678
Competitive Achievement Motivation	698	512	0.037	0.106	6.704	0.01	0.045	1.832	0.176	0.293
Self-esteem	698	512	0.097	0.098	10.767	0.001	0.011	8.6×10^{-5}	0.993	0.736
Need for uniqueness	697	512	0.042	0.148	9.917	0.002	0.014	2.829	0.093	0.187
Patriotism	697	512	0.085	−0.015	1.583	0.209	0.329	2.973	0.085	0.181
Nationalism	697	512	0.114	0.099	13.25	2.84×10^{-4}	0.005	0.162	0.688	0.645
Optimism	697	512	0.068	0.039	3.024	0.082	0.181	0.271	0.603	0.596
Pessimism	697	512	−0.063	−0.113	8.77	0.003	0.022	0.631	0.427	0.54
Self-efficacy	697	511	0.061	0.081	5.159	0.023	0.084	0.017	0.895	0.719
UCLA Loneliness Scale	698	512	−0.069	−0.1	7.839	0.005	0.028	0.168	0.682	0.645
CIS-20[5] (fatigue)	696	512	−0.113	−0.033	5.767	0.016	0.065	2.05	0.152	0.283
Beck Depression Inventory	640	475	−0.072	−0.102	8.339	0.004	0.023	0.333	0.564	0.595
STAI[6]_state (anxiety state)	640	475	−0.064	−0.08	5.39	0.02	0.078	0.055	0.815	0.694
STAI_trait (anxiety trait)	640	475	−0.087	−0.125	11.944	0.001	0.007	0.572	0.449	0.545
POMS-TMD[7] (mood disturbance)	688	508	−0.102	−0.074	8.79	0.003	0.022	0.097	0.755	0.678
Neuroticism	699	512	−0.04	−0.095	4.792	0.029	0.089	0.779	0.377	0.499
Extraversion	699	512	0.092	0.083	8.417	0.004	0.023	0.083	0.774	0.69
Openness	699	512	0.023	0.034	0.924	0.337	0.466	0.037	0.848	0.712
Agreeableness	699	512	−0.038	−0.028	1.653	0.199	0.322	0.006	0.936	0.727
Conscientiousness	699	512	0.022	0.073	2.352	0.125	0.24	0.64	0.424	0.54
Jealousy	643	475	−0.052	−0.081	4.044	0.045	0.116	0.266	0.606	0.596
Self-Preoccupation	643	475	−0.042	−0.083	3.674	0.056	0.134	0.491	0.484	0.552
External-Preoccupation	643	475	−0.019	0.095	1.834	0.176	0.293	3.787	0.052	0.133
SESRA-S[8] (sex role attitude)	643	475	−0.069	0.095	0.1	0.752	0.678	7.206	0.007	0.037
Life event										
Negative life event	700	512	0.003	0.022	0.419	0.517	0.57	0.215	0.643	0.627
Positive life event	700	512	0.043	0.123	8.383	0.004	0.023	1.978	0.16	0.283

[1] False discovery rate. [2] Raven's Advanced Progressive Matrices. [3] Tanaka B-type intelligence test. [4] General Health Questionnaire 30. [5] Checklist individual strength. [6] State-Trait Anxiety Inventory. [7] Profile of Mood States (POMS). Total mood disturbance. [8] Egalitarian Sex Role Attitudes-Short Form.

TABLE 3 | Main Effects of parents' average highest educational qualifications as well as effects of interaction between sex and parents' average highest educational qualifications on psychological measures.

	N male	N female	Correlation coefficient male	Correlation coefficient female	Main effect *F*-value	Main effect *P*-value, uncorrected	Main effect, *P*-value, FDR	Interaction effect *F*-value	Interaction effect *P*-value uncorrected	Interaction effect *P*-value FDR
Cognitive functions										
RAPM (intelligence, non-verbal reasoning)	701	514	0.088	0.054	6	0.014	0.062	0.353	0.553	0.588
TBIT (intelligence)	634	459	0.114	0.117	13.97	1.95×10^{-4}	0.004	0.006	0.939	0.727
Reading comprehension	608	423	0.048	0.03	1.583	0.209	0.329	0.069	0.793	0.691
S-A creativity test	702	514	0.153	0.098	18.603	1.7×10^{-5}	0.001	0.986	0.321	0.461
Digit span	699	511	0.011	0.021	0.274	0.601	0.596	0.02	0.889	0.719
Traits and states										
Empathizing	702	514	0.004	0.033	0.318	0.573	0.596	0.394	0.531	0.576
Systemizing	702	514	0.054	0.165	12.678	3.84×10^{-4}	0.005	2.978	0.085	0.181
Emotional Intelligence Scale	699	514	0.072	0.071	5.834	0.016	0.065	4.16×10^{-4}	0.984	0.736
GHQ30	698	513	−0.088	0.005	1.999	0.158	0.283	2.531	0.112	0.222
WHOQOL-26	699	514	0.12	0.068	10.369	0.001	0.012	0.837	0.361	0.482
Critical thinking disposition	700	514	0.052	0.175	14.553	1.43×10^{-4}	0.004	4.446	0.035	0.101
Cognitive reflectivity–Impulsiveness	699	514	−0.024	0.072	0.762	0.383	0.5	2.855	0.091	0.187
Need for Cognition	700	514	0.054	0.12	8.674	0.003	0.022	1.329	0.249	0.372
Self-fulfillment Achievement Motivation	700	514	0.045	0.084	4.887	0.027	0.089	0.558	0.455	0.545
Competitive Achievement Motivation	700	514	−0.037	−0.046	2.027	0.155	0.283	0.06	0.806	0.694
Self-esteem	700	514	0.059	0.071	4.835	0.028	0.089	0.075	0.784	0.691
Need for uniqueness	699	514	0.135	0.082	13.964	1.95×10^{-4}	0.004	0.961	0.327	0.461
Patriotism	699	514	0.044	−0.066	0.1	0.752	0.678	3.503	0.062	0.141
Nationalism	699	514	0.061	−0.062	0.003	0.96	0.736	4.334	0.038	0.103
Optimism	699	514	0.08	0.04	4.111	0.043	0.115	0.371	0.543	0.583
Pessimism	699	514	−0.058	−0.047	3.161	0.076	0.171	0.031	0.861	0.712
Self-efficacy	699	513	0.056	0.059	3.666	0.056	0.134	0.014	0.906	0.719
UCLA Loneliness Scale	700	514	−0.041	−0.04	1.869	0.172	0.293	1.32×10^{-4}	0.991	0.736
CIS-20 (fatigue)	698	514	−0.082	−0.07	6.677	0.01	0.045	0.015	0.903	0.719
Beck Depression Inventory	641	476	−0.062	−0.073	4.976	0.026	0.088	0.069	0.792	0.691
STAI_state (anxiety state)	641	476	−0.088	−0.078	7.418	0.007	0.034	0.023	0.88	0.719
STAI_trait (anxiety trait)	641	476	−0.088	−0.109	10.467	0.001	0.012	0.291	0.589	0.596
POMS-TMD (mood disturbance)	690	510	−0.095	−0.022	3.691	0.055	0.134	1.198	0.274	0.404
Neuroticism	701	514	−0.048	−0.08	4.608	0.032	0.097	0.478	0.49	0.552
Extraversion	701	514	0.095	0.053	6.302	0.012	0.054	0.483	0.487	0.552
Openness	701	514	0.097	0.125	14.661	1.35×10^{-4}	0.004	0.305	0.581	0.596
Agreeableness	701	514	−0.022	−0.023	0.721	0.396	0.512	0.007	0.935	0.727
Conscientiousness	701	514	−0.018	0.023	0.001	0.976	0.736	0.57	0.451	0.545
Jealousy	644	476	−0.078	−0.053	4.34	0.037	0.103	0.055	0.815	0.694
Self-Preoccupation	644	476	−0.025	−0.005	0.159	0.69	0.645	0.042	0.838	0.708
External-Preoccupation	644	476	−0.036	0.075	0.559	0.455	0.545	3.507	0.061	0.141
SESRA-S (sex role attitude)	644	476	−0.027	0.063	0.279	0.597	0.596	2.164	0.142	0.267
Life event										
Negative life event	702	514	0.014	0.021	0.507	0.477	0.552	1.35×10^{-6}	0.999	0.736
Positive life event	702	514	0.043	0.123	4.447	0.035	0.101	0.169	0.681	0.645

cluster 2 (**Table 4**), which mainly involves the left fusiform gyrus, left hippocampus and parahippocampal gyrus, left insula, left lingual gyrus, left occipital lobe, left parietal lobe, and perisylvian areas and the left thalamus ($p = 0.006$); (3) a significantly positive main effect of the competitive achievement motivation score on the mean rGMV values of the significant

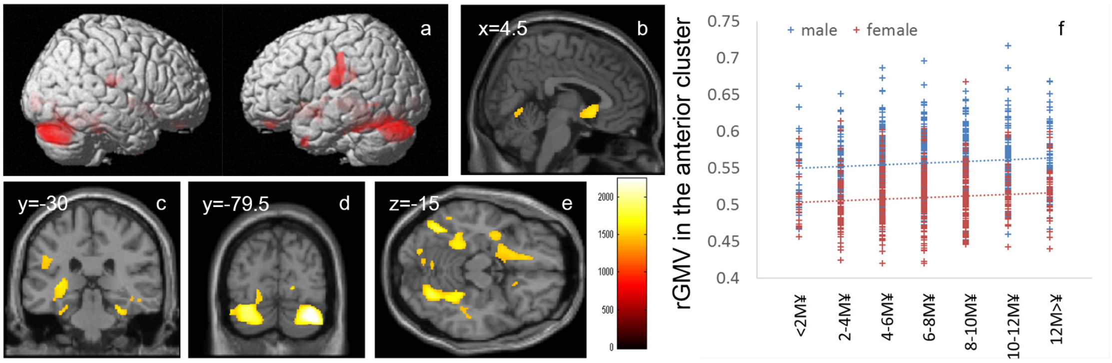

FIGURE 2 | Positive main effects of family annual income on rGMV. **(a–e)** The results shown were obtained using a threshold of threshold-free cluster enhancement (TFCE) of $P < 0.05$ based on 5000 permutations. The results were corrected at the whole-brain level. **(b–e)** Regions with significant correlations are overlaid on a "single subject" T1 image of SPM8. The color represents the strength of the TFCE value. Significant positive main effects of family annual income on family income were mainly observed in **(a)** the bilateral perisylvian areas, **(b)** subgenual cingulate gyrus, **(c)** bilateral hippocampus, **(d)** bilateral cerebellum, and **(e)** bilateral fusiform gyrus and occipital areas. **(e)** A scatter plot with trend lines depicting correlations between mean rGMV in the significant cluster of the anterior brain areas in males (blue) and females (red). **(f)** A scatter plot with trend lines depicting correlations with mean rGMV for the largest significant cluster in males (blue) and females (red).

TABLE 4 | Brain regions exhibiting significant main positive effects of family income on rGMV.

	Included gray matter areas (number of significant voxels in the left and right side of each anatomical area)*	*x*	*y*	*Z*	TFCE-value	Corrected *P*-value (FWE)	Cluster size (voxel)
1	Calcarine Cortex (L:7, R:320)/Fusiform gyrus (R:1300)/Lingual gyrus (R:426)/Parahippocampal gyrus (R:71)/Inferior temporal gyrus (R:20)/Middle temporal gyrus (R:2)/Cerebellum (R:5284)/	37.5	−81	−33	2238.828	0.011	7629
2	Fusiform gyrus (L:1255)/Heschl gyrus (L:5)/Hippocampus (L:312)/Insula (L:268)/Lingual gyrus (L:303, R:21)/Inferior occipital lobe (L:137)/Parahippocampal gyrus (L:379)/Inferior parietal lobule (L:47)/Postcentral gyrus (L:817)/Putamen (L:13)/Rolandic operculum (L:443)/Supramarginal gyrus (L:628)/Inferior temporal gyrus (L:578)/Middle temporal gyrus (L:92)/Superior temporal gyrus (L:103)/Thalamus (L:3710, R:3)/	−46.5	−69	−22.5	1909.474	0.0202	10585
3	Amygdala (L:62)/Caudate (L:365, R:339)/Superior frontal orbital area (L:153)/Hippocampus (L:1)/Insula (L:205)/Pallidum (L:102, R:12)/Putamen (L:333, R:4)/Rectus gyrus (L:456, R:63)/Rolandic operculum (L:2)/Superior temporal gyrus (L:10)/	−13.5	16.5	−10.5	1593.939	0.037	3505
4	Inferior temporal gyrus (L:82)/Temporal pole (L:66)/	−42	10.5	−48	1483.472	0.0448	348
5	Heschl gyrus (R:7)/Insula (R:1)/Rolandic operculum (R:338)/Supramarginal gyrus (R:58)/Superior temporal gyrus (R:36)/	54	−22.5	18	1475.474	0.045	448
6	Insula (R:113)/Putamen (R:11)/	40.5	−1.5	0	1442.859	0.048	193
7	Parahippocampal gyrus (R:2)	9	−6	−19.5	1436.221	0.0482	76

Labelings of the anatomical regions of gray matter were based on the WFU PickAtlas Tool (http://www.fmri.wfubmc.edu/cms/software#PickAtlas/) (Maldjian et al., 2003, 2004) and on the PickAtlas automated anatomical labeling atlas option (Tzourio-Mazoyer et al., 2002). Temporal pole areas included all subregions in the areas of this atlas.

cluster 5 (**Table 4**), which mainly involves the right insula, right Rolandic operculum, right supramarginal gyrus, and right superior temporal gyrus ($p = 0.008$); (4) a significantly negative main effect of the Beck Depression Inventory score on the mean rGMV values of the significant cluster 5 (**Table 4**), which involves the right insula, right Rolandic operculum, right supramarginal gyrus, and right superior temporal gyrus ($p = 0.008$); and (5) a significantly positive main effect of the positive life events score on the mean rGMV values of the significant cluster 7 (**Table 4**), which involves the right parahippocampal gyrus ($p = 0.010$).

Regarding the *post hoc* analyses of the parents' educational qualification, under the applied criteria, no significant association was found between the significant imaging correlates of the parents' educational qualification and psychological correlates of the parents' educational qualification in the specified direction. However, although in this study the parents' educational qualifications were not significantly associated with rGMV in whole brain analyses, the scores of intelligence tasks (TBIT; which comprise a significant psychological correlate of the parents' educational qualification's main effect) showed significant positive main effects (regardless of sex) on the mean

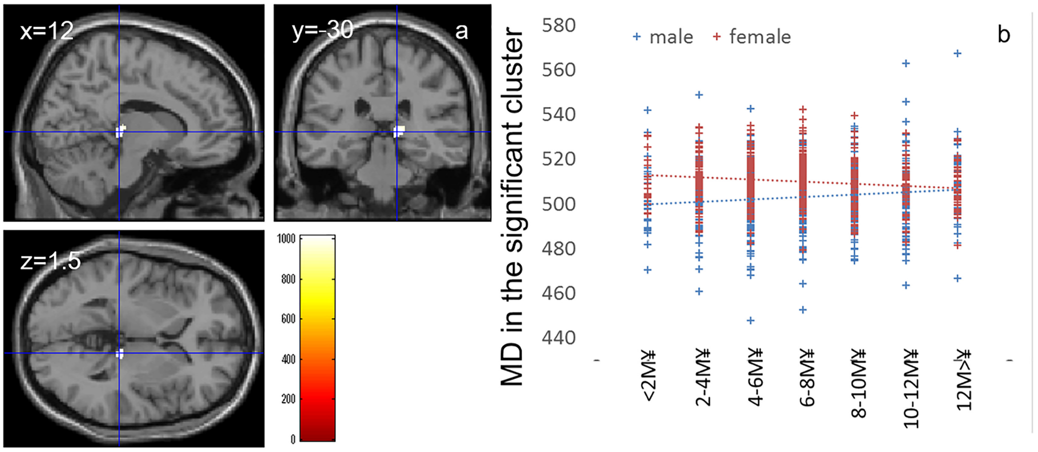

FIGURE 3 | Effects of interaction between sex and family annual income on MD that show a positive correlation in males and negative correlation in females. **(a)** The results shown were obtained using a threshold of threshold-free cluster enhancement (TFCE) of $P < 0.05$, based on 5000 permutations. The results were corrected at the whole brain level. Regions with significant correlations are overlaid on a "single subject" T1 image of SPM8. The color represents the strength of the TFCE value. Significant effects were observed in the thalamus. **(b)** A scatter plot with trend lines depicting correlations between mean MD for significant clusters of males (blue) and females (red).

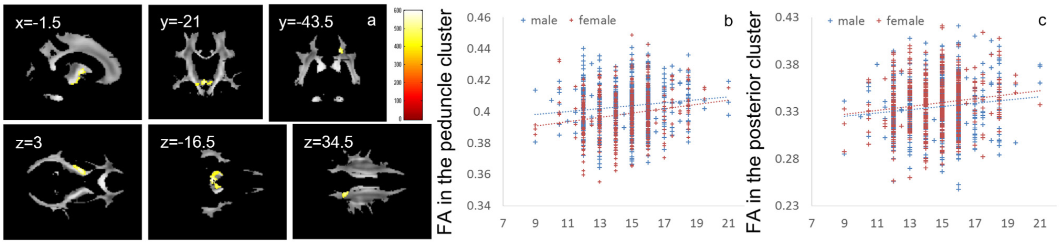

FIGURE 4 | Positive main effects of parents' average highest educational qualifications on FA. **(a)** The results shown were obtained using a threshold of threshold-free cluster enhancement (TFCE) of $P < 0.05$, based on 5000 permutations. The results were corrected at the whole brain level. Regions of correlation were overlaid on mean preprocessed, but not smoothed, FA images of a subset of participants. The color represents the strength of the TFCE value. Significant effects were observed near the peduncle and in posterior white matter areas. **(b–c)** Scatter plots with trend lines depicting correlations of mean FA for significant clusters in males (blue) and females (red) in the areas around the internal capsule and peduncle **(b)** and the white matter area in the parietal cortex **(c)**.

TABLE 5 | Brain regions exhibiting significant main positive effects of parents' average educational qualification on FA.

	Included large bundles* (number of significant voxels in left and right side of each anatomical area)	*x*	*y*	*z*	TFCE value	Corrected *p*-value (FWE)	Cluster size (voxel)
1	Superior cerebellar peduncle (L:1)/Cerebral peduncle (L:91, R:57)/Anterior limb of internal capsule (L:50)/Posterior limb of internal capsule (L:155)/Retrolenticular part of internal capsule (L:1)/	−1.5	−25.5	−13.5	598.9525	0.0086	729
2	Splenium of corpus callosum (13)/Posterior corona radiata (R:99)/	18	−43.5	34.5	517.5639	0.0168	170
3	None	7.5	−7.5	−15	407.5656	0.0424	5
4	None	−24	−4.5	13.5	393.8078	0.0494	2

**The anatomical labels and significant clusters of major white matter fibers were determined using the ICBM DTI-81 Atlas (http://www.bmap.ucla.edu/portfolio/atlases/ICBM_DTI-81_Atlas/).*

rGMV values of the significant cluster 3 (**Table 4**; significant correlates of main effects of family income; $p = 0.003$) and on the mean rGMV of the significant cluster 7 (**Table 4**; $p = 0.005$).

DISCUSSION

In this study, we newly investigated the effects of family SES on MD as well as the effects of interaction between family SES and

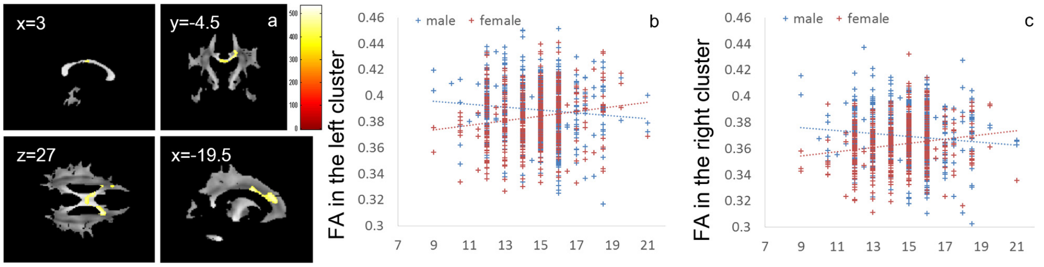

FIGURE 5 | Effects of interaction between sex and parents' average highest educational qualifications on FA that are moderated by positive correlation in females and negative correlation in males. **(a)** The results shown were obtained using a threshold of threshold-free cluster enhancement (TFCE) of $P < 0.05$, based on 5000 permutations. The results were corrected at the whole brain level. Regions of correlation were overlaid on mean preprocessed, but not smoothed, FA images of a subset of participants. The color represents the strength of the TFCE value. Significant effects were observed in areas around the body and genu of the corpus callosum and the bilateral corona radiata. **(b–c)** Scatter plots with trend lines depicting correlations with mean FA for significant clusters in males (blue) and females (red) in white matter areas in the left hemisphere **(b)** and right hemisphere **(c)**.

TABLE 6 | Brain regions exhibiting significant effects of interaction between parents' average educational qualification and sex (that are moderated by positive correlation in females and negative correlation in males) on FA.

	Included large bundles* (number of significant voxels in left and right side of each anatomical area)	*x*	*y*	*z*	TFCE value	Corrected *p* value (FWE)	Cluster size (voxel)
1	Genu of corpus callosum (18)/Body of corpus callosum (283)/Anterior corona radiata (L:189)/Superior corona radiata (L:68)/	–18	3	31.5	534.0439	0.0126	618
2	Genu of corpus callosum (14)/Body of corpus callosum (304)/Anterior corona radiata (R:213)/Superior corona radiata (R:175)	19.5	16.5	25.5	499.8084	0.0164	801

**The anatomical labels and significant clusters of major white matter fibers were determined using the ICBM DTI-81 Atlas (http://www.loni.ucla.edu/).*

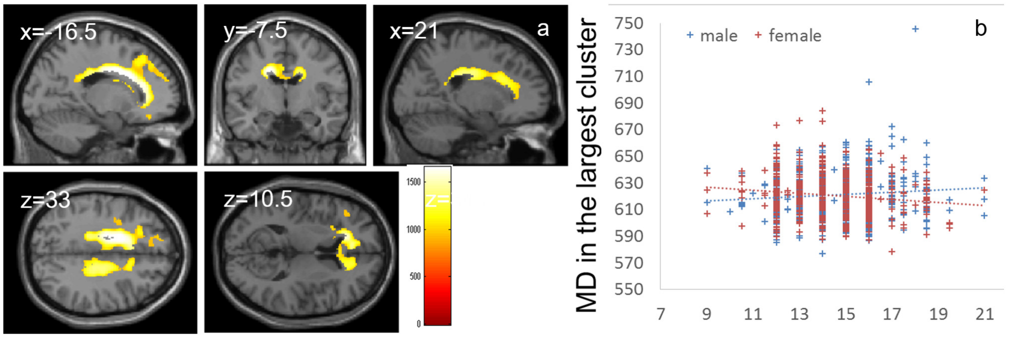

FIGURE 6 | Effects of interaction between sex and parents' average highest educational qualifications on MD that are moderated by positive correlation in males and negative correlation in females. **(a)** The results shown were obtained using a threshold of threshold-free cluster enhancement (TFCE) of $P < 0.05$, based on 5000 permutations. The results were corrected at the whole brain level. Regions with significant correlations are overlaid on a "single subject" T1 image of SPM8. The color represents the strength of the TFCE value. Significant effects were observed in areas around the body and genu of the corpus callosum, bilateral corona radiata, caudate, prefrontal areas, and insula. **(b)** A scatter plot with trend lines depicting correlations with mean MD for the largest significant cluster in males (blue) and females (red).

sex, particularly in terms of neural correlates. In contrast to our hypothesis, there were no significant main effects (regardless of sex) of family SES on MD. However, our first novel findings were that partly consistent with our hypothesis, there were significant effects of interaction between sex and parents' educational qualification on MD and FA in the body of the corpus callosum as well as in the white matter areas between the anterior cingulate cortex and lateral prefrontal cortex. Our second novel findings were, there was a significant effect between sex and family income on MD was in the thalamus. Consistent with previous studies, higher family income was associated with larger rGMV in areas related to effects, language-related areas, in both sexes together with other areas such as the visual cortex. Furthermore, higher educational qualification of parents was associated with greater FA in the white matter areas connecting cortical and subcortical areas.

Additional psychological analyses showed that greater family annual income was associated with a wide range of psychological measures related to positive effects and experiences (greater QOL, self-esteem, and experiences of positive life events as

TABLE 7 | Brain regions exhibiting significant effects of interaction between parents' average educational duration and sex (that are moderated by positive correlation in males and negative correlations in females) on MD.

Included gray matter areas*(number of significant voxels in left and right side of each anatomical area)	Included large bundles** (number of significant voxels in left and right side of each anatomical area)	*x*	*y*	*z*	TFCE value	Corrected *p*-value (FWE)	Cluster size (voxel)
Caudate (L:129, R:64)/Anterior cingulum (L:814, R:1135)/Middle cingulum (L:642, R:420)/Posterior cingulum (R:3)/Inferior frontal orbital area (L:40)/Middle frontal medial area (R:33)/Middle frontal orbital area (L:121)/Middle frontal other areas (L:612)/Superior frontal medial area (L:390, R:23)/Superior frontal orbital area (L:63)/Superior frontal other areas (L:729)/Insula (L:111)/Supplemental motor area (L:1)/	Genu of corpus callosum (1478)/Body of corpus callosum (1993)/Splenium of corpus callosum (551)/Anterior limb of internal capsule (L:30)/Anterior corona radiata (L:1551, R:847)/Superior corona radiata (L:951, R:750)/Posterior corona radiata (L:123, R:383)/External capsule (L:10)/Cingulum (L:458, R:234)/Superior longitudinal fasciculus (R:1)/Superior fronto-occipital fasciculus (L:42, R:5)/Tapatum (L:15, R:20)	–16.5	3	33	1659.942	0.0072	14756
Inferior frontal operculum (L:38)/Inferior frontal triangular (L:354)/Middle frontal other areas (L:17)/Precentral gyrus (L:162)/	None	–34.5	1.5	36	984.6044	0.04	619
Inferior frontal triangular (L:11)/Middle frontal other areas (L:9)	None	–43.5	34.5	27	911.0997	0.0494	20

**Labelings of the anatomical regions of gray matter were based on the WFU PickAtlas Tool (http://www.fmri.wfubmc.edu/cms/software#PickAtlas/) (Maldjian et al., 2003, 2004) and on the PickAtlas automated anatomical labeling atlas option (Tzourio-Mazoyer et al., 2002). Temporal pole areas included all subregions in the areas of this atlas. **The anatomical labels and significant clusters of major white matter fibers were determined using the ICBM DTI-81 Atlas (http://www.loni.ucla.edu/).*

well as lesser pessimism, loneliness, and trait anxiety) and traits that are supported by or support positive effects (greater emotional intelligence, extraversion, and need for uniqueness). These findings are generally consistent with the pattern reported in previous studies (lesser psychological distress, lesser stress, and greater well-being) (Ursache and Noble, 2016a). In contrast to previous studies, we found that family annual income was not associated with cognitive function (Ursache and Noble, 2016a). This may be because we focused on college students and the educational qualification of subjects was generally high. Among individuals in this study population, family income may have little association with cognitive function. Interestingly, family income was associated with greater nationalism and competitive achievement motivation, which is a third novel finding. The reason for this association is not clear; however, we have previously shown greater nationalism is associated with a feeling of superiority to others (Takeuchi et al., 2016b), and the data in the present sample also showed a positive correlation between competitive achievement motivation and a feeling of superiority to others. This kind of feeling caused by greater family income may lead to nationalism and competitive achievement motivation. Our results suggest that greater annual family income is associated with a greater stereotype regarding the sex role in males but a smaller stereotype regarding the sex role in females. This finding is congruent with the previous report that high SES females are more likely than low SES females to choose male-dominated occupations (Hannah and Kahn, 1989) and may reflect that regardless of sex, subjects hold beliefs that allow them to work. On the other hand, higher educational qualification of parents was positively associated with greater cognitive functioning (intelligence and creativity measured by divergent thinking) and greater traits and states related to more positive effects and experiences (greater QOL, lesser chronic fatigue, and lesser state and trait anxiety), which is consistent with the findings of previous studies (Ursache and Noble, 2016a). The present finding, which was not reported in the previous review (Ursache and Noble, 2016a), was that higher educational qualification of parents was associated with increase in multiple traits that facilitate more academic thoughts, such as systemizing (drive to analyze a system) (Baron-Cohen et al., 2005), need for cognition (tendency for an individual to engage in and enjoy thinking) (Kouyama and Fujiwara, 1991), and openness (which includes intellectual curiosity and ideas) (Costa and MacCrae, 1992). This effect may be due to the parents' educational qualification or genetics (parents with greater familiarity with academic issues tend to have children with the same characteristic), but this speculation cannot be validated with a cross-sectional study.

Higher family income was associated with greater rGMV in (a) areas involved in language, such as the cerebellum, fusiform gyrus, lingual gyrus, and perisylvian areas, and (b) areas involved in effects, mood, and stress, such as the insula, the hippocampus, amygdala, and the subgenual cingulate gyrus, and its surrounding area (although the results are widespread and include other sparse areas such as areas in the visual cortex). Language areas, medial temporal lobe structures, and the prefrontal cortex are areas associated with family SES, and the positive effects of family income on rGMV are consistent with previous findings (Ursache and Noble, 2016a). The fusiform gyrus is associated with visual word recognition (Price, 2000). The perisylvian areas are consistently activated during language processing, and cortical structures in this area play key roles in various language-related processing, such as phonological processing, syntactic processing, and articulatory processing (Price, 2000). The cerebellum is also involved in articulatory processes (Baddeley, 2003). Larger rGMV in these areas may underlie the associations between higher family SES and a wide range of greater language-related competence (Ursache and Noble, 2016a). The prefrontal cortex, particularly the medial prefrontal areas, hippocampus, and amygdala, is most affected by stress (Takeuchi and Kawashima, 2016). A previous review suggested that lower SES leads to greater stress, which in turn impacts the function and structure of these areas (Ursache and Noble, 2016a). Dysfunction of the amygdala caused by stress has been suggested to lead to dysfunction of social and emotional processing (Ursache and Noble, 2016a). Particularly, the subgenual cingulate gyrus is most consistently affected by depression and plays a key role in emotion regulation (Drevets et al., 2008). Greater rGMV in these areas may underlie the associations between higher family SES and a wide range of positive effects and self-regulatory behaviors found in this study and previous studies (Ursache and Noble, 2016a). Partly consistent with this notion, our exploratory supplemental analyses showed that (1) lower pessimism, which may decrease the personal subjective stress as well as (2) more experience of positive life events, is associated with greater rGMV of the significant clusters involving the hippocampus and contingent areas. Both these psychological characteristics were associated with a greater family income. Furthermore, the insula receives inputs from a wide range of areas and is involved in a wide range of emotions (Nagai et al., 2007). We have previously shown that the insula's regional gray matter structure is associated with greater competitive achievement motivation (Takeuchi et al., 2014b), and a previous review pointed out that rGMV reduction in this area is associated with depression and a wide range of psychiatric disorders (Nagai et al., 2007). Partly consistent with this notion, our exploratory supplemental analyses show that both a lower level of depression and a higher competitive achievement motivation are associated with greater rGMV of the significant clusters involving the insula. Both those psychological characteristics were associated with a higher family income.

The lack of significant associations between brain volume measures and parents' average highest educational qualifications may be due to the complex associations between neural plasticity and rGMV. Previous studies on the associations between parents' educational qualification and measures of gray matter are inconsistent. Studies have generally shown positive associations between family SES and measures related to gray matter volume (Ursache and Noble, 2016a). However, a few studies in young adults have not shown this association. Kong et al. (2015) have revealed that a mother's educational qualification is negatively correlated with rGMV in the medial prefrontal cortex in young adults. Yang et al. (2016) have also shown a negative relationship between family SES and rGMV in the medial prefrontal cortex. Another recent study has investigated the associations between parents' educational qualification and cortical thickness and surface area in a wide developmental age range (Piccolo et al., 2016). This study has revealed that children of parents with high educational qualification show greater developmental cortical thinning in the later phase of development and as a result, it seems, while during the age of elementary school and junior high school, children of parents with high education level show greater cortical thickness, that difference becomes unclear by the age of the young adults (Piccolo et al., 2016). The reason for this phenomenon is not clear; however, the authors have suggested that a low level of stimulation from environments in the children of parents with low educational qualification leads to earlier pruning or a shorter window for sensitive developmental periods which are counterproductive (Piccolo et al., 2016). The mean age of participants in the present study was approximately 21 years (young adults), an age that may make the associations between rGMV and parents' educational qualification unclear according to this observation (Piccolo et al., 2016).

There were positive correlations between FA and parents' average highest educational qualifications in (a) the internal capsule, which connects the midbrain and extensive areas of the cortex and underlies the brain's extensive information processing, and (b) the splenium of the corpus callosum and right posterior corona radiata, which underlies higher-order information processing. The internal capsule consists of white matter fibers that connect the midbrain and brainstem as well as extensive areas of the brain; thus, these fibers are responsible for a wide range of basic information processing in the brain (Greenstein and Greenstein, 2000). The posterior corona radiata includes axons from and to the cerebral cortex, parietal lobe, and sensorimotor cortex (Dougherty et al., 2007). The dorsal part of the splenium of the corpus callosum connects the bilateral inferior parietal lobule (Pandya et al., 1971). These parietal areas are involved in a wide range of higher-order information processing, such as attention and spatial information processing (Yantis et al., 2002). The positive associations between parents' average highest educational qualifications and FA in these areas may underlie many of the associations observed between cognitive function and parents' average highest educational qualifications. However, *post hoc* exploratory analyses showed no associations between the mean DTI values of significant clusters of the educational qualification of parents and psychological correlates of the educational qualification of parents in the expected direction. Therefore, other neural mechanisms that could not be detected with the methods used in the present study may underlie the significant associations between psychological variables and the parents' educational qualifications. A previous study (Ursache and Noble, 2016b) has shown that parents' educational qualification positively correlates with similar white matter tracts in the parietal cortex in the left hemisphere and that family income positively correlates with higher FA in areas of the right parahippocampal cingulum and right white matter in the frontal cortex. The present study failed to find significant associations with FA. The reasons for discrepancies between these two studies are unclear. One possible reason could be the lack of statistical power (as well as weak true effects of family SES on FA) to reveal the whole picture of the associations between family SES and FA. Consistent with this speculation, our present data show weak associations between FA and parents' educational qualification in the frontal cortex and parahippocampal areas.

It is not possible to ascertain the causal mechanism underlying the positive associations among rGMV, FA, and family SES from the cross-sectional design of this study. One possible mechanism is use-dependent neural plasticity. It is known that higher family SES leads to a rich cognitive environment that includes more cognitive stimulation and a better educational environment (Ursache and Noble, 2016a). On the other hand, cognitive stimulation leads to an increase in rGMV and FA, perhaps through increased myelination and tissue components, such as synapses (Takeuchi et al., 2010a). However, other environmental influences, such as nutrition and stress, which are associated with family SES, as well as genetic influences cannot be excluded (Ursache and Noble, 2016a).

The interaction effects of MD, FA, and parents' average highest educational qualifications were mainly found in the areas of (a) the body of the corpus callosum (Barbas and Pandya, 1984), which connects the bilateral dorsolateral prefrontal cortices that play a key role in the central executive system, and (b) the anterior part of the corona radiata and superior longitudinal fasciculus, which exists between the bilateral lateral prefrontal cortex and anterior cingulate cortex, as well as the parietal area (Pandya et al., 1971); all these areas play a key role in higher-order cognitive functions (Takeuchi et al., 2010a). Similarly, interaction effects between MD and family income were found in the thalamus, which plays a fundamental role in information processing involving the cortex (Sato et al., 2015). The thalamus also plays a fundamental role in coordinating information flow in the brain, integrating broad cognitive processes, such as incoming sensory impulses of pain, and regulating arousal and sleep (for summary, see Sato et al., 2015). The present interaction effects suggest that an association of family SES with higher-order information processing and basic information processing. The interaction effects were mediated by tendencies of negative/positive correlations in males/females for FA and positive/negative correlations in males/females for MD. An increase in FA and decrease in MD may be mediated by increases in myelination and synapses (in the Introduction, see the list of possible tissue mechanisms that impact these values) while the MD changes without FA can be caused by a wide range of neural tissue changes.

We can speculate on why these interaction effects on FA and MD were observed. First, previous animal studies have shown that in response to stressors, females and males show opposite neural changes in some measures. For example, Shors et al. (2001) have reported that in response to stress, females show decreased synapse density, whereas males show increased synapse density. Notably, family SES is associated with stress levels (Ursache and Noble, 2016a). Thus, family SES may impact FA and MD differently in males and females. Second, there may be a sex difference in how family SES is associated with behaviors or traits, which leads to use-dependent plasticity and changes in FA and MD. As shown in the present study, family income was negatively associated with sex role stereotypes in women (which includes the idea that women should not have jobs) but not in men. The egalitarian view regarding sex roles may lead to more eager learning, which may facilitate neural plasticity (Draganski et al., 2006). In addition, parents' educational qualification was positively associated with more "cognitive" thinking styles or traits (systemizing, critical thinking disposition, and need for cognition). However, there were no significant interaction effects between sex and parents' educational qualification on these measures after correction for multiple comparisons. Uncorrected, there was a significant interaction effect on systemizing and a trend toward an interaction effect on critical thinking disposition (females partly showed a stronger positive correlation). Traits involving more cognitive activities may lead to an increase in use-dependent plasticity in females. Third, there may be non-linear effects of stress. Stress is assumed to have an inverted-U effect on neural mechanisms, where small amounts of stress cause adaptive changes in neural systems but too much stress is detrimental. On the other hand, higher family SES is associated with lesser stress (Salehi et al., 2010), and human studies have shown that females tend to have more stress events (Hankin et al., 2007). Therefore, greater family SES may reduce males' stress too much (to too small level) and may not be adaptive in some aspects while for in females things are the opposite and greater family SES may reduce females' stress to appropriate level. However, our macro-level cross-sectional neuroimaging study cannot determine which of these factors contribute to our findings on the effects of interaction between sex and family SES on FA and MD.

The effects of family SES on brain structure have often been investigated using objective SES methods i.e., family income, income to needs, parents' education levels; (for review, see Hurt and Betancourt, 2015). On the other hand, for several topics such as health-related outcomes, the subjective effects of SES (i.e., the individual's perception of his own position in the social hierarchy) are well investigated. Previous studies have shown that the subjective SES are more strongly or independently associated with health-related outcomes (Singh-Manoux et al., 2005; Cohen et al., 2008). Therefore, in some brain structures, especially those related to stress, subjective SES may be more or independently associated with brain imaging measures and the difference between the effects of subjective and objective SES measures on brain imaging measures constitutes an interesting topic for further studies.

The present study had at least one other limitation, i.e., limited sampling. Subjects of this study were young and healthy, consisting of mostly undergraduate and postgraduate students, meaning that they are well educated and the variance of relevant psychological measures may be relatively smaller than that in the general population. This is a common hazard of studies using college students (Jung et al., 2010). This may explain the lack of significant effects of SES measures on some basic cognitive function measures, such as non-verbal reasoning and working memory. In addition, although the present study was focused on the association between family SES and brain structures among imaging measures, when functional activities during working memory and simple cognitive processes [i.e., activities during the 2-back working memory task and the 0-back working memory task (Takeuchi et al., 2018)] are used as dependent variables, no significant main effects of the family SES or of the interaction between family SES and sex were found on such brain activity measures (briefly, the analyses were performed according to our previous study on genotype (Takeuchi et al., 2018), except that the independent variable of interest was replaced from the genotype to either family income or parents' educational qualifications). The associations between SES measures and psychological/imaging measures may be different in other demographic groups. However, these observations support the importance of assessing the effects of SES measures on a wide range of measures related to traits, states, and effects and relevant neural mechanisms. Also, effects of environment on cognitive mechanisms may be more evident during childhood and in disadvantaged environments and this fact might lead to smaller effects in the present study involving educated samples in developed countries (Haworth et al., 2010). On the other hand, our sample involved young adults and the development of the brain is still continuing and sex differences of developmental timing exist and any sex differences observed in this study may have something to do with sex differences of developmental timing (Taki et al., 2013). Nonetheless, future studies are needed to elucidate the effects of SES measures on the psychological/imaging measures in the general population. Also, as were the cases of all studies in the field, we used SES measures, and any associations between SES measures and outcome measures can be due to intermediate factors. These intermediate factors of course include genetic factors. Since it is a common matter in studies of correlates of SES measures, we did not even try to control these intermediate factors, and future studies can reveal them.

CONCLUSION

In conclusion, previous studies have revealed that family SES is positively associated with greater cognitive abilities, brain volume, and FA (white matter structural property). These findings were at least partly replicated in the present study involving young adults with a high educational qualification. The present study revealed that family income was associated with microstructural properties of the thalamus (females with greater family income show lower MD and males showed opposite patterns), which plays a key role in basic information processing in the brain. Furthermore, parents' educational qualification was associated with sex-specific microstructural properties of white matter areas that play a key role in higher-order cognitive activities (females with family education level show greater FA or lower MD in females and opposite in males). These results suggest that sex-specific neural and/or cognitive mechanisms are associated with family SES and neural tissue characteristics. Family income also showed sex-specific associations with sex role stereotypes (females with more family income showed reduced sex role stereotypes). In addition, family SES was associated with a wide range of psychological properties related to well-being. Family income was also associated with greater nationalism and competitive achievement motivation, and parents' educational qualification was associated with traits related to more cognitive thinking styles. These results suggest that family SES impacts a wide range of traits.

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

ETHICS STATEMENT

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

AUTHOR CONTRIBUTIONS

HT, YT, and RK designed the study. HT, AS, RN, YK, SN, CM, KI, RY, YY, SH, TA, YS, KS, TN, SI, SY, and DM collected the data. HT analyzed the data and prepared the manuscript.

FUNDING

This study was supported by a Grant-in-Aid for Young Scientists (B) (KAKENHI 23700306) and a Grant-in-Aid for Young Scientists (A) (KAKENHI 25700012) from the Ministry of Education, Culture, Sports, Science, and Technology.

ACKNOWLEDGMENTS

We respectfully thank Yuki Yamada for operating the MRI scanner, Yuriko Suzuki from Philips for advice on the DTI, and Haruka Nouchi for being an examiner of psychological tests. We also thank study participants, the other examiners of psychological tests, and all of our colleagues in Institute of Development, Aging and Cancer and in Tohoku University for their support. We would also like to thank Enago (www.enago.jp) for the English language review.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2018.00543/full#supplementary-material

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

BRIEF RESEARCH REPORT
published: 12 February 2019
doi: 10.3389/fnhum.2019.00041

No Money, No Problem: Enhanced Reward Positivity in the Absence of Monetary Reward

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The reward-related positivity (RewP) is an event-related potential (ERP) with a positive amplitude occurring approximately 250–350 ms post-feedback at frontocentral electroencephalogram (EEG) electrode sites. The RewP is typically elicited in monetary gambling tasks and has a relatively larger amplitude for positive vs. negative outcomes. However, the extent to which RewP amplitude is modulated by non-monetary feedback is less clear. To address this issue, EEG was used to record reward-related electrocortical activity during a simple non-monetary gambling task. We hypothesized that the RewP would be enhanced for non-monetary wins relative to losses, which was supported by the results. In our supplementary material, we provide additional analyses suggesting that this effect was not observed for the P3. In sum, RewP amplitudes were larger for positive (nonmonetary) feedback relative to negative feedback at frontocentral electrode sites—suggesting that monetary reward is not necessary to elicit the RewP.

Keywords: monetary, reward positivity, EEG, feedback negativity, medial frontal negativity, feedback error-related negativity

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Received: *28 August 2018*
Accepted: *25 January 2019*
Published: *12 February 2019*

Citation:
Tunison E, Sylvain R, Sterr J, Hiley V and Carlson JM (2019) No Money, No Problem: Enhanced Reward Positivity in the Absence of Monetary Reward. Front. Hum. Neurosci. 13:41. doi: 10.3389/fnhum.2019.00041

INTRODUCTION

The reward-related positivity (RewP) is an event-related potential (ERP) with a positive amplitude occurring approximately 250–350 ms post-feedback at frontocentral electroencephalogram (EEG) electrode sites. The RewP is derived from earlier ERP terminology including the feedback negativity (FN), feedback-related negativity (FRN), medial frontal negativity (MFN), and feedback error-related negativity (FERN) used to describe this component (Miltner et al., 1997; Holroyd et al., 2008; Proudfit, 2015; Krigolson, 2017). However, RewP amplitude is relatively larger for rewarding or positive feedback compared to neutral or negative feedback and therefore more accurately reflects neural activity associated with reward (rather than error) processing (Holroyd et al., 2008; Proudfit, 2015). In particular, the RewP is thought to index reward-related activity in the mesocortical dopamine system (Holroyd and Coles, 2002; Holroyd et al., 2004).

In support of this point of view, converging evidence from functional and structural magnetic resonance imaging studies have linked RewP amplitude to activity in the ventral striatum and other reward system circuitry (Carlson et al., 2011; Becker et al., 2014), as well as the volume of dopaminergic midbrain structures such as the ventral tegmental area (Carlson et al., 2015). At a behavioral level, variability in RewP amplitude has been shown to correlate with symptoms of blunted reward processing in anhedonic depression (Foti et al., 2014; Liu et al., 2014) and serve as a risk factor for the development of major depressive disorder (Bress et al., 2013). Conversely, RewP amplitudes are elevated in individuals with higher levels of self-reported reward responsiveness

(Bress and Hajcak, 2013) and is sensitive to reward magnitude (San Martín et al., 2010). Thus, RewP amplitudes can be thought of as a neural index of reward reactivity.

Most studies use simple gambling tasks with monetary rewards/wins and non-rewards/losses to elicit RewP responses (e.g., Hajcak et al., 2006; Holroyd et al., 2008; Proudfit, 2015). Recently, however, RewP amplitudes have been studied in other contexts. For example, one study found an enhanced RewP for monetary, but not social (i.e., a smiling face), rewards (Flores et al., 2015). In addition, a study by Weinberg et al. (2014) found that RewP amplitudes were elevated in conditions where participants received monetary rewards relative to conditions where participants received non-monetary feedback. This study also found that participants elicited a (non-significant) trend-level enhancement of the RewP for wins vs. losses in the non-monetary condition. Similarly, RewP amplitudes have been found to be enhanced for non-monetary points, but not rewarding images (Brown and Cavanagh, 2018). Thus, the RewP appears to be most sensitive to monetary feedback, but may also be sensitive to rewarding non-monetary feedback as well. This pattern of results is consistent with previous findings that feedback processing reflects the relative value of an outcome based on the range of possible outcomes rather than the objective outcome value (Holroyd et al., 2004). That is, the abovementioned studies have included multiple reward values (e.g., monetary and non-monetary) and in this context RewP amplitudes for non-monterary rewards may be relatively smaller due to the relatively lower value associated with non-monetary rewards compared to monetary rewards.

Given that the evidence for RewP reactivity to non-monetary rewards in gambling tasks is based on a limited number of studies that include of a range of possible reward outcomes, the sensitivity of the RewP to non-monetary feedback warrants further investigation. The primary aim of this study was to directly compare RewP amplitudes for wins and losses in a non-monetary (i.e., point-based) version of a simple gambling task with only two outcome types: wins and losses. We hypothesized that RewP amplitudes would be larger for non-monetary wins compared to losses.

MATERIALS AND METHODS

Participants

Thirty undergraduate students (female = 21, right handed = 29) between the age of 18–26 ($M = 19.7$, $SD = 2.05$) provided informed consent and participated in the study for course credit. Data were excluded for four participants who did not have at least 20 artifact free trials in all conditions (e.g., Marco-Pallares et al., 2011) and an additional four participants due to technical problems (e.g., experiment crashed during testing session). The remaining sample consisted of 22 students (female = 16, right handed = 21, $M = 19.45$, $SD = 1.74$). The appropriate sample size was determined by utilizing the effect size reported in Weinberg et al. (2014) for the non-monetary win vs. loss difference. In particular, using G*Power 3.1.9.2 with $d = 0.58$, $\alpha = 0.05$, and power = 0.80 it was determined that an $N \geq 20$ would be needed to detect win > loss RewP amplitudes. The study was approved by the Northern Michigan University Human Subjects Committee. All participants provided informed written consent.

Gambling "Doors" Task

The task was based on previous RewP studies using monetary rewards (Hajcak et al., 2006; Carlson et al., 2011), but modified to use non-monetary (i.e., point-based) rewards and losses. Points in the current study were entirely abstract and not exchanged for prizes at the end of the study. The task was programmed and administered using E-prime (Psychology Software Tools, Pittsburg, PA, USA) and trial events were linked to Net Station acquisition software (Phillips Neuro, Eugene, OR, USA).

As seen in **Figure 1**, each trial began with a white fixation cue (+) centered on a black background for 500 ms. Two doors were then simultaneously presented side-by-side on the horizontal midline. Participants were instructed that behind one door there was a gain of points and behind the other door there was a loss of points; they were then instructed to choose one door. The doors remained until a response was made. Afterwards, the fixation cue (+) re-appeared for 500 ms and was followed by feedback indicating a win/gain or loss of points. Gains (+1,250 points) were indicated by a green upwards arrow and losses (−625 points) were indicated by a red downwards

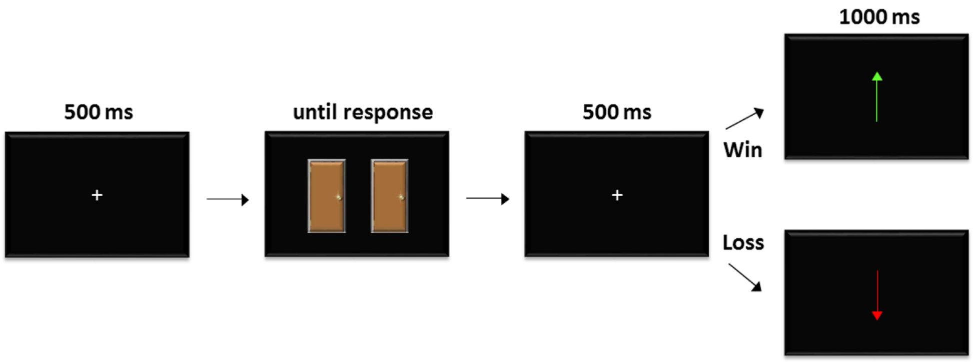

FIGURE 1 | Participants were told to make a choice in door, and that one door contained a gain in points (win) and the other contained a decrease in points (loss). After a choice, predetermined feedback was given (120 wins and 120 losses).

arrow (losses perceived twice as valuable as wins; Tversky and Kahneman, 1992). Unknown to participants, feedback was pre-determined and randomized with 120 wins and 120 losses.

EEG Acquisition and Data Processing

Continuous EEG recordings were collected using EGI's HydroCel GSN 130 series 64-electrode cap based on a 10/20 system. The sampling rate for data digitization was 250 Hz. Similar to other studies using the EGI net, electrode impedances were kept under 75 kΩ (Carlson and Reinke, 2010; Rizer et al., 2018). All aspects of EEG data processing were performed with EGI NetStation Waveform Tools. Continuous EEG data were low-pass filtered at 30 Hz and high-pass filtered at 0.1 Hz. The EEG segmentation was time-locked to the stimulus feedback with 200 ms prior to feedback and 600 ms post feedback. Data then underwent an artifact detection process where amplitude deflections of at least 140 μV at eye-blink electrodes were considered eye-blinks and amplitude deflections of 55 μV or greater at eye-movement electrodes were considered horizontal eye-movements. Segments containing eye-blinks or eye movements were excluded from data analysis. Additionally, segments with more than 10 bad channels were discarded. Channels were considered bad in each segment if the fast average amplitude exceeded 200 μV (this is a weighted running average algorithm within the NetStation software where a single data point exceeding threshold would not necessarily be marked as a bad channel, but several beyond threshold data points would be marked as bad), the differential average amplitude exceeded 100 μV, or a channel displayed zero variance. Additionally, channels were considered bad and replaced across segments if they met the above-mentioned criteria in more than 20% of segments. Bad channels were replaced with interpolated data using spherical splines from the remaining channels. The ERP segments were then averaged for each participant so that each electrode had a single waveform for each condition. The averaged segments were re-referenced to the average of all electrodes. A baseline correction of −100 to 0 ms was applied. Based on visual inspection, average RewP amplitudes were extracted between 250–300 ms from electrode FCz and Cz (Proudfit, 2015) for each participant.

RESULTS

A 2 × 2 repeated measures analysis of variance (ANOVA) was used to assess the effects of feedback type and electrode location on RewP amplitudes. There was an effect of feedback type, $F_{(1,21)} = 8.90$, $p = 0.007$, $\eta_p = 0.30$, where wins ($M = 3.82$ μV, $SE = 0.56$) resulted in larger RewP amplitudes compared to losses ($M = 2.66$ μV, $SE = 0.42$). As displayed in **Figure 2**, this was true at both electrode FCz (Wins: $M = 3.08$ μV, $SE = 0.63$; Losses: $M = 2.05$ μV, $SE = 0.51$, $p = 0.01$) and Cz (Wins: $M = 4.56$ μV, $SE = 0.61$; Losses: $M = 3.26$ μV, $SE = 0.43$, $p = 0.01$). There was a main effect of electrode location ($F_{(1,21)} = 8.70$, $p = 0.008$, $\eta_p^2 = 0.29$) where amplitudes were larger at Cz ($M = 3.91$ μV, $SE = 0.47$) relative to FCz ($M = 2.56$ μV, $SE = 0.54$); however, the feedback type × electrode location interaction was not significant, $F_{(1,21)} = 0.58$, $p = 0.45$, $\eta_p = 0.03$.

Given that the timeframe of the RewP overlaps with the P3, we preformed supplementary analyses on the P3. The P3 was not sensitive to outcome type (see **Supplementary Material**).

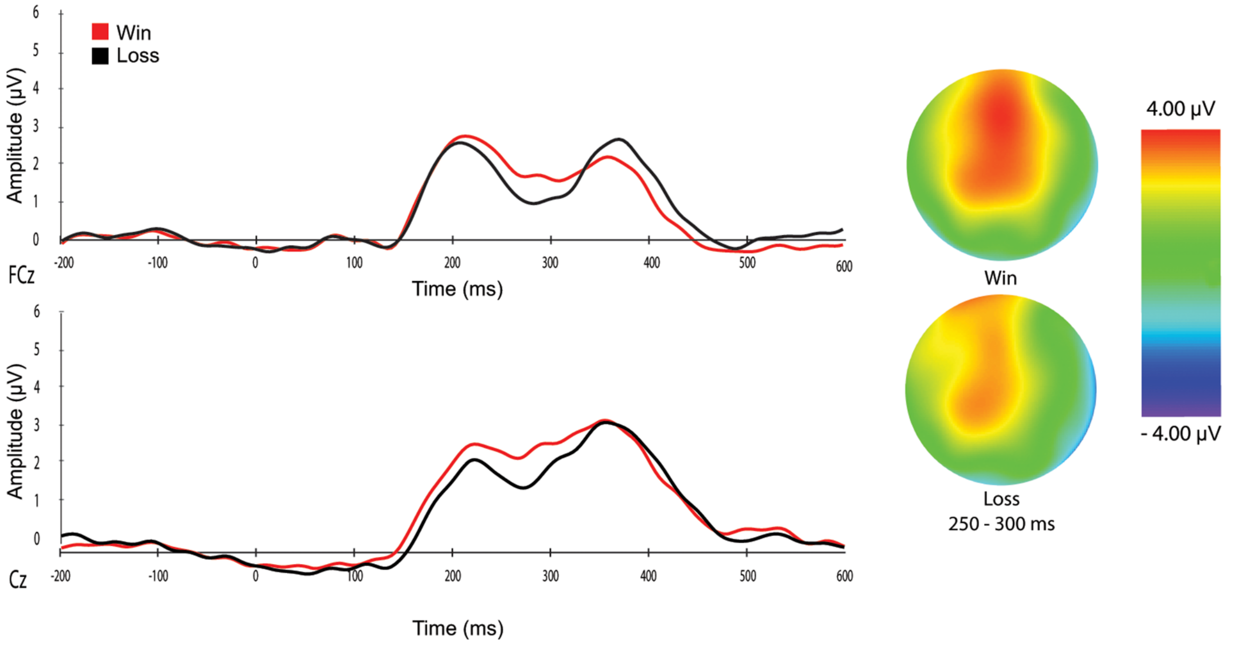

FIGURE 2 | (Left) Reward-related positivity (RewP) was maximally elicited at frontocentral electrode cites FCz and Cz. Amplitudes for wins (red) were larger than losses (black). (Right) A map of electrocortical polarity at 250–300 ms after presentation of either win or loss feedback. Areas in red reflect maximal positive amplitudes.

DISCUSSION

In this study, we used a well-defined gambling paradigm (Hajcak et al., 2006) to measure electrocortical responses associated with non-monetary gain or loss feedback. As hypothesized, we saw larger RewP amplitudes for non-monetary gains compared to non-monetary losses. The timing and location of this effect is consistent with previous research (Proudfit, 2015). As shown in **Figure 2**, the RewP was maximally observed at frontocentral electrodes (FCz and Cz) with a peak amplitude occurring approximately 280 ms post-feedback. The enhanced RewP for non-monetary wins observed in our results is consistent with previous findings that RewP amplitudes are modulated in non-monetary tasks (Weinberg et al., 2014; Brown and Cavanagh, 2018).

Given our results, in conjunction with previous studies (Weinberg et al., 2014; Brown and Cavanagh, 2018), it appears a financial incentive for participants may not be necessary. On the other hand, previous studies have shown that RewP (and other ERP) amplitudes are enhanced for monetized (relative to non-monetized) rewards (Van den Berg et al., 2012; Weinberg et al., 2014). Therefore, researchers will want to weigh the pros and cons of paying participants in their particular studies. Yet, for researchers wondering if it is *necessary* to pay participants to elicit the RewP, our results suggest the answer is no—the RewP can be measured without monetary incentive. This detail may be important for labs or institutions with limited financial resources.

Although we observed a RewP for non-monetary wins and losses in a simple gambling task, other forms of non-monetary rewards such as smiling faces (Flores et al., 2015) or other types of pleasant images (Brown and Cavanagh, 2018) do not appear to be effective in eliciting reward system activity as measured by the RewP. Previous research has shown that approach motivated states (Threadgill and Gable, 2016, 2018) or motivation for particular reward types (Angus et al., 2015) can affect RewP amplitude. Taken together, our findings and previous research (i.e., Weinberg et al., 2014; Flores et al., 2015; Brown and Cavanagh, 2018) indicate that non-monetary points or non-monetary wins in gambling tasks are more motivationally salient than other non-monetary reward types. This may be due to the fact that points are generally accumulated and can be used to gage one's performance over time, whereas rewarding images are rewarding in themselves, but are not cumulative in nature. Given that point-based and other types of non-monetary feedback are ubiquitous in popular culture—e.g., likes on Facebook and other social media outlets as well as badges and points in online video games—it should not be surprising that non-monetary wins elicit reward system activity.

The RewP observed in the present study appears to mirror that seen in studies using monetary outcomes. However, we did not measure the RewP in a separate group receiving monetary feedback. Thus, from the current results we can only conclude that non-monetary positive feedback is rewarding and enhances RewP amplitude. The degree to which monetary and non-monetary RewP responses are one in the same will require further research.

AUTHOR CONTRIBUTIONS

JC designed the study and analyzed the data and significantly edited and revised the manuscript. ET, RS, JS, and VH collected data and drafted the manuscript.

ACKNOWLEDGMENTS

We thank Hayley Gilbertson and other students in the Cognitive × Affective Behavior and Integrative Neuroscience (CABIN) Lab at Northern Michigan University for assisting with this project.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2019.00041/full#supplementary-material

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

PERSPECTIVE
published: 13 February 2019
doi: 10.3389/fnhum.2019.00048

The Role of One's Motive in Meditation Practices and Prosociality

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No individual exists without exhibiting prosociality in one or another situation during their lifetime. The argument however, is to what extent? Does it arise spontaneously, out of true empathy and compassion for others, or it is goal-oriented with some hidden motive? Here, our primary intention is to convey that, though various meditation-based interventions can be utilized for different purposes like cultivating prosocial behaviors such as compassion, empathy etc., one's underlying motive and intent seems to play a crucial role in an individual's development. Most of the studies exploring prosociality, in the context of meditation, usually do not consider the role of hidden or underlying motivation in one's prosocial expression. By considering an example of how mindfulness may sometimes lead to the wrong consequences, we try to analyze why it is important to include the aspect of inner motivation in future studies exploring the effects of meditation on prosociality. We also propose that while practicing meditation one may need traditional assistance and ethical/moral teachings in addition to those merely isolated techniques.

Keywords: meditation, prosocial, motive, compassion, intent, mindfulness, imagination

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Received: *19 June 2018*
Accepted: *29 January 2019*
Published: *13 February 2019*

Citation:
Reddy JSK and Roy S (2019) The Role of One's Motive in Meditation Practices and Prosociality. Front. Hum. Neurosci. 13:48. doi: 10.3389/fnhum.2019.00048

INTRODUCTION

It is natural that we question the nature of the world we perceive, but we also question the very nature and purpose of life. Thus, many ancient cultures and civilizations across the globe have already put forward and proposed that the social wellbeing of all and of the self is the goal of an individual life (Neusner and Chilton, 2005). In addition, these cultures even developed various techniques and practices of meditation, capable of cultivating prosociality (Monteiro et al., 2015; FitzPatrick, 2017; Kirby and Gilbert, 2017; Luberto et al., 2018). The set of behaviors that involves the concern and helpful feelings for others, are commonly defined as prosocial (San Martín et al., 2016; FitzPatrick, 2017; Goetz and Simon-Thomas, 2017). At times, these behaviors are expressed even at the cost of self-suffering or personal benefit. In general, apart from the internal motivation caused by the feelings of empathy, it also essentially involves transcending one's selfishness (Saslow et al., 2013). Therefore, prosociality is usually associated with social behaviors such as compassion, kindness and altruism. The extent and type of prosocial expression of an individual, may also vary as per the situation and the nature of the interaction.

In the present context, it is meaningful to ask- is prosociality an inherent nature of one's social expression? Or does it have to be cultivated only through external means? The question is if it is innate, why should one practice it by other means? If so, what does it take for us to realize that prosocial expression is a natural quality? A recent study also supports the idea that we are all altruistic (selfless) at heart and that it takes some effort to be selfish; which means that altruism is our default social expression (Christov-Moore et al., 2017). Currently, we only have preliminary evidence supporting such claims and we need more studies to explore the evolutionary and functional basis of prosociality. Although prosocial behaviors are mostly studied in the context of social psychology and evolutionary psychology, recently some studies have attempted to explore these behaviors in relation to meditation.

In recent times, because of the popularity of different practices of meditation; mainly mindfulness and mindfulness-based interventions (MBIs), there is growing interest in studying not only the effects of meditation on an individual (focused on isolated physical and psychological effects) but also its social influence (mainly interpersonal and collective effects). In order to explore the ability of meditation for prosociality, we now have numerous studies quoting the benefits of practicing several techniques like mindfulness, compassion and loving-kindness meditation (LKM) and other meditation-based interventions (Hofmann et al., 2011; Gilbert and Choden, 2013; Gilbert, 2014; Kirby et al., 2017; Matos et al., 2017; Luberto et al., 2018). But, as these studies indicate, though one may develop prosocial behaviors like compassion and altruism by means of certain meditation practices, conventionally cultivating prosociality alone does not seem to be the essential goal of meditation. Accordingly, all these claimed aspects are epiphenomenal, resulting from practicing different meditation techniques (Gilbert and Choden, 2013).

Nowadays, we reduce meditation as just a tool or technique for cognitive enhancement and wellbeing. Subsequently, different practices of meditation are treated as a set of relaxation techniques and stress relieving methods. Some even propose meditation as a practice for enhancing various cognitive functions based on the evidence that it helps to focus ones attention, concentration, and heightens cognitive inhibition (Ospina et al., 2007; Rao, 2011; Schmidt and Walach, 2014; Tang et al., 2015; Coronado-Montoya et al., 2016; Luberto et al., 2018). There are also others who use various meditation techniques as alternate methods of healing, to replace conventional practices, or at times in association with other treatment methods.

Although some acknowledge the benefits of meditation practices, there are others who argue that the contemporary view of meditation deviates from the traditional understanding (Rukmani, 2001; Rao, 2011; Awasthi, 2013; Nash and Newberg, 2013; Monteiro et al., 2015; Reddy and Roy, 2018). They indicate that different practices of meditation, though they may be beneficial, have an essentially different purpose. They propose that to study meditation in its extent and entirety, one would also need to be aware of its traditional significance and the teachings that accompany these practices. Here, one must note that meditation has a higher purpose, and different techniques have been devised for the purpose of self-realization and enlightenment, and for understanding the nature of one's own mind (Rukmani, 2001; Rao, 2011; Schmidt and Walach, 2014; Reddy and Roy, 2018).

Even when considering meditation as just a tool, without any traditional aspects, we already have numerous studies investigating the role of meditation for different purposes. Thus, it is a reasonable attempt to develop a consistent overview of various claims put forth by different scientific studies on meditation. The major focus of these studies, apart from exploring meditation as a tool for wellbeing and alternative clinical intervention, is to study its potential to cultivate prosociality. Many studies have focused on meditations ability to develop prosocial behaviors like compassion, kindness etc. Since some studies claim to show evidence that certain meditation-based interventions can be used to cultivate prosociality, there is a need to review and analyze these studies to see if such claims are true. Thus, the focus in Kreplin et al. (2018) was to systematically review and meta-analyze the effects of these practices on prosociality in randomized controlled trials (RCTs) of healthy adult subjects. Although the authors agreed with meditation's potential to influence prosociality to some extent, they were skeptical of various overstated claims and popularity. They noted that most of the concerned studies presented a very tenuous and unclear justification as to why a meditation intervention ought to improve prosocial outcomes.

Kreplin et al. (2018) authors even indicated that meditation seems to only have a limited influence on prosocial behaviors; mainly towards the feelings of compassion and empathy. Their findings also suggest that these prosocial effects, at least in part, may be a result of methodological frailties involved in the concerned studies, for instance, biases introduced by the meditation instructor, the type of control group selected and the beliefs and expectations of participants about the power of meditation. Therefore, they offer potential ways to overcome these issues to some extent in future studies.

In addition, while studying social behavior, another significant aspect which needs critical attention is the underlying motive and intent (Hirschberger and Lifshin, 2013). The role of underlying motivation in one's prosocial expression has received very little attention in studies concerned with the effects of meditation on prosociality. If we analyze carefully, an individual's hidden motivation and intention can reduce a social interaction to a goal-oriented task which also applies to prosocial behaviors like compassion and empathy. Considering the aspect of inner motivation as a defining factor, here, we propose that some practices of meditation, without a rightful intent and motive, may be incomplete and when addressing these aspects, traditional knowledge and insight might be helpful (Ricard, 2009; Rao, 2011; Monteiro et al., 2015; Reddy and Roy, 2018). This means that neither practicing different meditation techniques by themselves nor their potential to cultivate prosocial effects make them wholesome and complete in the absence of moral teachings. Although some scientific studies on meditation seem to lack traditional understanding, it is important to note that meditation as a practice (without being associated with any tradition) shows many benefits for various purposes. Thus, currently, it is being explored for different clinical and psychological purposes.

THE ROLE OF RIGHT MOTIVE AND INTENT IN THE PRACTICE OF MEDITATION

Nowadays, meditation is promoted mainly as the practice of wellbeing. Since numerous studies attribute various benefits to the practice of meditation, many individuals are inclined to learn and practice meditation techniques (Kreplin et al., 2018). It therefore creates high expectations among participants, which creates the need for more meditation courses and retreats. While it is a good sign that many people want to practice and benefit from these ancient techniques, an individual can truly merit only when he/she is well aware of the traditional understanding of these practices and their consequences (Monteiro et al., 2015). This is because most of the devised techniques are not isolated practices (not complete practices by themselves), and should be combined and supplemented with a specific lifestyle and moral teachings (Ricard, 2009; Monteiro et al., 2015). Here, the ethical component comes into the picture. For a detailed argument, let us consider "mindfulness practices." These practices usually involve some form of meditation, with the goal to create and maintain a non-reactive and non-judgmental state of focused awareness. These techniques can still be exercised independently of spiritual motive. Thus, most researchers and traditional practitioners believe that mindfulness in the absence of traditional knowledge and ethical teachings may sometimes lead to the wrong consequences (Ricard, 2009; Monteiro et al., 2015; Kreplin et al., 2018).

For instance, a sniper whose intention is to kill another human being would be as mindful as a meditator of his body, thoughts, and feelings before pulling the trigger (Ricard, 2009; Kreplin et al., 2018). While he/she acts mindfully in this situation, it is the intention and inner motivation which matters. It shows that mindfulness by itself, as a focused state of attention, is neither good nor bad. As specified by a well-known Buddhist monk Matthieu Ricard (2009)

> *"bare attention, as consummate as it might be, is no more than a tool that can certainly be used to achieve enlightenment and is needed for this purpose, but which can also be used to cause immense suffering. Obviously, what is entirely missing is the ethical dimension of a mindfulness that deserves the qualification of 'wholesome' and can lead to enlightenment"*

He also stated that genuine mindfulness teachings should not only include a means to direct and maintain one's attention on the chosen object, but also the understanding of the nature of the mind and one's own mental state. In addition, these teachings should also embed an ethical element which enables one to clearly distinguish if it is helpful to maintain the present state of mind and behavior. Thus, it appears that mindfulness should be practiced with the aspiration to achieve enlightenment for the welfare of oneself and for all beings (Ricard, 2009; Monteiro et al., 2015).

In addressing such claims, some researchers propose that one should consider meditation only for its evidence-based benefits, with ethical and moral aspects being independent attributions of different cultural biases and ethical dogmas (Coronado-Montoya et al., 2016; Klein and Epley, 2016; Kabat-Zinn, 2017; Mattes, 2018). Here, they consider moral behaviors to be independent of these practices. They are acquired not through practice alone but by means of the induced cultural dogmas. Accordingly, the sniper's analogy (in connection to the moral behavior and mindfulness) cannot simply be used without the context, as we have various instances in the same culture where highly revered spiritual masters have killed their enemies to maintain dharma (or righteousness) in the world. Addressing the context, in Mattes (2018), the author states that—"*More mindfulness of our human cognitive limitations should lead to less dogmatism in general, and in ethical matters in particular.*" In the current situation, and simply based on the preliminary evidence, it is tough to say if prosocial abilities attributed to meditation is because of the practices alone or because of the supplemented traditional teachings. Such a connection has not been explored in detail and thus we propose that more studies on meditation and its potential to develop prosocial behaviors in the context of moral and ethical dogmatism, in a particular culture, are needed. The role of traditional teachings in cultivating prosocial behaviors should therefore also be studied in depth.

UNDERLYING MOTIVE AND ITS ROLE IN PROSOCIAL BEHAVIOR

In the modern world, we have reached a state where we make ourselves and our behaviors so encrusted and complex that it becomes tough to comprehend. In some instances, it is hard to know why people behave the way they do because their true motives remain hidden (Hirschberger and Lifshin, 2013). The conditions where motives drive a specific behavioral choice are quite possible. For example, there are many instances in life where we should take one or the other decision. Although every decision we make is intended to benefit us, sometimes it is true that we make decisions for others in order to help them. Here, our prosocial nature enters the picture. It is more important when we are dealing with matters where others are involved. The extent and type of prosocial expression may vary according to the situation. In some cases, while few individuals may express such behaviors only during conditions where others are in trouble or pain, others try to cultivate a behavior which is spontaneously selfless in all conditions.

Just like the possibility of cultivating mindfulness for the wrong purposes, one may also develop wrongful prosocial behaviors; acting prosocial with the wrong motives and intent. On the fringe, one may act compassionate and look altruistic, but how reliable is it? We need a way to identify if altruistic behavior of an individual is prompted by one's selfish motives and goal-oriented thoughts or by true empathy and compassion. In the present context, it is central to study and understand not only the behavior of an individual, but also the motive and intent behind any such conduct (Hirschberger and Lifshin, 2013). It is surprising to see that none of the previous studies that explored the effects of meditation on prosociality take note of inner motivation, which is crucial when it comes to the application of practices or teachings that one learns. Therefore, different practices of meditation and various other interventions, which are known to assist in cultivating prosocial behaviors, should consider the hidden or underlying motivation.

In addition, as there are various meditation practices across different traditions, it is not true that every meditation technique will cause the same influence on prosociality.

Leaving prosociality, the regions of the brain affected by different meditation techniques are also dissimilar. Studies show that each meditation technique will have a unique neural impact associated with a particular practice. In a recent meta-review study (Fox et al., 2014), 78 functional neuroimaging studies on meditation practices were examined. The findings suggest a clear neurophysiological dissociability among different meditation practices, in addition to some methodological issues and concerns. They also establish that although several brain regions may be equally affected in various meditative practices, differences greatly outnumber the existing similarities. So, they state that "commonality across meditation categories is the exception rather than the rule." In another meta-review, Lee et al. (2018) examined the neural oscillations that underlie meditation. They also noticed some significant changes in the neural oscillatory activity among different meditation practices, in agreement with Fox et al. (2014). They also indicate that more rigorous studies are needed to elucidate the nuanced imaging and physiological changes that occur with each type of meditation. In addition to the distinct physiological and psychological changes associated with different meditative practices, another important aspect to study and identify is inner motive and intent. This aspect plays an important role in prosocial behavioral studies. We therefore need to study and understand the neural basis in order to distinguish between our inner motivations and intentions.

Considering the functional complexity of the brain, it is truly tough to indicate a specific region in the brain connected with one's inner motive and intent. Nevertheless, it is interesting to see that some recent studies have attempted to delineate various neural patterns connected to these aspects (Hein et al., 2016; Cutler and Campbell-Meiklejohn, 2019). A recent study showed that, if some active brain regions can give information regarding one's behavior, then studying how the respective brain areas interact helps in understanding the motive behind such behavior (Hein et al., 2016). Which implies that one's motives can be distinguished from each other, as they are characterized by a specific interplay between different brain regions. Another study reported, for the first time, the way in which to differentiate between the motives of individual subjects (Cutler and Campbell-Meiklejohn, 2019). They showed how to split the mechanisms between what happens in the brain when we act out of genuine altruism—where there is no personal benefit, and when we express a strategic kindness—with the intention to personally gain or benefit as a consequence.

Such findings can contribute effectively to knowing the extent and role of one's hidden motive in future studies on compassion and altruism. It also provides a reliable foundation/base for studying the efficacy of various practices of meditation. Even though research into finding the underlying neural mechanisms and correlates are in preliminary stages, such studies would help us better understand the areas associated with our inner motivations and intentions. We therefore appreciate these studies and call for more research on connecting these aspects. These studies will be helpful not only in the context of meditation research, but with prosociality in general.

THE POTENTIAL INFLUENCE OF MOTIVE ON MENTAL FACULTY IN CULTIVATING PROSOCIALITY

If we review different meditation practices and other interventions used to cultivate prosocial behaviors like compassion and empathy, we find that most make use of one's capacity to imagine. This is because, a person's capability to imagine them self in another person's situation or condition forms the very basis of empathy and compassion (Gilbert and Choden, 2013; Matos et al., 2017). On the other hand, if imagination can assist in cultivating prosocial behaviors, there is a possibility that the same can easily be applied to develop antisocial behaviors. That means the same technique can also be used to develop a negative attitude towards others. So, what is significant is the ethical sense and traditional knowledge, rather than the simple techniques which employ the use of cognitive faculties such as imagination and visualization etc. As specified in Kreplin et al. (2018), sometimes, one may cultivate prosociality not truly because of practicing these techniques, but through the expectation factor which motivates one to learn. So, meditation in no way looks different from other techniques that simply help in developing focused cognitive enhancement. Even in the above context, it is very important to see and study what really matters, whether the practice itself can cultivate a prosocial behavior or if it is a result of the supplemented ethical teachings.

FUTURE DIRECTIONS FOR STUDIES ON MEDITATION AND PROSOCIALITY

In addition, like in the Buddhist tradition, philosophical schools of Hinduism also emphasized prosocial aspects such as compassion and altruism. Although we have some preliminary evidence from recent studies that meditation affects prosocial behaviors, the main focus of the majority of these studies were on Buddhist contemplative practices (Hofmann et al., 2011; Gilbert and Choden, 2013; Gilbert, 2014; Kirby et al., 2017; Matos et al., 2017; Luberto et al., 2018). Since exhibiting these prosocial aspects is the fundamental and essential teaching in different schools of Hinduism, we need scientific studies that investigate the role of these practices in cultivating empathy, compassion and altruism etc. Along these lines, one can also have a comparative study on the potential influence of different practices that emanates from different spiritual traditions.

As discussed earlier, we have two groups of researchers, one group argues that meditation should be considered solely for its evidence-based benefits and the other group claims that the contemporary view of meditation is different from the traditional view. Thus, the latter group argues that the role of traditional aspects has to be considered in meditation research. Findings of Kreplin et al. (2018) show that what we consider evidence—meditation practices being helpful in developing prosociality—suffers from various biases and issues, and thus cannot be regarded as true evidence. We need more scientific studies with a better methodological design and conceptual framework to avoid such biases. In light of various such perspectives, future studies on meditation and prosociality should address the following possibilities: (i) different biases and issues associated with the studies concerned with meditation's influence on prosocial behaviors; (ii) the role of ethical and moral teachings and other traditional aspects in cultivating prosocial behaviors in the context of meditation; and (iii) the influence of one's inner motives and intent on prosocial behaviors.

DISCUSSION

> *"It is quite true that a meditator resting in pure awareness and perfect understanding of the fundamental nature of mind, unaltered by mental constructions, will be unable to pull the trigger and kill someone. This kind of luminous awareness is a state of wisdom and is the natural state of a mind that is entirely free from ignorance and mental toxins and spontaneously imbued with unconditional altruism and compassion. Such a state is the result of having achieved inner freedom and should not be confused with mere mindfulness and bare attention"* (Ricard, 2009).

The above quote describes the mental state of a meditator who has achieved the goal of meditation as indicated by the cultural tradition. Considering the sniper example, it states that a meditator with genuine kindness and who is well aware of the nature of the mind, will not be able to pull the trigger to kill someone. It is because he/she is not only resting in a state of perfect mindfulness but is also aware of the perturbations of the mind that may result in immoral acts. Here, we are not sure if such an understanding results from meditation practices or from supplemented traditional teachings. Thus, it is always important to study the role of traditional teachings and cultural claims in the context of meditation and prosociality.

CONCLUDING REMARKS

In the present scenario, where there is a sharp decline of moral and ethical values across the globe, causing individual and social degradation in all possible forms, it is essential to investigate different possible ways to cultivate prosocial behaviors. In light of this, it is important to examine the potential of different contemplative practices, like meditation, to cultivate prosocial behaviors. Since some studies suggest that meditation can bring about long- and short-term functional, physiological and psychological changes, it is essential to explore meditation as a means to develop prosociality.

Exhibiting different prosocial emotions and behaviors is important for both individual and societal well-being. This is one reason why practicing and exhibiting prosocial behaviors such as empathy, kindness and compassion has been emphasized across diverse social institutions and major religions of the world. The outcome of prosociality has a positive impact on public health because it not only benefits the individual receiving help, but also the individual offering the help. This aspect of prosociality has been emphasized in Hindu and Buddhist philosophical systems as well—where they state that, by helping others, an individual is actually helping them self. Indeed, this traditional understanding is now supported by some research studies that demonstrate that engaging oneself in prosocial behavior is not only associated with greater happiness and psychological well-being but also has other indices of physiological health.

Studies exploring the role of meditation in cultivating different prosocial behaviors like empathy, kindness, compassion and altruism have received much attention lately. Although, meditation includes a diverse set of practices across different traditions, these studies mainly focus on Buddhist contemplative practices such as mindfulness, vipassana, LKM etc. On one side, a large body of studies suggest that meditation practices influence prosociality to a greater degree, whereas on the other side, some researchers indicate that the majority of the claims regarding the prosocial effects of meditation are overstated and could be a result of various issues associated with the methodology and design of the respective study.

Therefore, in this article, we examined some issues related to the studies associated with meditation and prosociality. We emphasize one's inner motive and intent as a crucial aspect to take into consideration in prosocial studies. In addition, our primary purpose here is to highlight the role of traditional knowledge and the ethical teachings associated with meditation practices; mainly mindfulness and its based interventions, in cultivating prosociality. We also indicate that, in order to study and examine the ability of meditation practices to develop prosocial behaviors in an individual, we need more studies with a clear methodology and research design as well as studies across different spiritual traditions. We also offer some direction for future studies on meditation and prosociality.

AUTHOR CONTRIBUTIONS

JR came up with an idea to write the manuscript. Both JR and SR analyzed and wrote the article.

ACKNOWLEDGMENTS

We thank our reviewers for important corrections and suggestions to improve the article. SR is indebted to the Homi Bhabha Trust, Mumbai for their support.

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Conflict of Interest Statement: 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.

frontiers in Human Neuroscience

ORIGINAL RESEARCH
published: 26 March 2019
doi: 10.3389/fnhum.2019.00101

The Immediate and Sustained Positive Effects of Meditation on Resilience Are Mediated by Changes in the Resting Brain

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While recent studies have explored the maintenance of the effect of meditation on stress resilience, the underlying neural mechanisms have not yet been investigated. The present study conducted a highly controlled residential study of a 4-day meditation intervention to investigate the brain functional changes and long-term effects of meditation on mindfulness and resilience. Thirty participants in meditation practice and 17 participants in a relaxation retreat (control group) underwent magnetic resonance imaging scans at baseline and post-intervention and completed the Cognitive and Affective Mindfulness Scale (CAMS) and Resilience Quotient Test (RQT) at baseline, post-intervention, and the 3-month follow-up. All participants showed increased CAMS and RQT scores post-intervention, but only the meditation group sustained the enhancement after 3 months. Resting-state functional connectivity (rsFC) between the left rostral anterior cingulate cortex (rACC) and the dorsomedial prefrontal cortex (dmPFC), precuneus, and angular gyrus was significantly increased post-intervention in the meditation group compared with the relaxation group. The changes in rACC-dmPFC rsFC mediated the relationship between the changes in the CAMS and RQT scores and correlated with the changes in the RQT score both immediately and at 3 months post-intervention. Our findings suggest that increased rACC-dmPFC rsFC *via* meditation causes an immediate enhancement in resilience that is sustained. Since resilience is known to be associated with the preventative effect of various psychiatric disorders, the improvement in stress-related neural mechanisms may be beneficial to individuals at high clinical risk.

Keywords: resilience, meditation, mindfulness training, templestay, resting-state functional connectivity

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Received: *14 November 2018*
Accepted: *05 March 2019*
Published: *26 March 2019*

Citation:
Kwak S, Lee TY, Jung WH, Hur J-W, Bae D, Hwang WJ, Cho KIK, Lim K-O, Kim S-Y, Park HY and Kwon JS (2019) The Immediate and Sustained Positive Effects of Meditation on Resilience Are Mediated by Changes in the Resting Brain. Front. Hum. Neurosci. 13:101. doi: 10.3389/fnhum.2019.00101

INTRODUCTION

Resilience is defined as an individual's capacity for recovery after significant adversity. Recent studies have suggested the importance of strengthening individuals' resilience through appropriate interventions (Padesky and Mooney, 2012; van der Werff et al., 2013; Vanhove et al., 2015). For individuals, especially those at risk of mental disorder, enhanced resilience helps protect against their clinical conversion due to various stressful events (Ludwig and Kabat-Zinn, 2008; Creswell and Lindsay, 2014; Goyal et al., 2014). Moreover, resilience serves as a framework to promote stable remission in individuals with psychiatric disorders and to attenuate symptom severity in patients with inadequate responses to medication (Segal et al., 2010; Hoge et al., 2013; Waugh and Koster, 2015; Sharma et al., 2016). In this context, meditation has been shown to exert psychological and physiological effects on stress resilience and self-awareness and has been acknowledged as a promising adjunctive treatment in a broad range of psychiatric patients (Rubia, 2009; van der Velden and Roepstorff, 2015). However, most previous studies, which adopted meditation intervention for a few weeks, included possible limitations, such as isolation of the effects of meditation from other confounding factors or difficulty for subjects to regularly participate in the intervention. Therefore, recent studies have adopted several-day intensive residential meditation retreats designed to maximize training compliance and minimize the effects of non-meditative factors (Tang et al., 2007, 2015; Xue et al., 2011; Hwang et al., 2017).

Despite the growing interest in meditation and the significant progress achieved in understanding the associated dynamic neural changes *via* meditation (Lazar et al., 2005; Tang et al., 2015, 2007; Jang et al., 2011; Kang et al., 2012), only a few studies have focused on the maintenance of the effect. According to studies involving several months of follow-up after the intervention, both the meditation and active control groups exhibit improvements in stress-related psychological or physiological characteristics immediately after the intervention, but the effect is maintained only in the meditation group (Epel et al., 2016; Hwang et al., 2017). These findings suggest that meditation practices may induce changes in neural mechanisms to maintain the improvement, but the putative neural correlates underlying the maintenance of the effect have not yet been explored in neuroimaging studies.

According to recent meta-analyses, changes in anterior cingulate cortex (ACC) activation is consistently reported under various types of meditation and in short-term meditation studies (Bush et al., 2000; Fox et al., 2016). The ACC functions as a nexus of information processing, and 1 month of 30-min meditation interventions were shown to significantly increase the network efficiency and connectivity of the ACC in terms of resting-state functional connectivity (rsFC; Bush et al., 2000; Xue et al., 2011). However, the ACC can be differentiated into the rostral ACC (rACC) and the caudal ACC (cACC) based on its cytoarchitecture and functional connectivity. In general, the rACC appears to mainly be involved in the default mode network (DMN) and affective system, while the cACC is related to the sensorimotor and attention network (Milham and Banich, 2005; Margulies et al., 2007; Mohanty et al., 2007; Habas, 2009). Despite its distinguishing features, the majority of studies on the effects of meditation on the brain have not addressed its subregions. Moreover, only a few studies have explored the neural mechanism underlying the improvement of resilience through meditation. Although a recent study identified a decrease in subgenual ACC-amygdala rsFC, the region was associated with the perceived stress level based on region of interest (ROI)-wise rsFC analysis, and such an ROI-based approach limits the understanding of changes in resilience in the whole brain (Taren et al., 2015). Therefore, the neural correlates of resilience that are altered by short-term meditation remain unknown.

Motivated by previous findings, we sought to investigate whether changes in the rsFC contribute to improved resilience and its maintenance after 4 days of intensive residential meditation. Hence, we estimated whole-brain seed-to-voxel rsFC with ACC subregions and explored group-by-time interactions in rsFC maps for each ACC subregion. We hypothesized that: (1) the meditation group would present significant changes in rACC functional connectivity after the intervention; and that (2) these neural changes would be associated with improved resilience both immediately and at the 3-month follow-up.

MATERIALS AND METHODS

4-Day Intensive Meditation (Templestay) Project

This project is aimed to investigate the behavioral and neural effects of three nights and 4 days of intensive meditation (Templestay program) using multidimensional approaches, including self-reported questionnaires, behavioral tasks, and multiple brain imaging modalities. The data used in the current study are part of the Templestay project. This study was carried out in accordance with the recommendations of Institutional Review Board of Seoul National University Hospital Committee with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Institutional Review Board of Seoul National University Hospital Committee. To minimize the placebo effect, all participants were informed about two types of Templestay programs—a Buddhism meditation type and a relaxation type—prior to participation. Those who were willing to be assigned to either type were enrolled and randomly allocated to either an intensive meditation group (MED) or the control group using a computerized algorithm based on 2:1 mixed block randomization (44 participants in the MED group, 23 participants in the control group). The brain imaging data were collected at two time points, baseline and immediately after the intervention, while self-report questionnaires were measured at three time points: baseline, immediate follow-up, and at a 3-month follow-up (**Figure 1**). The recruitment strategy, intervention program, and results from the self-report questionnaires were described thoroughly in a previous report (Hwang et al., 2017). A brief introduction to the materials is included in the Supplementary data and **Supplementary Figure S1**.

Image Data Acquisition

Image data were acquired from all participants 2 to 3 days before and after the intervention using a 3T Trio scanner (Siemens Medical Systems, Erlangen, Germany) with a 32-channel head coil. All participants were asked to relax with their eyes open during the resting functional magnetic resonance imaging (fMRI) scan [repetition time (TR) = 2000 ms, echo time

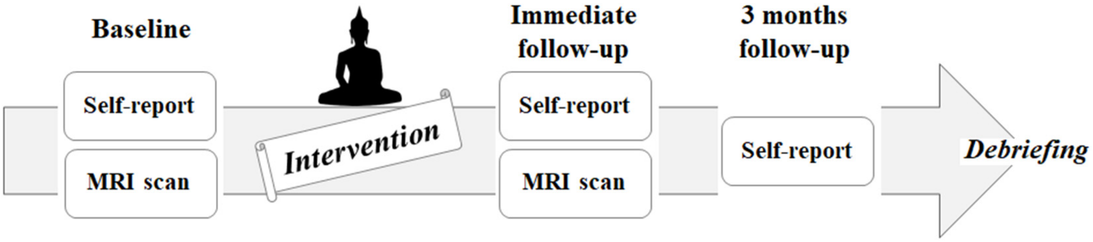

FIGURE 1 | Flowchart of the intervention study, including enrollment, allocation, baseline, follow-up, and analysis.

(TE) = 30 ms, 64 × 64 matrix, total of 150 volumes, one run, field of view (FOV) = 220 mm, flip angle (FA) = 80°, voxel size = 3.4 × 3.4 × 3.4 mm^3, 34 slices, and no gap]. To ensure that the participants stayed awake, they were reminded to stay awake immediately before resting fMRI acquisition and were observed during acquisition through an eye-tracker in the MRI scanner. Additionally, high-resolution T1-weighted anatomical images were acquired with three-dimensional magnetization-prepared rapid gradient echo [TR = 1,670 ms, TE = 1.89 ms, FOV = 250 mm, flip angle (FA) = 9°, number of slices = 208, voxel size = 1.0 × 1.0 × 1.0 mm^3].

Analyses of Psychological Measures

To assess individuals' resilience and mindfulness, all participants completed the modified Korean version of the Resilience Quotient Test (RQT) and the Cognitive and Affective Mindfulness Scale (CAMS)-Revised at three time points: baseline (T0), immediately after (T1), and 3 months after the intervention (T2). The RQT, developed by Reivich and Shatté (2002), is an inventory consisting of 27 items rated on a 5-point Likert scale, ranging from 1 (not at all) to 5 (very much so). CAMS measures everyday mindfulness, focusing mainly on the degree of participants' thoughts and feelings on their experiences (Feldman et al., 2007). It consists of 12 items and assesses the core characteristics of mindfulness: the ability to regulate attention and orientation, to be aware, and to be nonjudgmental towards experience. Each item is rated on a 4-point scale, ranging from 1 (rarely/not at all) to 4 (almost always).

Independent samples *t*-tests were conducted for each scale to compare the differences between the groups at each time point. The group-by-time interaction of each scale was analyzed with a 3 [time (baseline/immediate follow-up/3-month follow-up), within-subject factor]-by-2 (group, between-subject factor) mixed analysis of variance (ANOVA) in SPSS, version 23.0 (IBM). To examine the directions of changes, *post hoc t*-tests were also conducted. The short-term effects on psychological measures were estimated with the scores from T0 and T1, while the long-term effects were estimated with the scores from T0 and T2.

Functional Image Analysis

After discarding the first two scans, FMRIB Software Library (FSL[1]) was used to preprocess the image data. fMRI data analyses were performed with the following preprocessing steps: removal of nonbrain structures, slice-timing and motion correction, registration to T1-weighted images and spatial normalization to 2 mm the Montreal Neurological Institute (MNI) template using FMRIB's Linear Image Registration Tool (FLIRT). In terms of mean head motion parameters, neither significant group differences nor time differences were observed (group comparison: $t = -0.270$, $p = 0.788$; time comparison in the MED group: $t = -0.049$, $p = 0.961$; time comparison in the control group: $t = -1.704$, $p = 0.101$; Van Dijk et al., 2012; Zeng et al., 2014b). Using a general linear model (GLM), we removed the effects of nuisance covariates, including six head motion parameters, and signals from cerebrospinal fluid and white matter segmented T1-weighted images. Residual images were spatially smoothed using a Gaussian kernel of full width at half maximum (4 mm) and were temporally smoothed using a high-pass filter of a Gaussian-weighted least-squares line fitted with sigma = 100.

According to previous neuroimaging studies on the effects of aging, we only included brain data from young adults (age 40 or younger) in the current study (Ferreira and Busatto, 2013); in this study, 34 participants were included in the MED group and 19 in the control group. Among the remaining 52 participants, data from five participants were excluded due to excessive head motion (>3 mm for x, y, z planes, $n = 4$) and image distortion during acquisition ($n = 1$). As a result, we included data from 30 participants in the MED group and 17 participants in the control group in the final analysis.

We then defined four seed regions, the rostral and cACC in each hemisphere, based on the Destrieux atlas (Destrieux et al., 2010). Next, we calculated the mean time series of each seed region and produced individual subject-level maps of all positively correlated voxels for each seed. Due to the debate about negative rsFC, we specifically focused on the positive connectivity maps (Fox et al., 2009; Murphy et al., 2009). To examine the group-by-time effect of the intervention, second-level analyses were carried out using GLM analysis. A one-sample *t*-test and a paired *t*-test for each group were also conducted to clarify our assumption regarding the distinctive rsFC of rACC and cACC and to investigate the effect of each intervention. Multiple comparisons for all the above mentioned statistical analyses were carried out at the cluster level using Gaussian random field theory ($Z > 2.3$; cluster significance; $p < 0.010$, corrected).

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[1] https://fsl.fmrib.ox.ac.uk/fsl/

Correlation and Mediation Analyses

To evaluate the hypothesis regarding the relationship between changes in functional connectivity and mindfulness and resilience, Pearson's r correlation analysis was performed using SPSS v23.0. In the MED group, one participant at baseline and three participants at the 3-month follow-up were not available and were therefore excluded from the subsequent analyses. Normality and outliers in the raw data were checked prior to the analyses. In the correlation analysis, the strength of individual connectivity based on the significant clusters identified *via* the above rsFC analysis was extracted, and its variation was compared with the results of the self-reported questionnaires, RQT and CAMS. Both short (T0 to T1) and long-term (T0 to T2) improvements were analyzed based on the rsFC results. A p-value < 0.05 was considered statistically significant.

The mediation analysis test evaluated whether the association between X (predictor) and Y (outcome variable) was significantly reduced by including M (mediator) in the model when compared with the total relationship between X and Y. Thus, we further examined whether the association between the changes in mindfulness (X) and those in resilience (Y) could be explained *via* the indirect pathway based on the neural changes observed according to rsFC (M) using Mediation Toolbox[2]. Three variable-path models with bootstrap tests (10,000 iterations) were assessed.

Analyses of the Effect of Religion

Since the meditation used in the study is based on Buddhism, the religious preferences of participants were collected to examine the potential effect of religion on the study result. Participants reported their religion among the following choices: Buddhist, Catholic, Presbyterian, none, or other.

RESULTS

Demographic Characteristics

The demographic data for each group are summarized in **Table 1**. There were no significant differences detected in terms of demographic characteristics, including the age, sex, handedness, years of education, marital status, religion, or socioeconomic status of the participants or their parents.

Psychological Measures

The RQT and CAMS scores of both groups at three time points are provided in **Table 1**. The baseline RQT and CAMS scores of the MED group were lower than those of the control group, but not significantly lower ($t = 3.19$, $p = 0.08$, and $t = 3.35$, $p = 0.07$, respectively).

To test the short and long-term effects of the intervention on each psychological measure more objectively, group-by-time mixed ANOVAs were conducted. A significant group-by-time interaction ($F_{(1,47)} = 5.021$, $p = 0.031$, and $F_{(1,47)} = 5.913$, $p = 0.020$, respectively) and an effect of time ($F_{(1,47)} = 8.070$, $p = 0.007$, and $F_{(1,47)} = 2.903$, $p = 0.096$, respectively) were observed, but no effect of the group ($F_{(1,47)} = 0.615$, $p = 0.328$, and $F_{(1,47)} = 0.129$, $p = 0.722$, respectively) was observed. In the *post hoc* t-test, both groups demonstrated significant increases of RQT and CAMS scores in the T0 to T1 (MED group: $t = 4.734$, $p < 0.001$, and $t = 3.532$, $p < 0.005$, respectively/control group: $t = -3.676$, $p < 0.005$, and $t = -2.826$, $p < 0.005$, respectively). In the T0 to T2 comparison, only the MED group presented significant increases in both questionnaires (MED group: $t = -3.567$, $p < 0.005$, and $t = -2.910$, $p < 0.001$, respectively/control group: $t = -0.955$, $p = 0.354$, and $t = -1.000$, $p = 0.332$, respectively). In the T1 to T2 comparison, only the control group showed significant decreases in both questionnaires (MED group: $t = 1.329$, $p = 0.189$, and $t = 0.203$, $p = 0.841$, respectively/control group: $t = 2.217$, $p < 0.05$, and $t = 2.309$, $p < 0.05$, respectively).

Functional Connectivity Maps to Each Seed

As shown in **Figure 2**, the cACC and rACC seed regions exhibited distinct rsFC patterns based on network cortical maps (Yeo et al., 2011). Bilateral rACC seeds were largely connected with regions (medial prefrontal cortex, precuneus, angular gyrus, amygdala, and hippocampus) belonging to the limbic network and DMN, whereas bilateral cACC seeds were linked with regions (dorsolateral prefrontal cortex, inferior frontal gyrus, inferior parietal lobule, and supplementary motor area) belonging to the fronto-parietal network and the sensorimotor network.

Results of Group Analysis of Functional Connectivity Maps

Among the four seed regions, only the left rACC showed significant group-by-time interactions, in several regions. Compared with the control group, the MED group presented increased rsFC between the left rACC and the dorsomedial prefrontal cortex (dmPFC), precuneus and angular gyrus in the MED group at the immediate post-intervention follow-up, whereas there was no significant group difference in rsFC for this seed region at baseline (**Figure 3**).

To further investigate the effect of each intervention on the brain functional network for an exploratory purpose, paired t-tests were performed for each group. In the MED group, the rsFC between the left rACC and the regions involved in the DMN, including the dmPFC, precuneus, and angular gyrus, was significantly increased after the intervention. The rsFC of the right cACC with the posterior cingulate cortex (PCC) was also significantly increased after the intervention. No additional significant changes in rsFC with the right rACC and left cACC were observed. In the control group, bilateral rACC rsFC with the temporal gyrus was increased, while the rsFC of the right rACC with the thalamus was decreased after the intervention. No significant changes were observed in rsFC with the bilateral cACC (**Supplementary Figure S2**).

Correlation and Mediation Analyses

In the correlation analysis, the changes in the left rACC-left dmPFC connectivity in the MED group were significantly

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[2] http://github.com/canlab/MediationToolbox

TABLE 1 | Demographic and clinical characteristics.

Variables	Meditation (*n* = 30)	Control (*n* = 17)	Statistical differences	
			χ^2, *F* or *T*	*p*-value
Sex (male/female)	6/24	5/12	1.34	0.25
Handedness (right/left)[†]	26/4	17/0	2.48	0.12
Age (years, ± SD)	30.63 ± 4.97	31.71 ± 5.02	0.62	0.54
Education (years, ± SD)	16.53 ± 1.51	17.26 ± 1.62	−1.62	0.11
Religion (%)			0.34	0.57
None	21 (70.0%)	12 (70.6%)		
Buddhism	5 (16.7%)	2 (11.8%)		
Catholic	2 (6.7%)	2 (11.8%)		
Presbyterian	2 (6.7%)	1 (5.9%)		
Socioeconomic status (mean, ± SD)[‡]				
Participants'	2.60 ± 0.56	2.53 ± 0.64	0.52	0.47
Participants' parents	2.57 ± 0.82	2.74 ± 0.96	0.79	0.38
RQT (mean, ± SD)[§]				
Baseline	90.83 ± 17.28	96.59 ± 0.30	3.19	0.08
Immediate follow-up	103.93 ± 13.27	103.76 ± 12.56	0.01	0.93
3-month follow-up	101.41 ± 17.65	98.53 ± 10.50	5.13	<0.05
CAMS (mean, ± SD)[§§]				
Baseline	28.40 ± 6.67	30.29 ± 4.43	3.35	0.07
Immediate follow-up	33.00 ± 6.59	32.88 ± 4.61	2.39	0.13
3-month follow-up	32.19 ± 6.26	30.88 ± 4.64	3.30	0.08

[†] Annett Handedness scores. [‡] Hollingshead socioeconomic status index, where 1–2 = high, and 4–5 = low. [§] Korean version of the Resilience Quotient Test. [§§] Cognitive and Affective Mindfulness Scale-Revised.

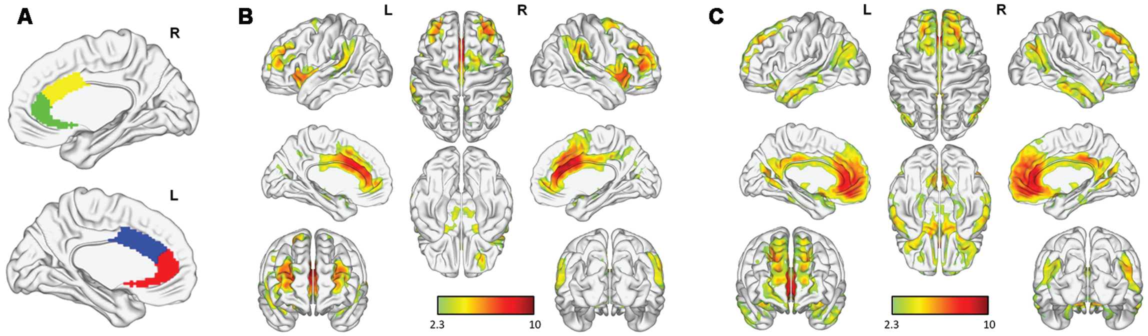

FIGURE 2 | Functional connectivity of anterior cingulate cortex (ACC) subregions: **(A)** rostral (green, red) and caudal (yellow, blue) ACC in each hemisphere. Distinct functional connectivity was observed in the bilateral **(B)** caudal ACC (cACC) and **(C)** rostral ACC (rACC).

correlated with the changes in RQT and CAMS ($r = 0.54$, $p = 0.002$ and $r = 0.41$, $p = 0.024$, respectively) in terms of the short-term effect. However, this correlation was not observed in the control group. No other type of rsFC from the GLM analysis was significantly associated with psychological measures. Concerning the long-term effect, the change in the rsFC was still significantly correlated with improved RQT ($r = 0.42$, $p = 0.034$) but not for CAMS ($r = 0.309$, $p = 0.124$; **Figure 4**).

As shown in **Figure 4**, the mediation analysis revealed a significant partially mediating effect on the rACC-dmPFC rsFC through the relationship between CAMS and RQT. In other words, the coefficient between X and Y was decreased when the change in the rACC-dmPFC rsFC was included ($c = 1.55$, $p < 0.001$; $c' = 1.32$, $p < 0.001$). Significant relationships were also observed for the path coefficients between X and M ($a = 0.03$, $p = 0.006$) and between M and Y ($b = 7.61$, $p = 0.003$).

Effect of Religion

To investigate the effect of the participants' religious beliefs on our results, ANOVAs and independent sample *t*-tests were conducted for the MED group. There were no significant differences in the baseline of rACC-dmPFC rsFC ($F_{(1,25)} = 0.81$, $p = 0.498$), CAMS ($F_{(1,25)} = 1.67$, $p = 0.199$), or RQT ($F_{(1,25)} = 2.59$, $p = 0.075$) depending on the participants' religions. In addition, there were no significant differences detected between participants with religion and those without religion in terms of baseline of rACC-dmPFC rsFC ($t = -0.41$, $p = 0.68$), CAMS ($t = 0.12$, $p = 0.90$), or RQT ($t = -1.25$, $p = 0.808$). In terms of the changes at the immediate follow-up, there were no significant differences in the changes in rACC-dmPFC rsFC ($F_{(1,25)} = 1.203$, $p = 0.328$), CAMS ($F_{(1,25)} = 0.925$, $p = 0.443$), or RQT ($F_{(1,25)} = 0.121$, $p = 0.947$) depending on the participants' religion. In addition, there were no significant differences detected between participants with religion and those

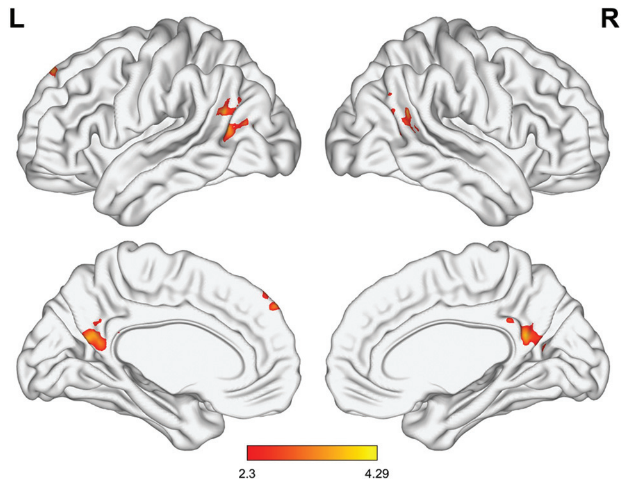

FIGURE 3 | Significant differences in the group-by-time interaction effect (meditation group > control group, minimum *Z* score >2.3, cluster significance: $p < 0.05$, corrected). Significant differences were observed in connectivity involved in the default mode network (DMN), including the left rACC, dorsomedial prefrontal cortex (dmPFC), precuneus and temporoparietal junction (TPJ).

without religion in terms of changes in rACC-dmPFC rsFC ($t = -0.93$, $p = 0.36$), CAMS ($t = 0.57$, $p = 0.57$), or RQT ($t = 1.70$, $p = 0.10$).

DISCUSSION

To our knowledge, this is the first highly controlled residential study to investigate the neural changes *via* short-term intensive meditation, which is associated with the enhancement and maintenance of resilience. Our results revealed that the DMN was significantly enhanced in the MED group after the intervention compared with that in the control group. In particular, the changes in the functional connectivity of the left rACC with the dmPFC were correlated with the change in resilience at both the immediate and 3-month follow-ups in the MED group. In addition, mediation analysis revealed that the change in the left rACC-dmPFC functional connectivity was a partial mediating factor in the association between the enhancement in mindfulness and resilience immediately after the intervention. Our results suggest that the increase in the rACC-dmPFC rsFC was not only related to the immediately enhanced level of resilience but also predicted the long-term maintenance of the improvement.

Consistent with previous studies, compared with the control group, the MED group showed significantly increased rsFC between the left rACC and dmPFC, precuneus and angular gyrus (Brewer et al., 2011; Jang et al., 2011; Hasenkamp et al., 2012; Prakash et al., 2012; Taylor et al., 2012; Garrison et al., 2013). Since the precuneus, angular gyrus, and dmPFC are the functional hubs of DMN, we suggest that there was an increase of DMN in the MED group after meditation (Andrews-Hanna et al., 2014). Among the regions, the rACC-dmPFC rsFC was specifically associated with the resilience improvement *via* meditation. Such changes in rACC and dmPFC activation have been observed consistently in previous meditation studies (Farb et al., 2007; Hölzel et al., 2007). Regarding the roles of the rACC and dmPFC in the monitoring of an individual's affective state and in mentalizing, rACC-dmPFC connectivity may reflect individuals' abilities to understand the mental state of self (Milham and Banich, 2005; Lombardo et al., 2010). As a central feature of Buddhist meditation, mentalization enhances self-awareness with mindfulness practices (Koriat, 2000). Moreover, it is considered a key component in strengthening individuals' resilience and shares some of the underlying neural mechanisms (Stein, 2006). Taken together, our results suggested that changes in rsFC in the regions related to mentalizing and resilience caused by mindfulness practice facilitated the short and long-term improvements of resilience in the MED group.

At the 3-month follow-up, the improvement in the resilience scores was significantly maintained in the MED group compared with that in the control group. Resilience is known to be relevant to the onset, recurrence, and symptom severity of various psychiatric disorders, including depression and anxiety disorders (Ludwig and Kabat-Zinn, 2008; Segal et al., 2010; Goyal et al., 2014). For this reason, many adjunctive therapies have been constantly developed to improve resilience and have proven to be effective (Fava and Tomba, 2009; Padesky and Mooney, 2012). However, only the meditation intervention, along with a few other interventions, has been shown to be effective within the short term and is self-trainable without an instructor after appropriate professional training. Furthermore, our results suggest that improved resilience *via* short-term meditation is maintained for up to 3 months. This evidence supports the hypothesis that short-term meditation might be a useful adjunctive intervention for individuals at high risk of psychiatric disorders. Moreover, the changes in the rACC-dmPFC rsFC may predict the maintenance effects of adjunctive therapy.

Interestingly, both groups demonstrated significant enhancements in psychological variables at the immediate follow-up, but the changes in rACC-dmPFC rsFC show different patterns between the groups. These results suggest that each group adopted different underlying mechanisms beyond the increased resilience and mindfulness scores. In the MED group, intensive meditation training seems to facilitate the resilience-related network, which eventually led to the psychological enhancement and its maintenance. In contrast, the changes in psychological measures in the control group were not able to show either significant correlation with rsFC or the maintenance of the scores. We suspect that their temporarily increased scores are due to the escape from everyday stress and relaxation rather than to the improvement in resilience.

In the present study, the control group was also exposed to interventions, such as escape from everyday stress, changes in environment and diet, and encountering new people. Such a design was based on an effort to minimize non-meditation factors, but our results suggest that the intervention also causes neural and behavioral changes. These changes may imply a "vacation effect," as reported in previous studies (de Bloom et al., 2009; Epel et al., 2016). The vacation effect refers

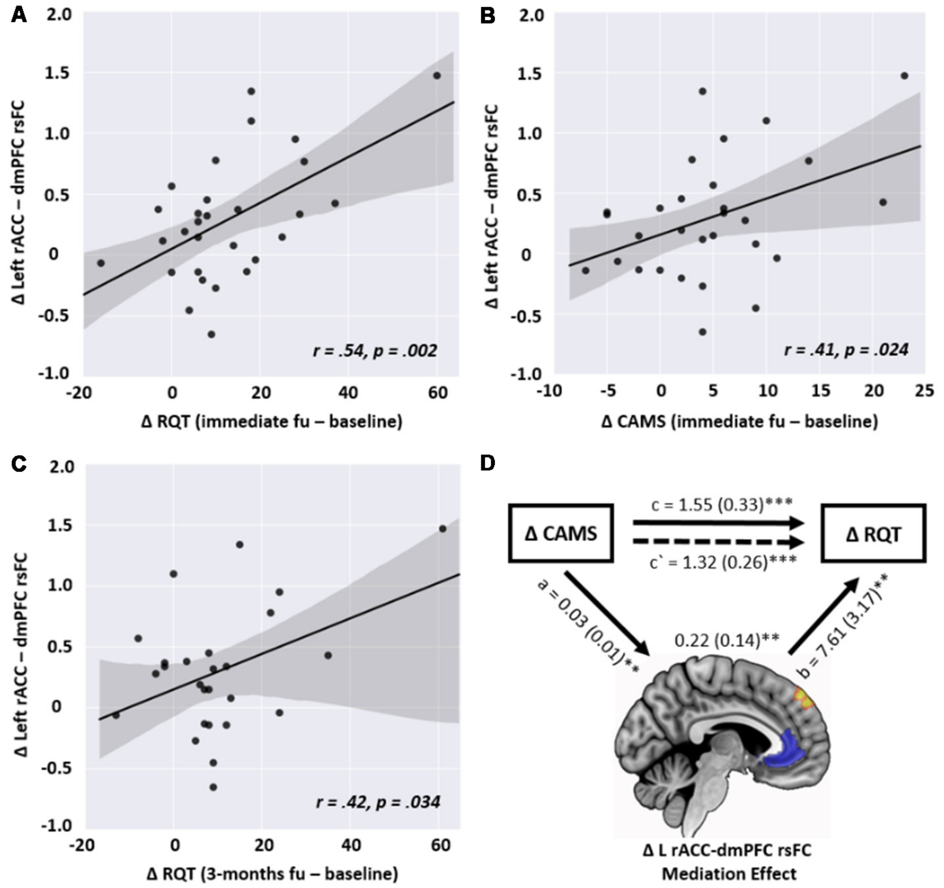

FIGURE 4 | Scatterplots of the relationship between the changes in left rACC—dmPFC resting-state functional connectivity (rsFC) and the changes in the following psychological measures in the meditation group: **(A)** changes in the Resilience Quotient Test (RQT) between baseline and immediate follow-up (r = 0.54, p = 0.002), **(B)** changes in the Cognitive and Affective Mindfulness scale (CAMS) between baseline and immediate follow-up (r = 0.41, p = 0.024), **(C)** changes in RQT between baseline and 3-month follow-up (r = 0.42, p = 0.034), **(D)** the positive association between the changes in CAMS (X) and RQT (Y), mediated by the changes in left rACC-dmPFC rsFC (M), showing that changes in rsFC partially contribute to the prediction of resilience enhancement. a, b, and c are path coefficients. $^{**}p < 0.01$, $^{***}p < 0.001$.

to the temporary improvements in health and psychological well-being after taking a vacation, which soon fades after work resumption. The absence of the maintenance effect of psychological measures in the control group also supports this definition. Unfortunately, we are unable to identify the exact factor that caused the changes in the rsFC of the control group after intervention because of the lack of any correlation with psychological measures. Moreover, randomized controlled studies to clarify the effect of vacation on neural levels, especially in resting-state connectivity, are very rare. In further studies, it will be necessary to explore the rsFC changes in the control group in more depth with various psychological measures, larger sample size and more follow-up time points.

We suspect a few possible few causes for the rsFC changes detected in the control group after the intervention. First, detachment from stress and everyday life may cause participants to feel relieved, which eventually led to changes in self-reported questionnaires and rsFC. Previous studies reported reduced rACC-temporal gyrus rsFC in veterans whether the individuals had PTSD or not (Kennis et al., 2015). The study suggested that experiencing stressful situations may alter the neural network. Unfortunately, we are unable to support the further explanation of the increased the rACC-temporal gyrus in the control because of the lack of correlation with psychological variables, but we suspect that the changes in the neural network were related to stress relief. Second, we cautiously assume that the diary writing in the control group might have enhanced language-related connectivity after the intervention. Some studies also demonstrated the effects of diary training at the cognitive and behavioral levels (Ho et al., 2011; Travers, 2011). The fronto-temporal rsFC has been known for its role in the language network; in particular, decoupling between ACC-temporal gyrus connectivity is associated with auditory hallucinations in individuals with schizophrenia (Stamatakis et al., 2005). However, it might be premature to suggest that writing in diaries account for the rsFC changes in the control group since previous studies used weeks of diary training. In the current study, further explanations of the rsFC changes in the control group are limited, but we suggest that these changes are due to the environmental modifications, including residence, diet, and other lifestyles.

The present study exhibits several strengths in exploring the effect of meditation exclusively. First, we recruited participants without prior experience in meditation or Templestay; therefore, all participants underwent the same period of intervention. Second, this study was designed as a longitudinal study and a randomized controlled trial to reduce possible pre-existing individual differences in the characteristics and brains of the participants. Third, we included an active control group to reduce the expectation effect on the participants. Finally, all of the participants, regardless of their group, were exposed to the same environment and diet in a retreat format to minimize any non-meditation-related factors.

When compared with previous studies, although the present study exhibits the above strengths, it also presents some potential limitations that should be noted. First, the individual level of mindfulness and resilience were assessed using self-reported questionnaires. Therefore, the scores may include some subjective bias. However, these scores have been used in many studies, and no objective tool for measuring these factors has been invented to date. Second, some participants' religion was Buddhism, and there is a possibility that their religion may have an effect on the result, even though they reported a lack of prior experience in meditation or Templestay. However, our statistical analyses support that the effect of religion was not statistically significant at either the baseline or in the changes in self-reported questionnaires or in the rsFC. Third, even though we assessed self-reported questionnaires at three time points (baseline, an immediate follow-up after the intervention, and a 3-month follow-up), we acquired brain imaging data only at baseline and at the immediate follow-up due to the participants' schedules and financial issues. For these reasons, it is unknown whether the change in neural connectivity was also maintained after 3 months. Further studies are needed to confirm the maintenance of neural changes and their relationships with other beneficial effects of meditation. In addition, more refined parcellation of ACC is recommended for the future studies, especially those with mental health conditions. Many recent studies suggest a distinct role of subgenual region and pregenual region of perigenual cingulate cortex, and different degrees of deficits in individuals with various psychiatric disorders (Davey et al., 2012; Zeng et al., 2014a). Adaptation of more elaborated ROI may clarify the effect of meditation in the neural level.

In conclusion, our highly controlled residential trial involving 4 days of meditation practice generated findings worthy of further study. Our study indicates that changes in the rACC-dmPFC rsFC may mediate improvement in and maintenance of individuals' resilience *via* short-term meditation. Given that resilience is a crucial factor in mental health conditions, our results may contribute to intervention and prevention programs for individuals at risk of psychiatric disorders. Moreover, the rACC-dmPFC rsFC may be a potential neural target for future adjunctive therapies.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

SK: acquisition of data, analysis, manuscript interpretation, making figures, revision and final approval of the article, agreement to be accountable for all aspects of the work. TL, WJ and J-WH: interpretation, critical comments on manuscript, revision and final approval of the article, agreement to be accountable for all aspects of the work. DB, KC and WH: acquisition of data, revision and final approval of the article, agreement to be accountable for all aspects of the work. K-OL, S-YK, HP and JK: acquiring fund, conception and design of the work, interpretation, critical comments on manuscript, revision and final approval of the article, agreement to be accountable for all aspects of the work.

FUNDING

This work was supported by the Basic Science Research Program of the National Research Foundation of Korea (NRF), which is funded by the Ministry of Science, ICT and Future Planning (Grant no. 2016R1E1A1A02921618) and Jogye Order of Korean Buddhism supported this research. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2019.00101/full#supplementary-material

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

ORIGINAL RESEARCH
published: 09 April 2019
doi: 10.3389/fnhum.2019.00120

fNIRS Evidence for Recognizably Different Positive Emotions

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The behavioral differentiation of positive emotions has recently been studied in terms of their discrete adaptive functions or appraising profiles. Some preliminary neurophysiological evidences have been found with electroencephalography or autonomic nervous system measurements such as heart rate, skin conductance, etc. However, the brain's hemodynamic responses to different positive emotions remain largely unknown. In the present study, the functional near-infrared spectroscopy (fNIRS) technique was employed. With this tool, we for the first time reported recognizable discrete positive emotions using fNIRS signals. Thirteen participants watched 30 emotional video clips to elicit 10 typical kinds of positive emotions (joy, gratitude, serenity, interest, hope, pride, amusement, inspiration, awe, and love), and their frontal neural activities were simultaneously recorded with a 24-channel fNIRS system. The multidimensional scaling analysis of participants' subjective ratings on these 10 positive emotions revealed three distinct clusters, which could be interpreted as "playfulness" for amusement, joy, interest, "encouragement" for awe, gratitude, hope, inspiration, pride, and "harmony" for love, serenity. Hemodynamic responses to these three positive emotion clusters showed distinct patterns, and HbO-based individual-level binary classifications between them achieved an averaged accuracy of 73.79 ± 11.49% (77.56 ± 7.39% for encouragement vs. harmony, 73.29 ± 11.87% for playfulness vs. harmony, 70.51 ± 13.96% for encouragement vs. harmony). Benefited from fNIRS's high portability, low running cost and the relative robustness against motion and electrical artifacts, our findings provided support for implementing a more fine-grained emotion recognition system with subdivided positive emotion categories.

Keywords: positive emotion, fNIRS, oxy-hemoglobin, deoxy-hemoglobin, classification

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Received: 27 December 2018
Accepted: 21 March 2019
Published: 09 April 2019

Citation:
Hu X, Zhuang C, Wang F, Liu Y-J,
Im C-H and Zhang D (2019) fNIRS
Evidence for Recognizably Different
Positive Emotions.
Front. Hum. Neurosci. 13:120.
doi: 10.3389/fnhum.2019.00120

INTRODUCTION

Feeling proud of good grades, getting amused by funny jokes, or being peaceful when staying with families. . .There is more than one kind of "happiness" in our daily life but the diversity of those positive emotions was much understated in previous studies. Positive emotions were often treated as a homogeneous group to be compared with negative or neutral emotion states, and the differentiation within positive emotions was largely neglected. More recently, some theoretical frameworks of discrete positive emotions have been proposed, mainly from the appraisal or adaptive function perspectives (Goetz et al., 2010; Fredrickson, 2013; Shiota et al., 2014; Tong, 2015; Graham et al., 2017). The appraisal approach to differentiate positive emotions could trace back to Smith and Ellsworth's (1985) and Ellsworth and Smith's (1988), which proposed six pleasant feeling states (hope/confidence, love, playfulness, tranquility, challenge, interest) associated with distinct appraisal patterns (appraisal of effort, agency, and certainty). Goetz et al. (2010) examined another three positive emotions (enjoyment, pride, contentment) and different relations with cognitive appraisal antecedents were found in the perception of control and value. Tong (2015) differentiated 13 positive emotions (amusement, awe, challenge, compassion, contentment, gratitude, hope, interest, joy, pride, relief, romantic love, and serenity) in 13 appraisal dimensions (pleasantness, relevance, problem, etc.), and the accuracies to classify positive emotions with appraisal profiles were reported to be above chance levels. Meanwhile, another vein of research focuses on the adaptive function of positive emotions. For example, Shiota et al. (2014) proposed a functional framework to define a number of discrete emotions, which included pride, amusement, nurturant love, attachment love, contentment, enthusiasm, awe, and sexual desire. Enthusiasm and contentment were thought as responses to material opportunities; Sexual desire, attachment love, nurturant love, as well as pride, were considered adaptive for their implications in the social domain; Amusement and awe were suggested to reflect opportunities to learn. Fredrickson (2013) qualitatively described both the appraisal themes and functional resources accrued of 10 representative positive emotions (joy, gratitude, serenity, interest, hope, pride, amusement, inspiration, awe, love), but empirical evidence is still limited. Most of those studies built their theories either on participants' subjective appraisals or researchers' personal interpretations for the proposed emotions; nevertheless, it is worth noting that cognitive appraisals do not necessarily cover all the aspects of the subjective experience of emotions. More importantly, the basic components of human emotion consist of not only subjective experience, but also behavioral expressions and neural responses (Izard, 1977). In the following paragraphs, we'll briefly review the empirical evidence for the differentiation of positive emotions based on these components.

Subjective Experience

Evidence for the differentiated subjective experiences of positive emotions has been found both from people's reports of the induced emotion states and daily emotion experiences. Recently, Linley et al. (2016) collected people's retrospective recall of the frequency and intensity of positive emotion experience in their daily life, and provided support for a set of 50 discrete positive emotions. Another study by Cowen and Keltner (2017) used 2,185 short video clips to elicit emotion responses from 853 participants and found 27 distinct varieties of the reported emotion experiences. About half of these 27 distinct varieties were positive emotions, and evidences for the difference between nuanced positive emotions such as romantic love and sexual desire were also reported.

Behavioral Expressions

Campos et al. (2013) found evidence for the different patterns of eight positive emotions in facial expression and body movement. Sauter (2017) reviewed the literature on the non-verbal expressions of positive emotions and reported the distinct recognizable vocal or facial displays of six positive emotions (amusement, awe, interest, and relief, pride, and elation). Hofmann et al. (2017) examined the Duchenne Displays of 16 positive emotions proposed by Ekman (2003), and found they differed in the intensity of Duchenne Displays and the propensity to induce laughter. While these studies were mostly based on static facial features or body gestures, review Mortillaro and Duk'es (2018) also stressed the importance of the dynamic facial expressions and body movement to differentiate positive emotions.

Neural Responses

Kreibig (2010) reviewed studies on the autonomic nervous system (ANS) responses to positive emotions, and reported considerable ANS specificity of eight distinct positive emotions. Shiota et al. (2011) assessed people's sympathetic and parasympathetic activations to five kinds of positive emotions, and provided evidence for the existence of physiologically distinct positive emotions in the aspect of ANS respondence. In addition to these ANS findings, a few studies have explored the central nervous system (CNS) responses to different positive emotions, mainly using the electroencephalography (EEG) technique. By analyzing the EEG-based neural electrical activities, Liu et al. (2017) realized a real-time recognition of three positive emotions (joy, amusement, and tenderness); in our previous EEG study, 10 typical positive emotions were included and recognizable EEG patterns of three distinct positive emotion clusters were found (Hu et al., 2017).

However, direct evidence of hemodynamic responses for the differentiation of positive emotions is still absent. Hemodynamic responses reflect the blood oxygenation level in the brain. It has been generally accepted that hemodynamic and neural electrical signals (e.g., EEG) provide complementary information about the underlying neural mechanism in various cognitive functions (Debener et al., 2006; Balconi et al., 2015). Using functional magnetic resonance imaging (fMRI) or functional near-infrared spectroscopy (fNIRS) technique, many researches have reported recognizable hemodynamic responses between positive versus negative emotions (eg., Tai and Chau, 2009; Sitaram et al., 2010; Moghimi et al., 2012; Bush et al., 2018) but not between different positive emotions. Nevertheless, the findings of the general-level positive emotion (usually termed "happiness") have been mixed (Vytal and Hamann, 2010; Hamann, 2012; Bendall et al., 2016). For instance, one study found positive emotions was accompanied by lower HbO responses in the right PFC compared to negative emotions (Balconi et al., 2015). Yet another study reported positive emotion was associated with increased oxygenation (HbO-HbR) in medial rostral PFC compared to negative states (Kreplin and Fairclough, 2013). Such inconsistent results might be explained by the oversimplified categorization of positive emotions and different manipulations for "positive" in different researches. Indeed, recent fMRI studies have also investigated the neural mechanisms of a few positive emotions and distinct brain regions were found for different positive emotions: amusement was found in relation to the activation in the left amygdala (Bartolo et al., 2006); gratitude was reported to be correlated with brain activity in the anterior cingulate cortex and medial prefrontal cortex (PFC) (Fox et al., 2015); Pride was found associated with activations in the right posterior superior temporal sulcus and left temporal pole, while joy activated the ventral striatum and insula/operculum (Takahashi et al., 2008). Employing fNIRS technique, researchers have also obtained a few preliminary findings: esthetic positive emotion was associated with activation in medial rostro PFC (Kreplin and Fairclough, 2013); Maternal and grandmaternal love was found involved with right and anterior PFC (Nishitani et al., 2011; Kida et al., 2014). Taken together, as different positive emotions seemed to be associated with distinct brain regions, these studies support the plausibility of differentiating positive emotions with hemodynamic responses. However, as most of these studies included only one positive emotion per study, it is necessary to include multiple positive emotions in a single study, in order to provide direct hemodynamic evidence for a more comprehensive and complete overview of the neural mechanisms of different positive emotions.

Compared to fMRI, fNIRS is less restrictive, more comfortable, and portable. This advantage may be especially crucial for positive emotion research, as unwanted interferences from device noises and claustrophobic environment are avoided, allowing for more natural positive emotion experience. Therefore, the present study employed fNIRS to study different positive emotions. We empirically focused on the PFC, because it involves less motion artifacts and signal attenuation due to hairs (Naseer and Hong, 2015), and previous emotion related fNIRS studies have reported positive findings in the PFC region, both for those researches focused on the general emotion valence (e.g., Tai and Chau, 2009; Moghimi et al., 2012; Trambaiolli et al., 2018; Wang et al., 2018) and specific positive emotions (e.g., Nishitani et al., 2011; Kreplin and Fairclough, 2013; Kida et al., 2014). Following our previous study (Hu et al., 2017), emotional videos were used to elicit 10 kinds of positive emotions (joy, gratitude, serenity, interest, hope, pride, amusement, inspiration, awe, and love), and the corresponding hemodynamic signals were recorded with an fNIRS system.

The aim of the present study is to explore the hemodynamic activities of different positive emotions. We hypothesize to observe distinct hemodynamic responses associated with different positive emotions. Here we referenced to existing fNIRS based affective computing studies (e.g., Tai and Chau, 2009; Moghimi et al., 2012; Heger et al., 2013; Aranyi et al., 2016), used a machine learning approach at a single-participant level: the classification accuracies of the fNIRS responses elicited by different positive emotion videos were taken to reflect the neural differentiation of positive emotions at the hemodynamic level. The classifications between positive and negative emotions were conducted as well, to provide a baseline for evaluation the results from between positive emotions. Such an approach could provide neural evidence not only for a better understanding of different positive emotions, but also for implementing practical brain-computer interface systems for emotion state recognition.

MATERIALS AND METHODS

Participants

Fifteen college students (seven females, mean age: 22.5 years, ranging: 20–25 years) participated in the experiment as paid volunteers. All participants had normal hearing, normal or corrected-to-normal vision. Written informed consent was obtained from all participants. The study was conducted in accordance with the Declaration of Helsinki and approved by the local Ethics Committee of Tsinghua University. Data from two participants was discarded, due to technical problems during data recording.

Materials

Thirty clips of films were used to elicit 10 typical kinds of positive emotions (joy, gratitude, serenity, interest, hope, pride, amusement, inspiration, awe, and love, following the proposal in Fredrickson, 2013). One neutral and six negative emotion stimuli (half with high arousal and the other half with low arousal) were used as a control condition. All the stimuli in use were the same as those in our previous study (Hu et al., 2017), except that one film clip to induce pride (the publicity film of Tsinghua University) was replaced by a TV news about the launching of Shenzhou-10 spacecraft for the general Chinese audience. The average duration of all the stimuli was 70 s (varied between 30 to 129 s). For those film clips containing non-Chinese dialogues, Chinese subtitles were added to guarantee a full understanding of the contents. Detailed information of the materials can be found in the **Supplementary Table S1**.

Procedure

The participants watched all the 37 film clips (30 positive, 6 negative, and 1 neutral) on an LCD monitor (22-inch, 60 Hz refreshing rate) in a laboratory environment, with their hemodynamic activities simultaneously recorded. After watching each film clip, participants were asked to report their emotion states on the 10 positive emotions and another four emotion dimensions (arousal, valence, familiarity, and liking) on seven-point Likert scales (1 = not at all, 7 = extremely). Between two sequential trials, participants took a rest for at least 45 s to recover from the previously induced emotion state.

Prior to the experiment, the participants were given an explanation of the 14 emotional items and the experimental procedure. Then, two practice trials were performed to get the participants familiarized with the procedure. In the formal experiment, the neutral clip was first presented, followed by the six negative emotion clips, and then the 30 positive emotion clips. The orders of the clip presentations were randomized within the negative and positive emotion clips, respectively. The experiment procedure was programmed in MATLAB (The Mathworks, United States) using the Psychophysics Toolbox 3.0 extensions (Brainard, 1997).

fNIRS Recordings

The fNIRS signals were recorded using a 24-channel fNIRS system (NirScan, HuiChuang, China) at a sampling rate of 50 Hz.

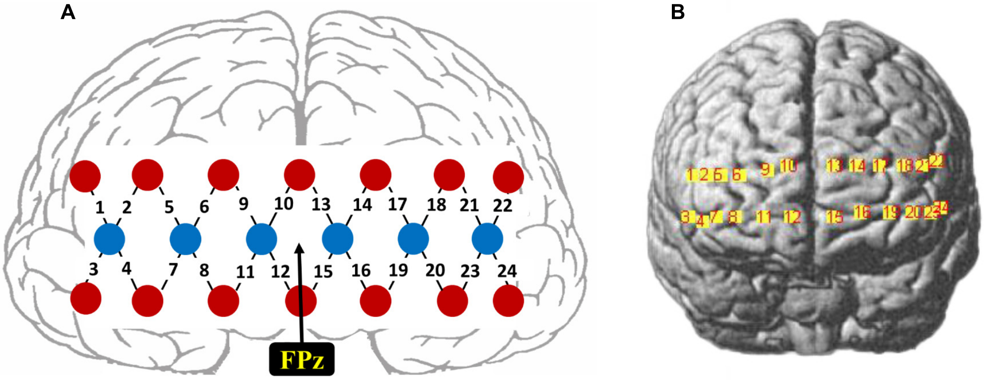

FIGURE 1 | (A) Schematic illustration of the fNIRS probe layout. **(B)** The topographical distribution of the fNIRS recording channels.

Near-infrared light of three different wavelengths (785, 808, and 850 nm) was used to detect the concentration change of oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR). Twenty probes (6 sources and 14 detectors) were placed to cover the frontal cortex (between-probe distance of 30 mm), resulting in a total of 24 channels, as shown in **Figure 1A**. The center of the middle probe set row was placed approximately at FPz, according to the 10/20 international system. The topographical distribution of the fNIRS channels were visualized on the standard human cortex surface using the NirsScan software (**Figure 1B**).

Data Analysis

Behavioral Data Analysis

Intra-class correlation coefficients (ICC) were calculated for all the 14 emotion items to examine the reliability of the ratings across participants. Then, repeated measures analysis of variance (rmANOVA) and *post hoc* paired t-tests were employed to check whether these film clips elicited the expected emotions. For each group of three film clips designated to elicit one specific positive emotion, participants' ratings on the 10 positive emotion items were compared to see whether the target emotion was more prominent than the other emotions. The false discovery rate (FDR) method was used to correct the p-values from the *post hoc* t-tests (Benjamini and Hochberg, 1995).

To obtain a general overview of the relationships among the 10 positive emotions, Pearson correlation coefficients were calculated on the cross-participant averaged ratings per film clip, for every pair of the 10 positive emotions. As significant correlations were found among many pairs of positive emotions (see Results), we then applied unsupervised multidimensional scaling (MDS) method on the cross-participant average ratings of the 30 positive emotion film clips, to further characterize the similarity across all the 10 positive emotions. These 10 positive emotions were manually categorized into three clusters according to their geometric similarity in the MDS space, and each film clip's cluster scores were calculated by averaging the ratings of all the emotions within each cluster, resulting in three cluster scores. For example, emotions in the "playfulness" cluster are interest, joy, and amusement. For a certain film clip, if the ratings of those three emotions were 1, 2, 2, then the "playfulness" score for this film clip would be 1.67. And the other two cluster scores were calculated in the same way.

fNIRS Signal Preprocessing

Raw light intensity data was filtered by 0.01–0.2 Hz bandpass to remove common noises including the physiological noises due to heartbeats, respirations, and Mayer waves (Zhang et al., 2017; Trambaiolli et al., 2018; Wang et al., 2018). Then, the filtered signals were converted into relative concentration changes of HbO and HbR according to the modified Beer-Lambert law (Scholkmann et al., 2014).

Specifically, the modified Beer-Lamber Law is formated as follows,

$$OD^{\lambda_i} = \ln \frac{I_{oi}}{I_I} = (\varepsilon^{\lambda_i}_{HbO} C_{HbO} + \varepsilon^{\lambda_i}_{HbR} C_{HbR}) \times r \times DPF^{\lambda_i} \quad i = 1, 2, 3 \quad (1)$$

$$\Delta OD^{\lambda_i} = (\varepsilon^{\lambda_i}_{HbO} \Delta C_{HbO} + \varepsilon^{\lambda_i}_{HbR} \Delta C_{HbR}) \times r \times DPF^{\lambda_i} \quad i = 1, 2, 3 \quad (2)$$

where the variable ε is the wavelength-dependent extinction coefficient for each hemoglobin types. The *DPF* (differential path-length factor) is added to account for the true effective path length between source and detector and r represents the linear distance of the paired probes. The change in light absorption, referred to as delta optical density, ΔOD. ΔC_{HbO} and ΔC_{HbR} represent the relative concentration changes of HbO and HbR respectively. HbO and HbR can be calculated by the following equation,

$$\begin{pmatrix} \Delta C_{HbO} \\ \Delta C_{HbR} \end{pmatrix} = \begin{pmatrix} \varepsilon^{\lambda_1}_{HbO} & \varepsilon^{\lambda_1}_{HbR} \\ \varepsilon^{\lambda 2}_{HbO} & \varepsilon^{\lambda 2}_{HbR} \\ \varepsilon^{\lambda 3}_{HbR} & \varepsilon^{\lambda_3}_{HbO} \end{pmatrix}^{-1} \begin{pmatrix} \Delta OD^{\lambda_1}/(r \times DPF^{\lambda_1}) \\ \Delta OD^{\lambda_2}/(r \times DPF^{\lambda_2}) \\ \Delta OD^{\lambda_3}/(r \times DPF^{\lambda_3}) \end{pmatrix} \quad (3)$$

HbO and HbR responses to each film clip were baseline corrected by subtracting the average response from the 10-s time window before the presentation of the film clip, then signals corresponding to the last 30 s of each film clip were extracted in order to obtain maximal emotional responses (following the procedure in Koelstra et al., 2012), and cut into three non-overlapping 10-s samples for further analyses. Besides band-pass filtering, we did not perform additional artifact rejection procedures.

Correlation Analysis

The response patterns to different positive emotion clusters were characterized by computing the Pearson correlation between the HbO/HbR responses of each individual fNIRS channel and three positive emotion scores. The correlation between HbO/HbR responses and the emotion valence ratings were also computed. The correlations were calculated for each individual participant, and the data of only positive emotion film clips was used. The topographies of the across-participant average Pearson correlation coefficients between the rating of emotion scores and the HbO/HbR responses were expected to illustrate the neural responses to the three positive emotion clusters.

Classification Based Analysis

A classification-based approach was adopted to evaluate the neural differentiation of different positive emotion clusters. A series of binary classifications were employed between (a) each positive emotion cluster and negative emotion, and (b) all the pairs of the three positive clusters. To be noted, there are thirty positive emotion stimuli and only six negative emotion stimuli in total. To have balanced sample sizes for the above classifications and to allow a direct comparison of these classification results, for each positive emotion cluster, six film clips with the highest cluster scores were selected, since there were six film clips for the negative emotion condition. The features for classifications were the HbO or HbR responses from all the 24 fNIRS channels, leading to 24 feature dimensions representing the spatial response patterns. These features were calculated as the average responses over each 10-s sample from the extracted 30-s period per each film clip, resulting in 3 (samples per film) × 6 (films per category) = 18 samples for each emotion category per participant. The linear-kernel-based support vector machine (SVM) classification method was employed, using the function provided by the Statistics and Machine Learning Toolbox of Matlab. The classifications were carried out using either HbO or HbR features separately, and both the HbO and HbR based classification were conducted on the basis of each individual participant's data.

The pairwise binary classifications of the three positive emotion clusters were expected to indicate the separability of different positive emotions on the hemodynamic level, and the classifications between each positive emotion cluster and negative emotion served as a comparison. To calculate the chance level of these classifications, permutation tests were conducted by randomly shuffling the labels 100 times for each classifier, and the mean of these 100 shuffle-based accuracies determined the chance levels. All the reported results were based on sixfold cross-validations. The selection of sixfold is for a convenience purpose: there were 18 + 18 = 36 samples per binary classification, hereby each fold had six samples for testing.

RESULTS

Emotion ratings from different participants showed strong consistency, as revealed by the ICCs of all the ratings on the 14 emotion items. ICC values varied from 0.72 (serenity) to 0.95 (amusement), with a mean ICC of 0.91 (*SD* = 0.06), indicating good reliabilities across the participants.

More than half of the film clips indeed showed the highest ratings on the target emotion (rmANOVA $p < 0.001$ for all positive emotion items and *post hoc* paired *t*-tests showed significantly higher ratings for the target emotion, $p < 0.05$) (**Figure 2**). However, as the correlation analyses showed, some positive emotions are highly correlated, and in some cases the target emotions did not significantly differ from other similar emotions (e.g., for film clips designated to elicit "pride," ratings on "hope," "inspiration," and "awe" did not significantly differ from the ratings on "pride") or even lower than them (e.g., for film clips designated to elicit "inspiration," ratings on "inspiration" are actually lower than "hope").

The pairwise correlation coefficients between the ratings on different positive emotions as well as arousal, valence, liking, and familiarity, were listed in **Table 1**. Significant correlations were observed in many cases. For example, participants' ratings on "inspiration" and "hope" achieved a correlation coefficient of 0.94 ($p < 0.05$), indicating a considerable overlap between the feelings of inspiration and hope in the present film clip materials. The follow-up MDS analysis revealed a clear separation of these positive emotions in three clusters, resembling the behavioral results in our previous EEG study (Kruskal's Stress I = 0.074, **Figure 3**). Cluster-1 is composed of awe, gratitude, hope, inspiration and pride, which is interpreted as "encouragement"; Cluster-2 is constituted by amusement, interest and joy, which is interpreted as "playfulness"; and Cluster-3 consists of love and serenity, which is interpreted as "harmony."

Figure 4 shows the topographies of the cross-participants averaged correlation coefficients between the HbO/HbR responses and the corresponding emotion scores (three positive emotion clusters and emotion valence). For the "encouragement" emotions (awe, gratitude, hope, inspiration, and pride), positive correlations with HbO responses were observed over the medial prefrontal area, and a mild right lateral pattern was found for HbR responses. The "playfulness" emotions (amusement, interest, and joy) showed prominent negative correlations with HbR responses over the whole frontal area. The "harmony" emotions (love and serenity) were associated with left lateral frontal activations both for HbO and HbR. The general emotion valence also showed mild lateral activations for HbO but not for HbR. However, none of these correlation results were significant after FDR correction.

The HbO-based binary classification accuracies for each positive emotion cluster vs. negative emotion are shown in **Table 2**. Individual-level binary classifications among them achieved an averaged accuracy of 83.69 ± 9.19% (83.33 ± 8.56% for encouragement vs. negative, 82.48 ± 10.17% for playfulness vs. negative, 85.26 ± 9.31% for harmony vs. negative; The chance levels determined by permutation tests were 49.29 ± 13.60, 49.06 ± 13.53, 49.08 ± 13.48%, respectively).

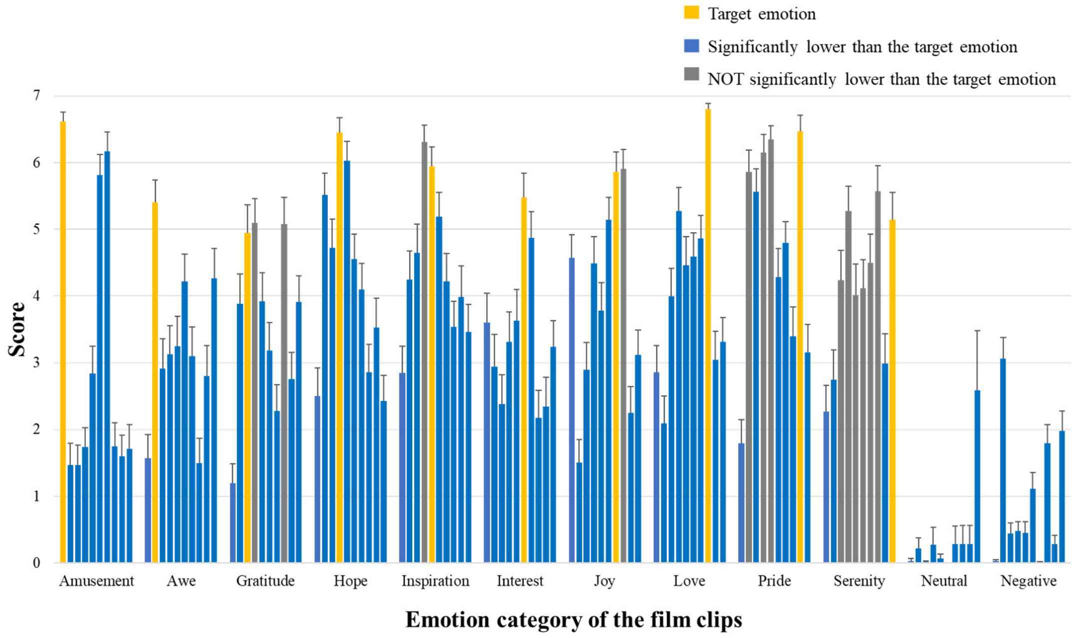

FIGURE 2 | Basic information of emotion ratings. Participants' ratings on the 10 positive emotional experience items. For each emotion category of film clips, the 10 bars indicate the mean ratings of these clips on amusement, awe, gratitude, hope, inspiration, interest, joy, love, pride, and serenity (from left to right). The bars in yellow show the ratings on the corresponding target emotion; The bars in blue mean their ratings significantly lower than those of the target emotion (*post hoc* paired *t*-tests $p < 0.05$, FDR corrected); The bars in gray indicate ratings NOT significantly different from those of the target emotion ($p > 0.05$, FDR corrected).

TABLE 1 | Pairwise correlation coefficients between the 14 emotion items.

	Amusement	Awe	Gratitude	Hope	Inspiration	Interest	Joy	Love	Pride	Serenity	Arousal	Valence	Familiarity	Liking
Amusement	–													
Awe	-0.48^{**}	–												
Gratitude	-0.05	0.56^{**}	–											
Hope	0.12	0.44^{**}	0.94^{**}	–										
Inspiration	0.27	0.47^{**}	0.87^{**}	0.94^{**}	–									
Interest	0.81^{**}	-0.05	0.36^{*}	0.51^{**}	0.66^{**}	–								
Joy	0.88^{**}	-0.23	0.31^{*}	0.48^{**}	0.60^{**}	0.92^{**}	–							
Love	0.14	-0.14	0.51^{**}	0.59^{**}	0.41^{**}	0.26	0.38^{*}	–						
Pride	0.03	0.62^{**}	0.85^{**}	0.83^{**}	0.89^{**}	0.45^{**}	0.41^{**}	0.34^{*}	–					
Serenity	-0.20	0.30	0.50^{**}	0.46^{**}	0.30	0.11	0.06	0.45^{**}	0.37^{*}	–				
Arousal	0.62^{**}	-0.02	0.09	0.19	0.42^{**}	0.56^{**}	0.58^{**}	-0.11	0.31	-0.56^{**}	–			
Valence	0.63^{**}	0.07	0.68^{**}	0.79^{**}	0.85^{**}	0.85^{**}	0.86^{**}	0.50^{**}	0.68^{**}	0.31^{*}	0.42^{**}	–		
Familiarity	0.43^{**}	0.02	0.33^{*}	0.41^{**}	0.53^{**}	0.51^{**}	0.53^{**}	-0.02	0.48^{**}	-0.02	0.50^{**}	0.58^{**}	–	
Liking	0.69^{**}	0.06	0.59^{**}	0.71^{**}	0.81^{**}	0.92^{**}	0.89^{**}	0.41^{**}	0.64^{**}	0.20	0.53^{**}	0.94^{**}	0.58^{**}	–

$^{*}p < 0.05$, $^{**}p < 0.01$.

The HbR-based results are shown in **Table 3**. Individual-level binary classifications among them achieved an averaged accuracy of 79.06 ± 9.47% (80.34 ± 9.98% for encouragement vs. negative, 80.34 ± 7.21% for playfulness vs. negative, 76.50 ± 11.03% for harmony vs. negative; The chance levels determined by permutation tests were 48.86 ± 12.85, 48.37 ± 13.05, 48.55 ± 12.72%, respectively).

The HbO-based binary classification accuracies between positive emotion clusters are shown in **Table 4**. Individual-level binary classifications among them achieved an averaged accuracy of 73.79 ± 11.49% (77.56 ± 7.39% for encouragement vs. playfulness, 73.29 ± 11.87% for playfulness vs. harmony, 70.51 ± 13.96% for encouragement vs. harmony; The chance levels determined by permutation tests were 49.55 ± 13.32, 48.64 ± 13.05, 48.87 ± 13.10%, respectively). The HbR-based results are shown in **Table 5**. Individual-level binary classifications among them achieved an averaged accuracy of 66.74 ± 13.04% (74.57 ± 9.94% for encouragement vs. playfulness, 64.53 ± 12.94% for playfulness vs. harmony, 61.11 ± 12.88% for encouragement vs. harmony; The chance

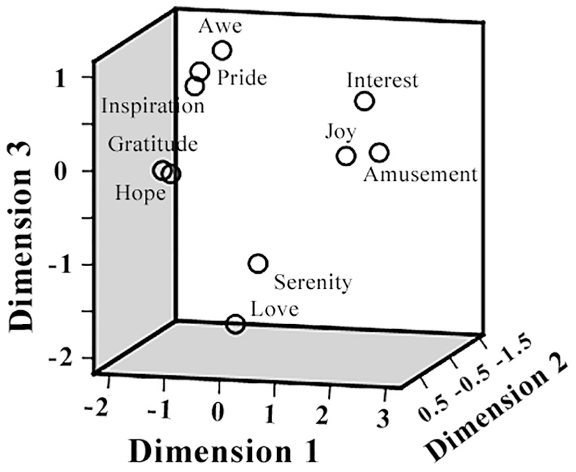

FIGURE 3 | Multidimensional scaling (MDS) space of 10 positive emotions. The MDS space shows the similarity of the 10 positive emotions, based on the participants' subjective ratings.

levels determined by permutation tests were 48.50 ± 12.53, 48.41 ± 11.97, 47.68 ± 12.30%, respectively).

DISCUSSION

The current study investigated the brain hemodynamic responses to different positive emotions using fNIRS. In line with our previous EEG study (Hu et al., 2017), considerable similarity among the 10 positive emotions induced in the experiment was evidenced by the participants' subjective reports, leading to three representative positive emotion clusters (encouragement, playfulness, and harmony). The three positive emotion clusters showed different hemodynamic responding patterns, and the HbO-based binary classification between the three clusters achieved an averaged accuracy of 73.79 ± 11.49%, suggesting possible distinct underlying neural mechanisms of the three positive emotion clusters. To the best of our knowledge, this is the first piece of fNIRS evidence demonstrating the differentiation of subdivided positive emotions.

TABLE 2 | HbO-based binary classification accuracies between negative emotion and each positive emotion cluster.

Participant	Accuracy (%)		
	Negative vs. Cluster 1	Negative vs. Cluster 2	Negative vs. Cluster 3
1	69.44	86.11	77.78
2	86.11	91.67	88.89
3	86.11	72.22	72.22
4	91.67	94.44	97.22
5	97.22	63.89	83.33
6	75.00	66.67	94.44
7	91.67	77.78	80.56
8	72.22	83.33	94.44
9	72.22	91.67	75.00
10	86.11	94.44	97.22
11	86.11	88.89	91.67
12	83.33	80.56	83.33
13	86.11	80.56	72.22
Mean	83.33 ± 8.56	82.48 ± 10.17	85.26 ± 9.31

Previous fNIRS findings on the activation in the PFC to the general-level positive emotion have been mixed. One study used image stimuli from the International Affective Picture System (IAPS) to induce positive/negative/neutral emotion states, and found positive emotion was associated with decreased HbO in the left dorsolateral PFC, while negative emotion was accompanied by increased HbO in the bilateral ventrolateral PFCs (Hoshi et al., 2011). Yet another IAPS based study found lower HbO responses in the right PFC to positive emotion than negative

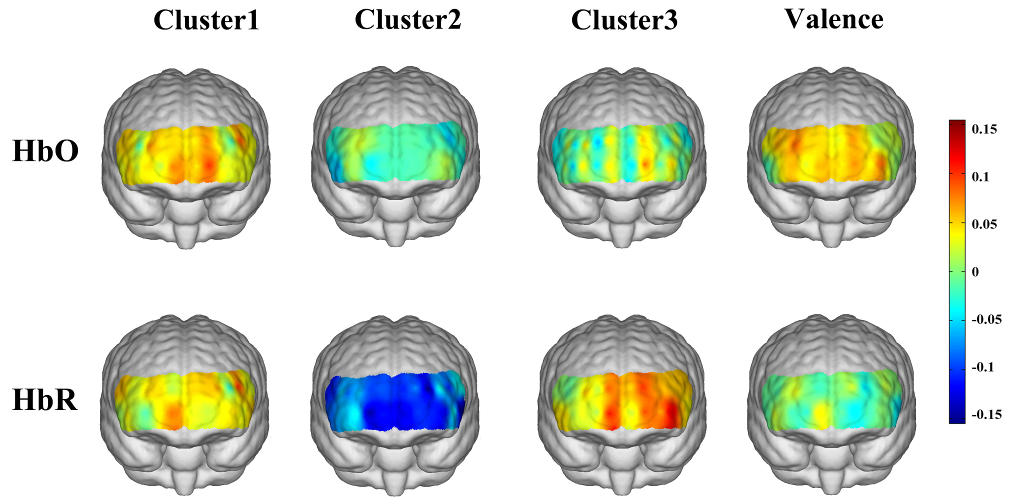

FIGURE 4 | Correlations between emotion scores and HbO/HbR responses.

TABLE 3 | HbR-based binary classification accuracies between negative emotion and each positive emotion cluster.

Participant	Accuracy (%)		
	Negative vs. Cluster 1	Negative vs. Cluster 2	Negative vs. Cluster 3
1	80.56	77.78	80.56
2	63.89	91.67	75.00
3	97.22	86.11	72.22
4	75.00	77.78	66.67
5	83.33	83.33	80.56
6	86.11	69.44	63.89
7	91.67	75.00	91.67
8	69.44	77.78	80.56
9	75	80.56	63.89
10	91.67	91.67	91.67
11	86.11	86.11	94.44
12	72.22	69.44	66.67
13	72.22	77.78	66.67
Mean	80.34 ± 9.98	80.34 ± 7.21	76.50 ± 11.03

TABLE 4 | HbO-based binary classification accuracies within three positive emotion clusters.

Participant	Accuracy (%)		
	Cluster 1 vs. Cluster 2	Cluster 2 vs. Cluster3	Cluster 1 vs. Cluster 3
1	75.00	63.89	66.67
2	75.00	86.11	75.00
3	83.33	69.44	77.78
4	83.33	55.56	86.11
5	80.56	69.44	86.11
6	77.78	66.67	50.00
7	88.89	86.11	80.56
8	66.67	69.44	58.33
9	83.33	80.56	58.33
10	83.33	88.89	75.00
11	69.44	83.33	72.22
12	77.78	80.56	86.11
13	63.89	52.78	44.44
Mean	77.56 ± 7.39	73.29 ± 11.87	70.51 ± 13.96

TABLE 5 | HbR-based binary classification accuracies within three positive emotion clusters.

Participant	Accuracy (%)		
	Cluster 1 vs. Cluster 2	Cluster 2 vs. Cluster3	Cluster 1 vs. Cluster 3
1	58.33	47.22	50.00
2	77.78	77.78	66.67
3	91.67	63.89	72.22
4	80.56	41.67	61.11
5	75.00	63.89	80.56
6	75.00	55.56	58.33
7	88.89	75.00	72.22
8	77.78	77.78	41.67
9	66.67	66.67	38.89
10	80.56	80.56	63.89
11	66.67	72.22	75.00
12	69.44	69.44	63.89
13	61.11	47.22	50.00
Mean	74.57 ± 9.94	64.53 ± 12.94	61.11 ± 12.88

emotion (Balconi et al., 2015). Studies with other emotion manipulation methods also revealed inconsistent findings: one study selected visual art to elicit positive and negative emotions, and reported increased oxygenation (HbO-HbR) in medial rostral PFC for positive emotion compared to negative states (Kreplin and Fairclough, 2013), while another study introduced participates to anticipate positive/negative/neutral emotion, and found activation in left dorsal lateral PFC was higher for positive emotion anticipation than negative and neutral conditions (Wang et al., 2018). In the present study, we found a mild correlation between the general emotion valence and lateral HbO activations, which suggests higher HbO responses in the lateral PFC were associated with more positive emotions. Although we cannot make further inference due to different experimental paradigms, these findings nevertheless indicated the importance of PFC in positive emotion processing.

When we examined the neural responses to the three positive emotion clusters respectively, distinct hemodynamic activation patterns were observed: "Encouragement" emotions were associated with HbO increase in the medial prefrontal area; "Playfulness" emotions reduced the HbR responses in the whole prefrontal area; "Harmony" emotions activated a salient left lateral prefrontal HbR responses. The increased HbO in the medial prefrontal area during "encouragement" emotions may be attributed to the activation of the medial prefrontal area associated with self-relevant processing, as these emotions (pride, inspiration, hope, gratitude, awe) require more self-relevant processing than the other positive emotions (e.g., Tangney, 1999; Van Cappellen and Rimé, 2013). Whereas our stimuli for "harmony" emotions contained film clips about maternal love, the association between maternal love and increased HbO in the right prefrontal area found by Nishitani et al. (2011) did not replicate in the present study. This may be because that the conclusion in Nishitani et al. (2011) was exclusive to mothers with new-born babies, but the participants in our study are all non-mother students. Another alternative explanation is that our stimuli contained not only maternal love but also romantic love, and further comparisons could be conducted between more specific kinds of love in future studies. While there are more distinct hemodynamic patterns for the three positive emotion clusters (such as the decreased HbR associated with "playfulness" emotions), more studies are necessary before providing further interpretation for these findings. In addition, the peak correlation coefficients between HbO/HbR and the three positive emotion cluster scores (0.11, 0.15, and 0.13 for the three cases, respectively) were larger than those between HbO/HbR and emotion valence (peak value of 0.09, as depicted by the colors in **Figure 4**), further arguing against the conventional view of treating positive emotions as a homogenous group. It should be noted that these correlation results were non-significant and therefore mainly for a descriptive purpose. The non-significance of these results might be due to the small sample size, or a possible high inter-participant variability of the positive emotion responses (e.g., Hamann and Canli, 2004; Kehoe et al., 2011). Further studies are necessary to localize the responsive regions of different positive emotions.

More importantly, the hemodynamic signal based classification results confirmed the separability of these specific positive emotion clusters (average accuracy for paired classifications between the three clusters achieved 73.79 ± 11.49% for HbO and 66.74 ± 13.04% for HbR). The HbO-based classifications in general showed better performance than HbR-based ones, which could be explained by the overall more reliable measurement of cerebral blood flow by HbO than HbR (Malonek et al., 1997; Strangman et al., 2002). These binary classification accuracies were lower than results obtained for positive vs. negative classifications (73.79 ± 11.49 vs. 83.69 ± 9.19% for HbO and 66.74 ± 13.04 vs. 79.06 ± 9.47% for HbR), suggesting one positive emotion is more similar to other positive emotions than negative ones. Nevertheless, the discriminability between the three positive emotion clusters was still well above chance level. In addition, the classifications were performed on an individual level at the time scale of 10 s without any artifact rejection procedures. While the neural separability between different positive emotion categories might be underestimated, these results offered direct support for the potential practical real-time emotion recognition applications.

It is worthwhile to note that a machine learning approach was employed in the present study. Here we mainly focused on single-participant-level classification results to reflect the separability of the neural responses to different positive emotions. While the sample size is smaller than typical neuroscience studies that have usually focused on group-level statistics, it is comparable with existing fNIRS based affective computing studies using machine learning methods (e.g., Tai and Chau, 2009; Moghimi et al., 2012; Heger et al., 2013; Aranyi et al., 2016). Moreover, our results for positive vs. negative classifications were in a similar range as these previous studies (i.e., 70∼95%) and most participants in the present study got classification results well above chance level (for the classifications between negative and positive emotions, mainly in the range of 70∼95%; for the classifications within three positive clusters, mainly in the range of 65∼85%; with one exception of the participant #13 showing chance-level performance for two out of three binary classifications), supporting the validity of our conclusion. Nevertheless, the machine learning approach is limited in its explanatory capacity toward mechanism interpretations (Shmueli, 2010), further studies with a larger sample size would help to gain more insights about underlying neural mechanisms of different positive emotions.

Admittedly, several limitations of the present study should be noted. First, the selection of the 10 kinds of positive emotions was supposed to include the most frequently experienced positive emotions in people's daily life (Fredrickson, 2013), rather than cover all the possible positive emotions. Accordingly, the three clusters based on these 10 positive emotions could not be expected to explain all the variants of positive emotions. Second, as mentioned above, different emotion-eliciting paradigms might lead to different conclusions. Future studies should be conducted with more kinds of emotion stimuli (such as images and sound), and this also calls for more standardized databases for emotion stimuli of different positive emotions (e.g., Ge et al., 2018). Third, data analyses in this study were based on the most basic HbO and HbR changes, not including more complex features such as slope, skewness, and kurtosis of HbO and HbR signals. Therefore, more feature extraction methods together with advanced machine learning techniques could be explored in future studies. Last but not least, due to the limited film clip materials and the limited fNIRS channel coverage, our results do not necessarily indicate that there are only three prominent positive emotion clusters, but rather suggest that at least three clusters could be well-separated based on human hemodynamic responses over the frontal regions.

The differentiation of positive emotions is not only of theoretical importance, but also of practical value. For example, the differentiation of specific positive emotion experience is highly valued in the field of affective product design and interaction, because user's emotion experiences to products are more nuanced than what is captured with a general bipolar dimension of valance (Yoon et al., 2016). Therefore, positive emotion evaluations with higher granularity are expected to be beneficial in product design process, and provide users with more fitting positive experiences. In the field of consumer decision-making, recent studies have also stressed that emotions of the same positive valence would have different effects on consumers' product preferences and decision-making behaviors (Griskevicius et al., 2010; Winterich and Haws, 2011), which indicated the significance of distinguishing different positive emotions in marketing strategy making. The plausibility of differentiating specific positive emotions has been supported by the present study at the neural level. Together with fNIRS's high portability, low running cost and the relative robustness against motion and electrical artifacts, our findings also suggested the potential of implementing a more fine-grained positive emotion recognition system with the fNIRS technique.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of Tsinghua University Research Ethics Committee in Psychology Department with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by Tsinghua University Research Ethics Committee in Psychology Department.

AUTHOR CONTRIBUTIONS

XH contributed to the conception design, data analysis, and drafting the work. CZ contributed to data collection and analysis. FW, Y-JL, and C-HI contributed to revising the work. DZ contributed to the conception design, data interpretation and drafting, revising the work. All authors approved the work for publication.

FUNDING

This work was supported by MOE (Ministry of Education China) Project of Humanities and Social Sciences (17YJA190017), National Social Science Foundation of China (17ZDA323), National Natural Science Foundation of China (U1736220), and National Key Research and Development Plan (2016YFB1001200).

ACKNOWLEDGMENTS

We thank Shizhao Liu, Yijun Yang, Andi Liao in Tsinghua University, and Dr. Daifa Wang, Yanchun Zheng, Shen Zhang in Beihang University, for their technical support of participant recruitment and data collection.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2019.00120/full#supplementary-material

TABLE S1 | Basic information of the materials.

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

ORIGINAL RESEARCH
published: 12 April 2019
doi: 10.3389/fnhum.2019.00112

Trait Mindfulness and Functional Connectivity in Cognitive and Attentional Resting State Networks

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Mindfulness has been described as an orienting of attention to the present moment, with openness and compassion. Individuals displaying high *trait* mindfulness exhibit this tendency as a more permanent personality attribute. Given the numerous physical and mental health benefits associated with mindfulness, there is a great interest in understanding the neural substrates of this trait. The purpose of the current research was to examine how individual differences in trait mindfulness associated with functional connectivity in five resting-state networks related to cognition and attention: the default mode network (DMN), the salience network (SN), the central executive network (CEN), and the dorsal and ventral attention networks (DAN and VAN). Twenty-eight undergraduate participants completed the Five-Facet Mindfulness Questionnaire (FFMQ), a self-report measure of trait mindfulness which also provides scores on five of its sub-categories (*Observing*, *Describing*, *Acting with Awareness*, *Non-judging of Inner Experience*, and *Non-reactivity to Inner Experience*). Participants then underwent a structural MRI scan and a 7-min resting state functional MRI scan. Resting-state data were analyzed using independent-component analyses. An analysis of covariance (ANCOVA) was performed to determine the relationship between each resting state network and each FFMQ score. These analyses indicated that: (1) trait mindfulness and its facets showed increased functional connectivity with neural regions related to attentional control, interoception, and executive function; and (2) trait mindfulness and its facets showed decreased functional connectivity with neural regions related to self-referential processing and mind wandering. These patterns of functional connectivity are consistent with some of the benefits of mindfulness—enhanced attention, self-regulation, and focus on present experience. This study provides support for the notion that non-judgmental attention to the present moment facilitates the integration of regions in neural networks that are related to cognition, attention, and sensation.

Keywords: functional connectivity, resting state networks, trait mindfulness, default mode network, salience network, central executive network, dorsal attention network, ventral attention network

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Received: *05 December 2018*
Accepted: *14 March 2019*
Published: *12 April 2019*

Citation:
Parkinson TD, Kornelsen J and Smith SD (2019) Trait Mindfulness and Functional Connectivity in Cognitive and Attentional Resting State Networks.
Front. Hum. Neurosci. 13:112.
doi: 10.3389/fnhum.2019.00112

INTRODUCTION

Originating in Buddhist traditions, mindfulness training has made its way into Western culture as a method to reduce stress, enhance emotional regulation, and reduce symptoms in a variety of mental health disorders (Teasdale et al., 1995; Farb et al., 2012; Cavanagh et al., 2013; Tabak et al., 2015). Indeed, mindfulness has been shown to reduce symptoms of depression (Chiesa et al., 2015), bipolar disorder (Ives-Deliperi et al., 2013), anxiety (Cavanagh et al., 2013), chronic dysphoria (Farb et al., 2012), and borderline personality disorder (O'Connell and Dowling, 2014), in addition to increasing self-esteem (Bajaj et al., 2016), reducing substance cravings (Witkiewitz et al., 2013), and enhancing overall quality of life (Chiesa et al., 2015). With such extensive benefits in clinical and non-clinical populations, there has been a growing interest in understanding mindfulness. While specific techniques used to treat these conditions may vary, mindfulness practices, in general, involve paying attention to the moment, purposefully and non-judgmentally (Kabat-Zinn, 1994) with an attitude of openness, compassion, and acceptance to the experience (Brown and Ryan, 2003; Bishop et al., 2004; Shapiro et al., 2006; Baer, 2011). This process typically leads to a perspective shift in which an individual detaches the contents of their thoughts and feelings from the self and instead engages in a clear and objective observation of his or her moment-to-moment experience (Shapiro et al., 2006). Given its numerous physical and psychological benefits, it is not surprising that a substantial number of studies have investigated the mechanisms underlying mindfulness (Ives-Deliperi et al., 2011; Farb et al., 2012; Dickenson et al., 2013; Gotnik et al., 2016; Haase et al., 2016; Kral et al., 2018).

The majority of the empirical investigations of mindfulness have focused on interventions that allow an individual to intentionally incorporate mindful practices into their daily lives (i.e., *state* mindfulness). However, personality researchers have noted that individuals also vary in their natural tendency to adopt a mindful perspective across experiences and contexts (i.e., *trait* mindfulness; Lu et al., 2014; Doll et al., 2015; Kong et al., 2016; Bilevicius et al., 2018).

Previous studies have found that state and trait mindfulness are very similar for experienced meditators; the long-term practice of entering and maintaining a mindful state appears to transform that transient mindful perspective of state mindfulness into a more stable, trait-like characteristic (Hölzel et al., 2011; Tanay and Bernstein, 2013; Wheeler et al., 2017). In contrast, state and trait mindfulness appear to be relatively independent processes in individuals who are meditation-naïve, with different personality characteristics and facets of mindfulness involved in each process (Thompson and Waltz, 2007). In the current research, we will assess brain activity in meditation-naïve participants. Specifically, we will use functional magnetic resonance imaging (fMRI) to examine how different facets of trait mindfulness are related to the functional connectivity of resting-state networks in the brain. This strategy will allow us to examine the neural underpinnings of trait mindfulness without the potential confound of mindfulness meditation training, which would blur the line between state and trait mindfulness.

Most previous fMRI investigations of trait mindfulness have examined how neural activity during a behavioral task differs between individuals who score high or low on a measure of this construct. For example, Dickenson et al. (2013) observed that during a focused breathing task, people who scored higher on a measure of trait mindfulness show greater activity in the temporo-parietal junction, superior parietal lobule, and dorsolateral prefrontal cortex (DLPFC) than did people who scored low on this measure. These brain areas are involved with orienting and sustaining of attention, a result consistent with cognitive psychology studies showing that mindfulness is associated with superior attentional abilities (Quaglia et al., 2015; Quan et al., 2018). Creswell et al. (2007) compared levels of trait mindfulness to neural activation patterns during an affect labeling task. They reported that during labeling, trait mindfulness was associated with a reduced amygdala response and more widespread prefrontal cortex (PFC) activation, highlighting particularly heightened activity in the medial PFC (MPFC). These researchers interpreted their findings to suggest that during affect labeling, greater trait mindfulness is linked to cortical regulation of limbic responses.

A component of trait mindfulness—the tendency to observe—has also been shown to predict activation of neural regions when attending to one's emotions (Frewen et al., 2010). Observing entails attending to your thoughts, feelings, or emotions without judgment (Baer et al., 2006). Individuals who tended to engage in mindful observation showed larger activity in the dorsomedial PFC (DMPFC) while individuals listened to both negative and positive audio emotional vignettes than did participants who scored low on this measure (Frewen et al., 2010). The authors suggested that this activation provides evidence that mindfulness involves an internal emotional reflection process that recruits the DMPFC (Frewen et al., 2010).

Voxel-based morphometry research has identified a positive correlation between trait mindfulness and gray matter volume in the bilateral anterior cingulate cortex (ACC) and a negative correlation with the gray matter volume of the left orbitofrontal cortex (Lu et al., 2014). This result is consistent with the role of the ACC in both attentional control and emotional regulation (Mohanty et al., 2007; Giuliani et al., 2011; Stevens et al., 2011).

An additional neuroimaging technique used to investigate the neural underpinnings of trait mindfulness is resting-state fMRI. In these studies, neural activity is measured while participants lie awake in the scanner but are not performing a cognitive or perceptual task (i.e., they are "at rest"; for a review, see Raichle, 2015). Although no task is being performed, spontaneous neuronal activity throughout the brain continues to occur. Importantly, the neuronal activity is not random; instead, the activity of groups of structurally disparate brain areas frequently correlate, suggesting that these areas function as a network (Raichle et al., 2001; Damoiseaux and Greicius, 2009). Researchers have identified a number of different resting-state networks in the brain and have examined how the magnitude of the correlation of activity in different regions, known as functional connectivity, is related to different cognitive abilities and clinical conditions (e.g., Raichle et al., 2001; Damoiseaux et al., 2006; Broyd et al., 2009; Damoiseaux and Greicius, 2009; van den Heuvel and Hulshoff Pol, 2010; Rosazza and Minati, 2011).

The functional connectivity of three of the most commonly studied networks—the default mode network (DMN), salience network (SN), and central executive network (CEN)—are involved with cognitive, attentional, and emotional processes that are related to both state and trait mindfulness (Hasenkamp et al., 2012; Taylor et al., 2013; Doll et al., 2015;

Bilevicius et al., 2018). The DMN is comprised of nodes in the precuneus, posterior cingulate cortex, MPFC, lateral anterior temporal lobe, and posterior parietal lobe. This network shows increased activity during mind-wandering, self-referential thought, remembering the past, and thinking about the future (Andrews-Hanna, 2012). Several of these functions are, in many ways, antithetical to mindfulness. The SN consists of the insula and anterior cingulate gyrus. It is involved with orienting an individual's attention to external and internal events based on sensory and limbic inputs while also mediating functions between the other networks (Seeley et al., 2007; Bressler and Menon, 2010; Bonnelle et al., 2012). For these functions, the SN would require essential components of mindfulness, present moment attention, and bodily self-awareness. The CEN consists of nodes in the DLPFC, the ACC/DMPFC, and the posterior parietal cortex. It is involved with several executive processes including attentional control, memory, language, and visual processes (Bressler and Menon, 2010; Rosazza and Minati, 2011). Attentional control is a requirement of focusing during a mindfulness practice; thus, the CEN also has functions related to mindfulness.

Two additional resting-state networks that have received considerably less attention from mindfulness researchers are the dorsal and ventral attention networks (DAN and VAN, respectively). The DAN and VAN are both attentional frontoparietal networks that operate during sensory orientation processes (Fox et al., 2006). The DAN consists of the lateral PFC, posterior inferior parietal cortex, and intraparietal cortex (Corbetta et al., 2008). The DAN is involved with voluntarily orienting and maintaining attention to a location (Corbetta et al., 2000) and is considered to be a goal-driven attentional network that uses internal goals or expectations to attend to sensory stimuli (Corbetta et al., 2008). Mindfulness requires sustained, focused attention; thus, the functions of the DAN are directly linked to mindfulness. The VAN contains nodes in the temporo-parietal junction, ACC, and anterior insula. It is another attentional network that is also involved with the detection of salient environmental information; however, this network is stimulus-driven and is implicated in detecting unexpected information (Corbetta et al., 2008). Unlike the SN, the VAN does not rely on interoception to orient attention to salient information in the environment. Mindfulness requires attention to the external environment, a primary function of the VAN. Understanding how these five cognitive and attentional networks relate to trait mindfulness would provide a valuable, comprehensive addition to a discussion of the neural correlates of trait mindfulness.

An additional advantage of the current research is that it utilizes a more nuanced measure of mindfulness than was used in previous studies. For example, Bilevicius et al. (2018) analyzed the relationship between trait mindfulness and functional connectivity in four resting state networks, the DMN, SN, CEN, and DAN. In their study, trait mindfulness was measured using the Mindful Attention Awareness Scale (MAAS), a self-report measure that assesses the attentional aspect of trait mindfulness (Brown and Ryan, 2003). Trait mindfulness negatively correlated with the left medial frontal gyrus, a mind-wandering region of the DMN, whereas a positive relationship was reported in the SN with the left ACC, a region associated with attentional control (Bilevicius et al., 2018). Doll et al. (2015), on the other hand, measured trait mindfulness with both the MAAS and the Freiburg Mindfulness Inventory (FMI) in participants who completed a brief mindfulness intervention (Doll et al., 2015). They found that inter-network functional connectivity between the DMN and SN and between the SN and left CEN positively correlated with mindfulness scores (Doll et al., 2015). Although these results were both novel and informative, both the MAAS and FMI are unidimensional assessments of trait mindfulness (Walach et al., 2006).

The current study used the Five-Facet Mindfulness Questionnaire (FFMQ), a scale created by Baer et al. (2006) using a composite of the Southampton Mindfulness Questionnaire, Cognitive and Affective Mindfulness Scale-Revised, Kentucky Inventory of Mindfulness Skills, MAAS, and FMI. On the FFMQ, participants rate their responses to each item on a 5-point Likert scale from 1 ("never or very rarely true") to 5 ("very often or always true"). Statements cover five sub-areas pertaining to mindfulness, including *Observing*, *Describing*, *Acting with Awareness, Non-Judgment to Inner Experience*, and *Non-Reactivity to Inner Experience* (Baer et al., 2006). *Observing* refers to the observation of internal and external stimuli (e.g., "When I'm walking, I deliberately notice the sensations of my body moving"). *Describing* includes statements assessing a person's ability to express their experiences, thoughts, and emotions (e.g., "I can easily put my beliefs, opinions, and expectations into words"). *Acting with awareness* (henceforth *Acting*) includes statements that refer to paying attention in the present moment (e.g., "When I do things, my mind wanders off and I'm easily distracted"). *Non-judgment to inner experience* (henceforth *Non-Judging*) statements assess the degree to which an individual rates their thoughts, feelings, and emotions as good or bad (e.g., "I make judgments about whether my thoughts are good or bad"). Finally, the *Non-reactivity to inner experience* (henceforth *Non-Reactivity*) items assess the degree to which an individual reacts to their feelings, emotions, and thoughts (e.g., "I perceive my feelings and emotions without having to react to them"). Psychometric studies of the FFMQ have shown that it possesses consistently good reliability and validity across a variety of cultures (i.e., Baer et al., 2008; Deng et al., 2011; Heeren et al., 2011; Cebolla et al., 2012; de Bruin et al., 2012; Giovannini et al., 2014; Taylor and Millear, 2016) with a five-factor hierarchical structure for meditators and a four-factor hierarchical structure (without the *Observing* facet) for non-meditators and clinical samples (Williams et al., 2014; Aguado et al., 2015). Because the present study used meditation naïve participants, the *Observing* facet will be interpreted with caution.

In the current research, overall trait mindfulness scores ($\text{FFMQ}_{\text{Total}}$) and values for each of the five facets of mindfulness were entered as covariates into analyses of functional connectivity. These ANCOVAs allowed us to examine whether individual differences in self-reported trait mindfulness were related to differences in the functional connectivity of five cognitive and attentional resting state networks (the DMN, SN, CEN, DAN, and VAN). Functional connectivity in each resting state network was identified using independent component analysis (ICA). This approach is data-driven, without restriction to *a priori* regions-of-interest. This allowed us to identify novel and/or counterintuitive results not previously reported in the literature.

MATERIALS AND METHODS

Participants

Twenty-nine meditation-naïve undergraduate students (15 females, age (M ± SD) = 19.89 ± 2.74, range = 18–29 years) from the University of Winnipeg volunteered to participate. Exclusion criteria included participants with a history of psychiatric or neurological disorders, metal in the body, pregnancy, or claustrophobia. Participants provided written consent and completed magnetic resonance safety screening prior to entering the MRI scanner. The University of Winnipeg Human Research Ethics Board and the Bannatyne Human Research Ethics Board provided ethical approval for this study. Participants received a $50 honorarium for their participation.

Psychological Measure

All participants completed the FFMQ prior to or after entering the scanner. The overall score and sub-scores of the FFMQ were tallied using standardized scoring guidelines (Baer et al., 2006). Scores included the overall score on the FFMQ ($\text{FFMQ}_{\text{Total}}$) and the five subscales or facets of mindfulness (*Observing, Describing, Acting, Non-Judging*, and *Non-Reactivity*). A high overall score on the FFMQ indicates elevated trait mindfulness. Higher scores in any of the five individual components indicate greater expression of that facet of mindfulness.

Data Acquisition

Structural and functional MRI data were acquired for all participants using a 3T Siemens TRIO MRI scanner (Siemens, Erlangen, Germany). Following the initial localizer scan, a 3D high-resolution anatomical MRI was acquired. This high resolution T1-weighted gradient-echo scan was 8 min in duration and was performed using an MP-RAGE sequence. This scanning sequence utilized the following parameters: 1-mm slice thickness, 0 mm gap, TR/TE = 1,900/2.2 ms, in plane resolution 0.94 × 0.94 mm, 256 × 256 matrix, field of view (FOV) 24 cm.

Following the acquisition of structural images, a 7-min resting state functional MRI scan was performed. Resting state data was acquired with a whole brain echo planar imaging (EPI) sequence using the following scanning parameters: 140 volumes were obtained using 3-mm slice thickness, 0 gap, TR/TE = 3,000/30 ms, flip angle = 90°, 64 × 64 matrix, FOV 24 cm. Participants were instructed to close their eyes without falling asleep throughout the scanning session.

Data Analysis

BrainVoyager QX 2.8 software (Brain Innovation, BV, Maastricht, Netherlands) was used to process imaging data and to perform all statistical analyses. Functional data were initially pre-processed using a trilinear/sync interpolation 3D motion correction, which examines movement output in six directions (three translations and three rotations). Visual inspection of participant movement was conducted. Data were not used if participants moved 2 mm or more in any of the six directions; however, none of the participants exceeded this threshold. After this initial step, further pre-processing was performed using a slice scan correction, high pass temporal filtering, and spatial smoothing (using an 8 mm full-width half-maximum Gaussian filter).

Following pre-processing, the functional data were co-registered to the high-resolution anatomical data. The anatomical data were spatially normalized to a standardized Talairach space and the functional time series data were transformed.

Single-subject ICA was performed for each individual using the fast ICA algorithm (Hyvärinen and Oja, 2000). Twenty independent components (ICs) were extracted from the data for all participants. A group-level ICA was then performed using a self-organizing group ICA (Sog-ICA) plugin. For this step, the most similar ICs for all participants were clustered at the group level, resulting in a total of 20 ICs. The 20 components were inspected manually and compared to the literature in order to identify each resting state network. Four cognitive/attentional resting state networks were identified (in separate ICs), including the DMN, SN, and CEN. While the CEN sometimes appears as two separate components as a right and left CEN (rCEN and lCEN; Damoiseaux et al., 2006; van den Heuvel et al., 2008; van den Heuvel and Hulshoff Pol, 2010), it appeared in the same component in this study. The fourth network was a frontoparietal network encompassing both the DAN and VAN, and will be henceforth referred to as the attentional network (ATN).

To determine the relationship between each resting state network and FFMQ scores, an analysis of covariance (ANCOVA) was performed. One ANCOVA was performed for every network using each facet of mindfulness as a covariate, with a predetermined significance level of $p < 0.01$. To illustrate, the component featuring the DMN was identified, and an ANCOVA was performed using the participants' $\text{FFMQ}_{\text{Total}}$ score as a covariate. Similar analyses were performed using the *Observing, Describing, Acting, Non-Judging*, and *Non-Reactivity* scores as covariates in separate ANCOVAs.

Each analysis produced cluster maps illustrating how scores on each of the six covariates associated with functional connectivity of a specific network. Voxels in these cluster maps exceeding a threshold ($p < 0.01$) represent areas whose functional connectivity in that network varied as a function of the covariate's value. These maps were corrected for multiple comparisons using a Monte Carlo cluster threshold estimator correction plugin with 1,000 iterations, evaluated at $p \leq 0.01$. Last, these maps were converted to volumes of interest (VOIs) to provide the coordinates of the peak intensity voxel, the number of significant voxels, and the probability value of the observed clusters.

VOI data were entered into Talairach Client software (Research Imaging Institute, Version 2.4.3, 2003–2015), providing an output on the anatomical label of the peak coordinate of each cluster including region, gyrus, hemisphere, and the specific Brodmann areas (BAs), when applicable.

Each cluster was analyzed individually, using each cluster's peak intensity coordinate and individual voxel information. Each cluster was reported with the corresponding correlation coefficient to indicate the strength and direction (positive or negative) of the relationship between functional connectivity for every network cluster and each facet of mindfulness. Additional tables consisting of the Montreal Neurological Institute (MNI) coordinates of each cluster are provided as **Supplementary Material**.

RESULTS

Data from one participant (female, age 24) was not included in any analyses due to electronic file corruption. Results refer to the remaining 28 participants. Statistics for FFMQ scores are featured in **Table 1** below. The six scores for each participant were used as covariates in each ANCOVA with each resting state network.

Internal reliability for trait mindfulness as represented by the overall FFMQ score was moderate and reliability for all of the FFMQ scales was high (**Table 1**). These results further attest to the fact that the FFMQ is a reliable measure of trait mindfulness.

The reporting of the functional connectivity data will be separated into four subsections, one for each network of interest. The Talairach coordinates for all network analyses indicate regions that showed an increased or decreased degree of functional connectivity as a function of FFMQ scores. Within each component, some of the clusters included traditional nodes from the resting state networks, whereas other clusters included non-traditional regions in individuals who scored high or low on FFMQ covariates. Orange voxels indicate that the FFMQ covariate values and the functional connectivity of that cluster are positively correlated, whereas blue voxels indicate that the FFMQ covariate values and the functional connectivity of that voxel are negatively correlated.

Default Mode Network Functional Connectivity

The significant clusters found in the six ANCOVAs assessing the functional connectivity of the component featuring the DMN are listed in **Table 2** (see **Supplementary Materials** for cluster locations described as MNI coordinates). Overall trait mindfulness scores ($\text{FFMQ}_{\text{Total}}$) correlated with four clusters in the DMN (**Figure 1A**). The first cluster positively correlated with $\text{FFMQ}_{\text{Total}}$ ($r = 0.67$, $p < 0.01$) and was located primarily in the anterior right hemisphere. The regions comprising this cluster included the anterior cingulate, mid-cingulate gyrus, caudate, and medial frontal gyrus. The second cluster negatively correlated with $\text{FFMQ}_{\text{Total}}$ ($r = -0.74$, $p < 0.01$) and was focused on the left middle and inferior temporal gyri and the left middle and superior occipital gyri. The third cluster negatively correlated with $\text{FFMQ}_{\text{Total}}$ ($r = -0.73$, $p < 0.01$) and was located in similar regions to the second cluster, except in the right hemisphere. The fourth cluster negatively correlated with $\text{FFMQ}_{\text{Total}}$ ($r = -0.77$, $p < 0.01$) and was located in the right middle temporal and superior temporal gyri.

TABLE 1 | Scoring statistics and Cronbach's Alpha (α) for each scale of the Five-Facet Mindfulness Questionnaire (FFMQ).

Scale	Mean	SD	Range	α
$\text{FFMQ}_{\text{Total}}$	128.11	13.93	95–148	0.69
Observing	28.50	3.69	23–35	0.88
Describing	27.00	5.62	17–39	0.88
Acting	25.68	5.56	14–38	0.90
Non-Judging	24.86	6.89	13–38	0.90
Non-Reactivity	22.07	3.59	13–29	0.89

Observing scores negatively correlated with one cluster in the component featuring the DMN ($r = -0.67$, $p < 0.01$; **Figure 1B**). Regions comprising this cluster included the right inferior frontal and precentral gyri.

Describing scores were also negatively correlated with one cluster in the DMN component ($r = -0.69$, $p < 0.01$; **Figure 1C**). This cluster was located in the left and right precuneus and superior parietal lobule.

Acting correlated with five clustersData from one participan in the DMN component (**Figure 1D**). The first cluster positively correlated with *Acting* ($r = 0.62$, $p < 0.01$) and was focused in the right lentiform nucleus, caudate, and claustrum. The second cluster positively correlated with *Acting* ($r = 0.63$, $p < 0.01$) and was located in the right and left cuneus and lingual gyrus. The third cluster negatively correlated with *Acting* ($r = -0.67$, $p < 0.01$) and appeared in the right superior and middle frontal gyri and sub-gyral frontal lobe. The fourth cluster also negatively correlated with *Acting* ($r = -0.68$, $p < 0.01$) and appeared primarily in the left middle, superior, and inferior temporal gyri, with some representation in the left fusiform gyrus and sub-gyral temporal lobe. The fifth cluster negatively correlated with *Acting* ($r = -0.64$, $p < 0.01$) and was located in the left inferior semi-lunar lobule and pyramis.

Non-Judging scores were positively correlated with one cluster in the DMN component ($r = 0.59$, $p < 0.01$; **Figure 1E**). This cluster was focused entirely on the right and left cingulate gyri (Brodmann Area 24).

Non-Reactivity scores correlated with four clusters in the DMN component (**Figure 1F**). The first cluster positively correlated with *Non-Reactivity* ($r = 0.64$, $p < 0.01$) and appeared in the right cerebellar tonsil and the right fusiform and inferior temporal gyri. The remaining three clusters were negatively correlated with *Non-Reactivity*. One cluster was focused within the right superior temporal gyrus (STG), extending slightly into the middle and transverse temporal gyri and the precentral gyrus ($r = -0.74$, $p < 0.01$). The second negatively correlated cluster included the right superior and middle temporal gyri and the insula ($r = -0.63$, $p < 0.01$). The remaining negative cluster was located primarily in the left middle temporal gyrus, with smaller areas in the superior temporal and middle occipital gyri ($r = -0.69$, $p < 0.01$).

Salience Network Functional Connectivity

The significant clusters found in the six ANCOVAs assessing the functional connectivity of the component featuring the SN are listed in **Table 3**. $\text{FFMQ}_{\text{Total}}$ positively correlated with one cluster in the SN ($r = 0.78$, $p < 0.01$). This cluster was focused in the right

TABLE 2 | Talairach coordinates of correlations between FFMQ scores and functional connectivity with the default mode network (DMN).

				Talairach coordinates					
Region	**Hemisphere**	**Gyrus**	**BA**	***X***	***Y***	***Z***	**Cluster size**	***r***	***p***
Trait mindfulness ($\text{FFMQ}_{\text{Total}}$)									
Limbic	Right	Anterior cingulate	32	8	37	24	10,757	0.67	0.000082
Temporal	Left	Middle temporal	39	−46	−74	12	6,350	−0.74	0.000008
	Right	Middle temporal	37	56	−65	3	3,312	−0.73	0.000012
	Right	Superior temporal	21	53	−5	−12	2,525	−0.77	0.000012
Observing									
Frontal	Right	Precentral gyrus	44	59	7	12	1,829	−0.67	0.000086
Describing									
Parietal	Right	Superior parietal	7	26	−63	66	9,435	−0.69	0.000056
Acting									
Sub-lobar	Right	Caudate	CH	20	22	0	2,392	0.62	0.000388
Occipital	Right	Cuneus	18	5	−98	3	1,647	0.63	0.000327
Frontal	Right	Superior frontal	6	5	37	61	5,209	−0.67	0.000107
Temporal	Left	Middle temporal	21	−55	7	−24	2,507	−0.68	0.000065
Posterior lobe	Left	Inferior semi-lunar	*	−19	−74	−39	2,269	−0.64	0.000272
Non-judging									
Limbic	Right	Cingulate gyrus	24	2	−8	36	2,247	0.59	0.001074
Non-reactivity									
Posterior lobe	Right	Cerebellar tonsil	*	41	−44	−39	2,705	0.64	0.000238
Temporal	Right	Superior temporal	22	56	−2	−3	6,429	−0.74	0.000006
	Right	Superior temporal	22	50	−47	15	2,931	−0.63	0.000367
	Left	Middle temporal	39	−40	−68	15	3,907	−0.69	0.000053

*Abbreviations: BA, Brodmann Area; CH, caudate head; *region not affiliated with a BA.*

and left cuneus, with smaller regions in the middle occipital gyrus and precuneus (**Figure 2A**).

Observing scores were negatively correlated with one cluster in the SN component ($r = -0.64$, $p < 0.01$; **Figure 2B**). Regions comprising this cluster included the left middle and superior frontal gyri.

Describing positively correlated with one cluster in the SN component ($r = 0.66$, $p < 0.01$; **Figure 2C**). This cluster was located in the left pre- and post-central gyri.

Acting values were correlated with three clusters in the SN component (**Figure 2D**). The first cluster positively correlated with *Acting* ($r = 0.68$, $p < 0.01$) in the right and left cuneus and middle occipital gyrus. The second cluster negatively correlated with *Acting* ($r = -0.68$, $p < 0.01$) and included bilateral regions of the medial and inferior frontal gyri, anterior cingulate gyrus, and rectal gyrus. The third cluster negatively correlated with *Acting* ($r = -0.69$, $p < 0.01$) and was located in the right inferior, middle, and superior temporal gyri and fusiform gyrus.

Non-Judging scores were positively correlated with two clusters in the SN component, one in the left hemisphere and the other in right hemisphere (first cluster $r = 0.65$, $p < 0.01$; second cluster $r = 0.61$, $p < 0.01$; **Figure 2E**). These clusters were similar, with the cuneus comprising the majority of each cluster and a smaller portion in the middle occipital gyrus.

Non-Reactivity values were correlated with four clusters in the SN component (**Figure 2F**). The first cluster positively correlated with *Non-Reactivity* ($r = 0.71$, $p < 0.01$). This cluster was located in the left insula, with smaller portions extending into the precentral gyrus, STG, and inferior frontal gyrus. The second cluster was also positively correlated with *Non-Reactivity* ($r = 0.55$, $p < 0.01$); however, it was not located in gray matter. The third and fourth clusters were negatively correlated with *Non-Reactivity* scores. One of these clusters was located in the right cerebellum ($r = -0.69$, $p < 0.01$). The cerebellar tonsil and tuber comprised the majority of this cluster, with smaller areas in the culmen, declive, and anterior lobe. The other negatively correlated cluster consisted primarily of white matter; the gray matter regions included the left uvula and declive in the cerebellum as well as the left fusiform lingual gyri ($r = -0.65$, $p < 0.01$).

Central Executive Network Functional Connectivity

The significant clusters found in the six ANCOVAs assessing the functional connectivity of the component featuring the CEN are listed in **Table 4**. $\text{FFMQ}_{\text{Total}}$ negatively correlated with one cluster in the CEN component ($r = -0.60$, $p < 0.01$; **Figure 3A**). Only a small portion of this cluster was located in gray matter and included the right middle and superior frontal gyri.

Observing scores were positively correlated with three clusters in the CEN component (first cluster $r = 0.76$; second cluster $r = 0.64$; third cluster $r = 0.63$; $p < 0.01$; **Figure 3B**). The first cluster, although the largest, contained the smallest representation of regions in gray matter. This cluster was located in the right lingual gyrus with a small portion extending into the right posterior cingulate. The second cluster was located primarily in the left lentiform nucleus, with a smaller portion in the left caudate. The third cluster spanned regions in the right cerebellum including the uvula, tuber, declive, and pyramis.

Describing correlated with three large clusters in the CEN component (**Figure 3C**). The first cluster positively correlated with *Describing* ($r = 0.65$, $p < 0.01$) and included bilateral regions

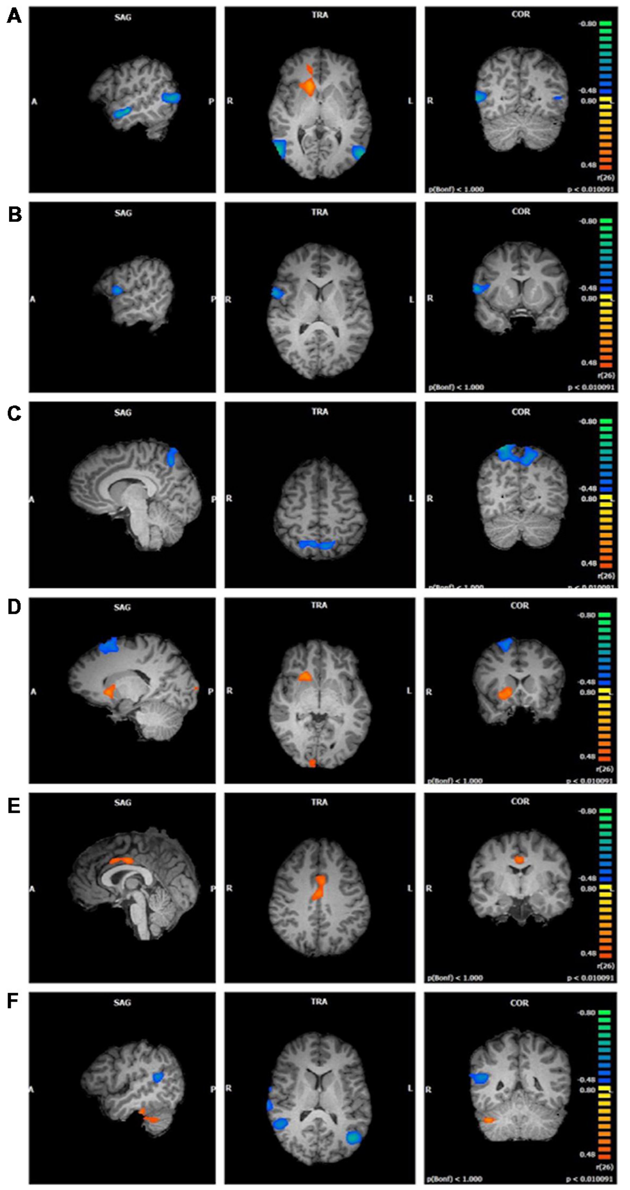

FIGURE 1 | Functional connectivity of default mode network (DMN) clusters correlated with trait mindfulness and five of its facets ($p < 0.01$, cluster threshold estimator corrected). From top to bottom: **(A)** $\mathrm{FFMQ}_{\mathrm{Total}}$; **(B)** *Observing*; **(C)** *Describing*; **(D)** *Acting*; **(E)** *Non-Judging*; **(F)** *Non-Reactivity*.

of the superior, middle, and medial frontal gyri, precentral gyrus, and posterior cingulate gyrus. The second cluster positively correlated with *Describing* ($r = 0.67$, $p < 0.01$) and was focused on the left cerebrum. The left precuneus, left inferior and superior parietal lobules, and the left posterior cingulate and angular gyri represented this cluster. The third cluster negatively correlated with *Describing* ($r = -0.58$, $p < 0.01$) and was located in the right declive and culmen in the cerebellum, as well as the right lingual, fusiform, and posterior cingulate gyri.

Acting was negatively correlated with three clusters in the CEN component (first cluster $r = -0.71$; second cluster $r = -0.65$; third cluster $r = -0.59$; $p < 0.01$; **Figure 3D**). The first cluster appeared primarily in white matter, with the right superior and middle frontal gyri comprising the gray matter areas. The second cluster was located in the left and right precuneus, cuneus, and posterior cingulate gyrus, regions typically associated with the DMN. The third cluster was focused in the right precuneus, with the right angular, superior occipital, and middle temporal gyri representing smaller portions.

There was no relationship between *Non-Judging* and the CEN component. *Non-Reactivity*, on the other hand, negatively correlated with one cluster in the CEN component ($r = -0.60$, $p < 0.01$; **Figure 3E**). This cluster was located in the left superior, middle, and transverse temporal gyri, claustrum, and insula.

Attention Network Functional Connectivity

The significant clusters found in the six ANCOVAs assessing the functional connectivity of the component featuring the ATN are listed in **Table 5**.

There was no relationship between $\mathrm{FFMQ}_{\mathrm{Total}}$ and the ATN component. *Observing* scores were correlated with three clusters in the ATN component. The first cluster positively correlated with *Observing* ($r = 0.70$, $p < 0.01$; **Figure 4A**) and was located in the right middle, inferior, and superior frontal gyri. The second cluster positively correlated with *Observing* ($r = 0.75$, $p < 0.01$) and was located in the left insula, precentral gyrus, and inferior frontal gyrus. The third cluster negatively correlated with *Observing* ($r = -0.61$, $p < 0.01$) and included the left supramarginal and angular gyri, inferior parietal lobule, and middle and superior temporal gyri.

Describing values were negatively correlated with two clusters in the ATN component (first cluster $r = -0.67$; second cluster $r = -0.68$; $p < 0.01$; **Figure 4B**). These clusters were similar in size and were both located in the superior and middle temporal gyri. The first cluster comprised these regions in the right hemisphere and the second cluster in the left hemisphere.

Acting was negatively correlated with one cluster in the ATN component ($r = -0.69$, $p < 0.01$; **Figure 4C**). The right lingual gyrus comprised most of this cluster, with smaller areas in the right parahippocampal gyrus, posterior cingulate, and culmen.

Non-Judging scores were positively correlated with one cluster in the ATN component ($r = 0.63$, $p < 0.01$; **Figure 4D**). This cluster was located in the right superior and medial frontal gyri. There was no relationship between *Non-Reactivity* values and the ATN.

DISCUSSION

The results of this study indicate that trait mindfulness influences functional connectivity in four resting state networks associated with cognition and attention. The following discussion provides several interpretations for the observed patterns of functional connectivity. However, it is important to advise caution in linking the results of functional connectivity studies to specific cognitive processes or behavioral patterns. Given that attentional or sensory processes were not directly tested in this study, stating that the significant voxels detected were associated with a specific cognitive or attentional process would be a "reverse inference"

TABLE 3 | Talairach coordinates of correlations between FFMQ scores and functional connectivity with the salience network (SN).

			Talairach coordinates						
Region	**Hemisphere**	**Gyrus**	**BA**	***X***	***Y***	***Z***	**Cluster size**	***r***	***p***
Trait Mindfulness (FFMQ_Total)									
Occipital	Right	Cuneus	18	17	−83	12	21,643	0.78	0.000001
Observing									
Frontal	Left	Middle frontal	46	−49	41	27	2,966	−0.64	0.000282
Describing									
Frontal	Left	Precentral gyrus	4	−49	−11	45	2,691	0.66	0.000129
Acting									
Occipital	Left	Cuneus	19	−7	−92	24	6,940	0.68	0.000077
Frontal	Right	Rectal gyrus	11	11	31	−19	7,983	−0.68	0.000066
Temporal	Right	Fusiform gyrus	20	59	−5	−24	3,947	−0.69	0.000054
Non-judging									
Occipital	Left	Cuneus	18	−7	−77	18	3,249	0.65	0.0002
	Right	Cuneus	18	17	−83	18	2,133	0.61	0.000517
Non-reactivity									
Frontal	Left	Precentral gyrus	44	−43	1	9	3,023	0.71	0.000025
No gray matter found			*	23	−50	27	2,390	0.55	0.00244
Posterior lobe	Right	Tuber	*	38	−56	−30	4,338	−0.69	0.000048
Occipital	Left	Lingual gyrus	17	−13	−95	−18	2,502	−0.65	0.0002

*Abbreviations: BA, Brodmann Area; *region not affiliated with a BA.*

error (Poldrack, 2006). We will, therefore, focus on specific trends in the data, focusing on how the current results relate to previous studies of mindfulness and on how our data could be used to generate hypotheses in future task-based studies.

Trait Mindfulness

$\text{FFMQ}_{\text{Total}}$ scores were related to the functional connectivity of two MPFC regions. The component featuring the DMN demonstrated increased functional connectivity in the right ACC for individuals scoring higher in trait mindfulness. This finding is consistent with previous structural neuroimaging studies (Tang et al., 2010, 2012). Tang et al. (2010, 2012) reported that a specific form of mindfulness training (Integrative Body-Mind Training, IBMT) increased the efficiency of white matter tract functioning—as shown by an increase in fractional anisotropy (FA) and decreases in both axial and radial diffusivity—between the ACC and its connecting structures. This increase in FA corresponds to a strengthening of ACC connections, with a possible association for enhanced self-regulation (Tang et al., 2010). These results complement a task-based study from Kilpatrick et al. (2011). Following an 8-week Mindfulness-Based Stress Reduction (MBSR) program, functional connectivity changed during a practice of state mindfulness in female meditation-naïve participants. They reported increased functional connectivity between the DMPFC and dorsal ACC, and suggested that this change was linked with a greater awareness of attentional and sensory experiences rather than engaging mainly in self-referential reflection (Kilpatrick et al., 2011).

$\text{FFMQ}_{\text{Total}}$ scores were also linked with altered functional connectivity in the DMPFC in the CEN component. The CEN component demonstrated reduced functional connectivity in the right superior frontal gyrus (SFG), located in the DMPFC. The DMPFC is a region of the DMN that is associated with weaker functional connectivity in experienced meditators (Taylor et al., 2013). Taylor et al. (2013) suggest that novice meditators use cortical structures to down-regulate regions related to emotional processing, such as the amygdala, whereas experienced meditators exhibit emotional stability and acceptance that do not require the control of affective systems by cortical structures. The current results suggest that individuals who score high on measures of trait mindfulness have patterns of functional connectivity that resemble (to some degree) experienced meditators. This conclusion would be consistent with other studies suggesting that trait mindfulness uses less input from medial cortical structures (Farb et al., 2007, 2012).

Facets of Trait Mindfulness

For the *Observing* facet, the ATN component demonstrated increased functional connectivity in the insula, a SN structure that is involved with interoceptive awareness (Critchley et al., 2004; Farb et al., 2013). Bilevicius et al. (2018) observed a similar result in their study of the MAAS, reporting a positive association between the attentional aspect of trait mindfulness and the left insula in the SN. Murakami et al. (2012) analyzed how gray matter volume correlated with a Japanese version of the FFMQ. Interestingly, they found that the right anterior insula positively associated with the *Describing* facet. While these results are not identical, they do indicate that the functional connectivity of the insula is related to multiple facets of trait mindfulness, and suggest that the insula should be a region of interest in future seed-based studies of functional connectivity and trait mindfulness.

The DMN component showed increased functional connectivity with the right mid-cingulate gyrus when its connectivity was co-varied with *Non-Judging* scores. This region is associated with the anticipation of pain (Brown and Jones, 2008). The practice of mindfulness brings non-judgmental

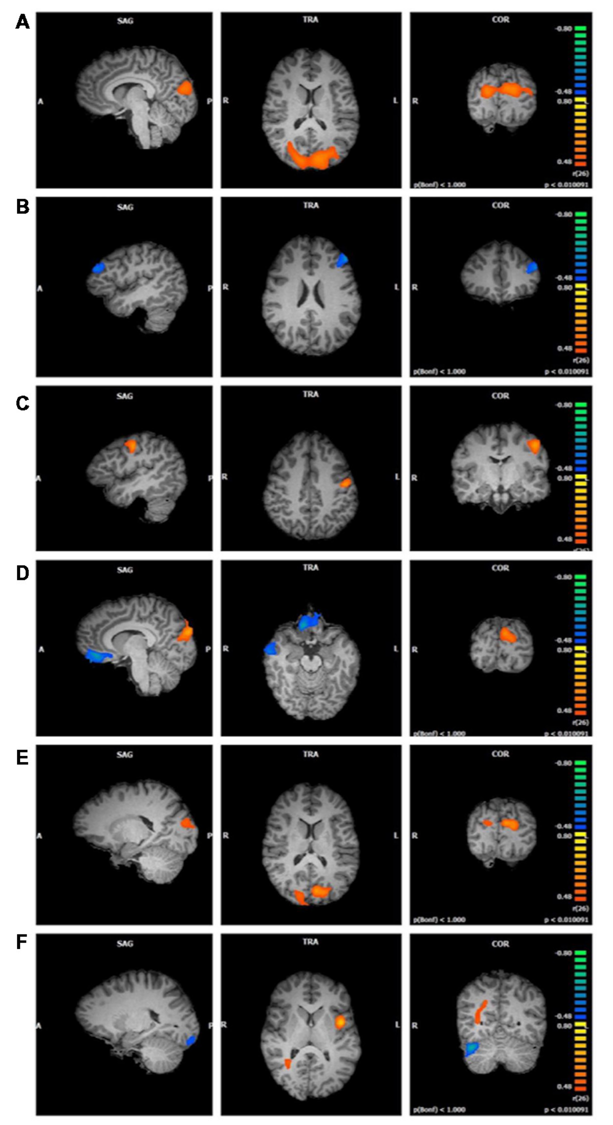

FIGURE 2 | Functional connectivity of salience network (SN) clusters correlated with trait mindfulness and five of its facets ($p < 0.01$, cluster threshold estimator corrected). From top to bottom: **(A)** FFMQ$_{\text{Total}}$; **(B)** *Observing*; **(C)** *Describing*; **(D)** *Acting*; **(E)** *Non-Judging*; **(F)** *Non-Reactivity*.

attention toward painful stimuli in an effort to decrease pain perception (Gard et al., 2011). It has also been shown that mindfulness practitioners rate pain as less unpleasant relative to controls (Gard et al., 2011). Brown and Jones (2008) suggest that mid-cingulate areas direct attentional resources toward a painful stimulus to reduce focus on the emotional aspect of pain and to increase focus on the sensory experience (Brown and Jones, 2008). In the present study, the DMN component correlating with the mid-cingulate gyrus for *Non-Judging* may be associated with a more sensory and less cognitive, self-referential process. However, behavioral studies would be necessary to test whether the functional connectivity between the mid-cingulate gyrus and the DMN is specifically related to altered nociceptive responses.

When co-varied with *Non-Judging* scores, the ATN component showed increased functional connectivity with the right anteromedial SFG, a region located in the rostral MPFC that is a node of the DMN and which connects to nodes in the SN (Ongür and Price, 2000). Other studies have reported increased functional connectivity with the MPFC in the DMN in meditators relative to controls (Jang et al., 2011; Hasenkamp and Barsalou, 2012). Hasenkamp and Barsalou (2012) suggested that experienced meditators show greater connectivity to this DMN node, thus reflecting a greater level of awareness of their internal states. In a study comparing experienced meditators and novice participants, Froeliger et al. (2012) demonstrated increased resting-state functional connectivity between the DAN (a network of the ATN) and the DMN as well as between the DAN and the right anterior PFC. These researchers suggested that these patterns of connectivity represented a greater allocation of resources towards attention and awareness (Froeliger et al., 2012). The current study suggests that this relationship may be specifically related to the *Non-Judging* facet of mindfulness.

Combined Trends

In analyzing the ICA results across resting state networks and mindfulness facets, four overarching patterns emerged. First, the components featuring two of the cognitive networks correlated with an additional sensory region (i.e., an area that is not typically associated with the network). The precentral gyrus, a region related to sensorimotor processing, correlated with the SN (*Describing*, *Non-Reactivity*) and CEN (*Describing*) components. Farb et al. (2012) suggest that mindfulness training enhances emotional regulation by transitioning from a cognitive focus to a present-moment awareness using the thalamus, insula, and sensorimotor regions. The present study provides support for this notion, demonstrating that individuals higher in trait mindfulness engage the insula and sensorimotor regions. Further behavioral studies would be required to examine the possibility that the correlation of sensorimotor nodes in resting state networks may be related to enhanced emotional regulation and a present-moment focus. If so, this would be consistent with two of the goals of mindfulness: to achieve greater emotional regulation and self-awareness.

Second, the components featuring the three cognitive networks correlated with two nodes related to visual processing. The cuneus, a region implicated in visual processing (Vanni et al., 2001), correlated with the DMN (*Acting*) and SN (FFMQ$_{\text{Total}}$, *Acting*, *Non-Judging*) components. The lingual gyrus, a region involved in color vision and dreaming (Corbetta et al., 1990; Domhoff and Fox, 2015), correlated with the CEN (*Observing*) component. This pattern of data may suggest that individuals with higher trait mindfulness more efficiently allocate neural resources during visual perception. This idea is indirectly supported by other studies identifying increased visual sensitivity (Brown et al., 1984) and vigilance (MacLean et al., 2010) following a 3-month intensive meditation program. Enhanced vigilance following mindfulness training appeared to be adaptive for attentional tasks in that fewer resources were required to

TABLE 4 | Talairach coordinates of correlations between FFMQ scores and functional connectivity with the central executive network (CEN).

			Talairach coordinates						
Region	**Hemisphere**	**Gyrus**	**BA**	***X***	***Y***	***Z***	**Cluster size**	***r***	***p***
Trait Mindfulness (FFMQ_Total)									
Frontal	Right	Superior frontal	6	26	34	61	3,490	−0.60	0.000805
Observing									
Occipital	Right	Lingual gyrus	19	29	−68	3	2,961	0.76	0.000002
Sub-lobar	Left	Lentiform nucleus	P	−22	7	0	2,872	0.64	0.000261
Posterior lobe	Right	Uvula	*	29	−77	−24	2,256	0.63	0.00035
Describing									
Frontal	Left	Precentral gyrus	6	−31	−2	33	31,308	0.65	0.000202
Parietal	Left	Precuneus	7	13	−62	36	17,808	0.67	0.000109
Occipital	Right	Fusiform gyrus	19	26	−74	−12	18,108	−0.58	0.00114
Acting									
No gray matter found			*	17	28	63	3,548	−0.71	0.000026
Occipital	Right	Precuneus	31	2	−62	27	2,315	−0.65	0.000159
Parietal	Right	Precuneus	19	38	−80	37	2,262	−0.59	0.00107
Non-reactivity									
Temporal	Left	Superior temporal	41	−46	−29	3	2,229	−0.60	0.000718

*Abbreviations: BA, Brodmann Area; P, putamen; *region not affiliated with a BA.*

visually discriminate a stimulus, thus allowing for enhanced attention and concentration (MacLean et al., 2010). Whether the perceptual changes associated with mindfulness training are related to changes in functional connectivity similar to those observed in the current study is an intriguing avenue for future investigations.

Third, two cognitive network components, the DMN and CEN, positively correlated with the cerebellum when co-varied with the *Non-Reactivity* and *Observing* facets, respectively. The cerebellum, while mainly known for its functions in motor control, has also been implicated in higher cognitive functions including the regulation of affect and cognition (Ramnani, 2006; Stoodley and Schmahmann, 2010). The DMN and CEN components associated with Crus I and lobule VI, respectively, regions in the right posterior lobe that are associated with language and executive functioning (Stoodley and Schmahmann, 2009). Hölzel et al. (2011) found that following the completion of an MBSR program, participants demonstrated an increase in gray matter concentration in the vermis and posterior cerebellar lobe, regions associated with the regulation of cognitive processes such as perception and thinking. One of the benefits of mindfulness is the regulation of cognition for healthy psychological functioning; thus, it is possible that the DMN and CEN correlating with these cerebellar regions indicates their involvement in these processes for those high in trait mindfulness.

Finally, the STG was found to be consistently negatively correlated across mindfulness facets. The anterior and posterior STG demonstrated reduced functional connectivity within cognitive and attentional (DMN, CEN, and ATN) network components. The STG is a primary node of the auditory network, with the posterior region associated with the perception of speech sounds (Chang et al., 2010) and the anterior region involved in the semantic processing of auditory and visual information (Visser and Lambon Ralph, 2011). Visser and Lambon Ralph (2011) provide evidence that the anterior temporal lobe (which includes the anterior STG) represents a hub for visual and sensory information that is activated during semantic processing of these modalities. Given that these regions are associated with active semantic processing, it seems likely that the STG would show widespread reduced connectivity during a resting state. Moreover, the reduced correlation between trait mindfulness and the STG is consistent with Bilevicius et al.'s (2018) study examining the relationship between functional connectivity and scores on the MAAS. These authors reported that the DMN and bilateral CEN demonstrated reduced connectivity between trait mindfulness and the STG (Bilevicius et al., 2018).

Collectively, these data indicate an overall greater integration of attentional, sensory, and interoceptive neural regions for individuals higher in trait mindfulness and its facets. This may be related to individuals higher in trait mindfulness demonstrating a more present-moment focus and enhanced emotional regulation, with less emphasis on self-reference.

Relationship to Lesion Studies

The correlative nature of resting-state fMRI makes it impossible to state that changes in functional connectivity *cause* a specific trait such as mindfulness (Poldrack, 2006). It is therefore interesting to examine whether other studies have identified impairments in mindfulness-like functions (e.g., emotional regulation) in patients who have experienced lesions in the brain areas highlighted in the current study. Such data would help reinforce the fact that many of the brain areas discussed in the current study do perform functions related to mindfulness; however, it is important to reiterate that the current data cannot be linked to specific functions.

The data from the current study indicate that individual differences in trait mindfulness are related to differences in functional connectivity in regions of the cerebellum, MPFC, posterior temporal lobe, anterior cingulate/insula, and precuneus. Previous patient-based research has found that cerebellar damage—particularly to posterior and medial regions—leads to impairments in executive control and emotional regulation (Schmahmann and Sherman, 1998). These functions are key facets of mindfulness. Notably, functional

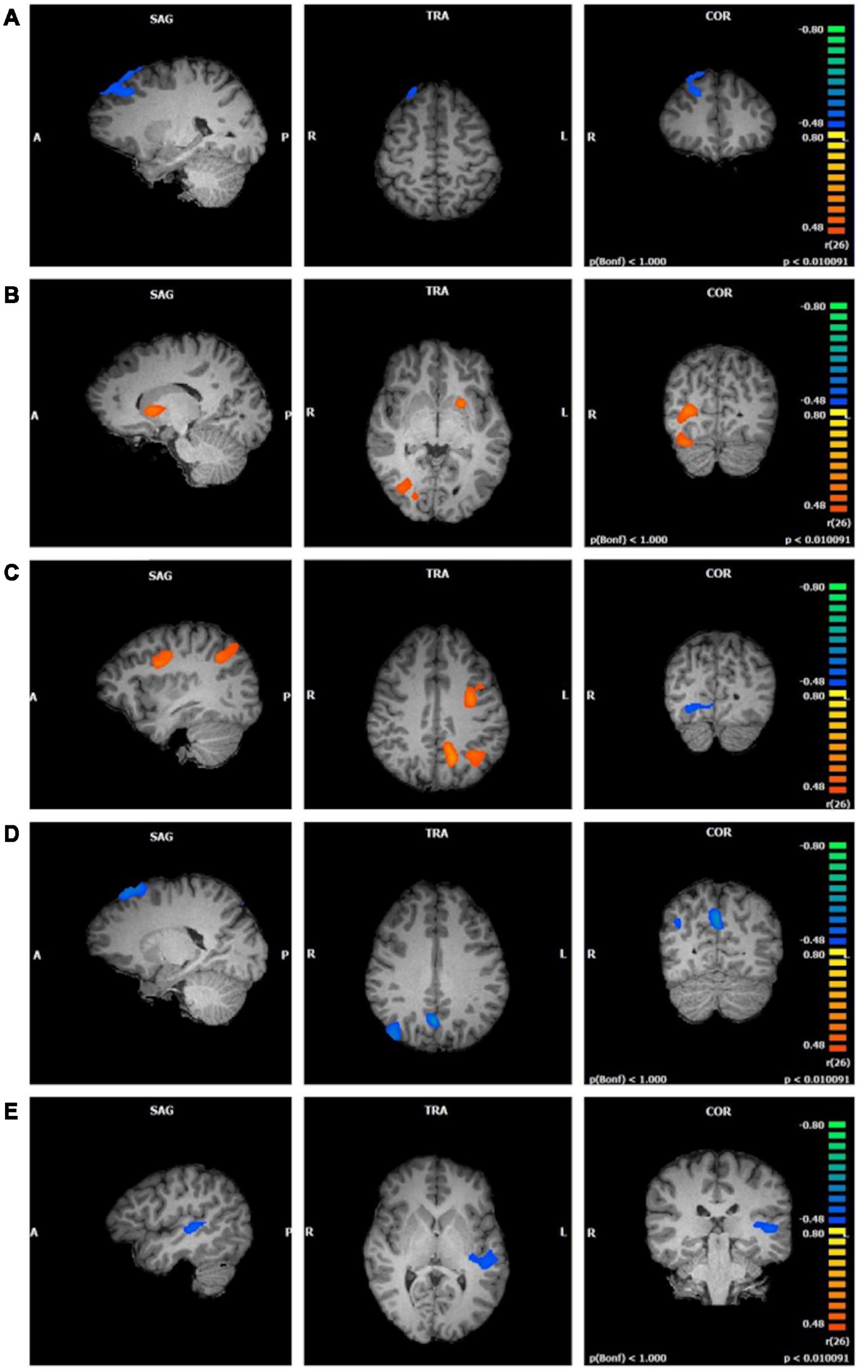

FIGURE 3 | Functional connectivity of central executive network (CEN) clusters correlated with trait mindfulness and four of its facets ($p < 0.01$, cluster threshold estimator corrected). From top to bottom: **(A)** $\text{FFMQ}_{\text{Total}}$; **(B)** *Observing*; **(C)** *Describing*; **(D)** *Acting*; **(E)** *Non-Reactivity*.

connectivity studies have found that the cerebellum has distinct connections with the medial and DLPFC (Krienen and Buckner, 2009). Damage to these prefrontal regions has been implicated in social cognition, self-relevant processing, and emotional perception (Hornak et al., 2003; for a review, see Lieberman et al., 2019). Similar impairments have been noted in patients with damage to the posterior regions of the temporal lobes (Campanella et al., 2014). Additional studies have noted that damage to the temporoparietal regions also leads to deficits in bodily awareness (Martinaud et al., 2017) and language comprehension (e.g., Benghanem et al., 2019), which would include the ability to describe one's experiences. Again, these

TABLE 5 | Talairach coordinates of correlations between FFMQ scores and functional connectivity with the attentional network (ATN).

Region	Hemisphere	Gyrus	BA	Talairach coordinates X	Y	Z	Cluster size	r	p
Observing									
Frontal	Right	Middle frontal	9	35	13	27	5,150	0.70	0.000035
Sub-lobar	Left	Insula	13	−40	1	21	3,037	0.75	0.000004
Parietal	Left	Supramarginal	40	−65	−50	36	2,141	−0.61	0.000592
Describing									
Temporal	Right	Superior temporal	22	47	−20	−6	1,731	−0.67	0.000094
	Left	Superior temporal	22	−49	−44	12	1,638	−0.68	0.000066
Acting									
Occipital	Right	Lingual gyrus	19	17	−56	0	3,256	−0.69	0.000051
Non-judging									
Frontal	Right	Superior frontal	9	11	58	27	1,686	0.63	0.00031

Abbreviations: BA, Brodmann Area.

functions are related to present-moment awareness of one's thoughts and bodily experiences. Lesions to the insula have been linked with alterations in sensitivity to somatosensory information (Karnath et al., 2005; for a review, see Craig, 2009). In contrast, the functional consequences of lesions to the precuneus are more difficult to identify, with damage to different subregions leading to different forms of impairments (Harroud et al., 2017). It is worth noting, however, that meditation training has been linked with increases in the volume of this region (Kurth et al., 2014).

Taken together, these lesion data suggest that the brain areas identified in the current study are related to behaviors that are associated with mindfulness (e.g., emotional regulation, interoception, attentional control). However, additional task-based fMRI investigating these behaviors in individuals who are high or low on trait mindfulness is necessary to help corroborate these speculations.

Limitations and Future Directions

Although the current research provides novel information about how the functional connectivity of four resting-state networks could be related to different facets of trait mindfulness, there are many limitations that could be addressed in future studies. One limitation to this study is the use of the ICA approach for statistical analyses. This approach, given the exploratory nature, may not be used to directly test hypotheses. Future research could employ other approaches to resting state fMRI analysis. For example, graph theory (although similar to ICA in that it is also data-driven) measures the local and global organization of the neural networks (Wang et al., 2010). Graph theory analysis would provide information regarding the topology of the brain networks and may provide further insight into the integration of nodes in different networks as a function of trait mindfulness. Alternately, hypothesis-driven analyses, such as seed-based or region-of-interest analyses, could be used to develop functional connectivity maps (e.g., of the insula or ACC) that examine how the functional connectivity of specific regions relate to trait mindfulness. A further limitation with the ICA approach is that the DAN and VAN networks were contained within the same component. Although both networks have complementary attention-related functions, it was not possible to discern whether their relationship with FFMQ facets differed with this method. Additionally, given that there was no cognitive task used in this study, it is problematic to relate the current data to specific cognitive, attentional, or emotional behaviors. Further experimentation using task-based fMRI would allow researchers to more definitively state whether a specific brain area was involved in a precise cognitive or interoceptive function related to mindfulness.

Additional limitations relate to variables that could have influenced the relationship between trait mindfulness and fluctuations in neural activity. First, additional personality questionnaires could have been administered to participants in order to determine whether these traits co-varied with the different facets of trait mindfulness. Second, although the exclusion criteria for this study precluded participants with psychiatric illness, it is possible that some people may have had sub-clinical symptoms. Future studies may include a standardized measure to objectively screen for underlying symptoms. Finally, information on participants' thought processes during the MRI scan was not collected. Future studies may provide this information to identify if patterns of functional connectivity are consistent with a particular mental state.

It is also important to note that while participants were meditation naïve, it is possible that they had other meditation-like experiences, such as through yoga or prayer. This issue is important because statements on the FFMQ related to the *Observing* facet may be interpreted differently between meditators and non-meditators (Williams et al., 2014). Williams et al. (2014) found that a four-factor hierarchical model of the FFMQ (without the *Observing* category) was a better fit than a five-factor model for both clinical and non-clinical samples. They suggested that the *Describing*, *Acting*, *Non-judging*, and *Non-reactivity* facets are important to well-being for non-meditators, and with increasing meditation experience the *Observing* facet becomes more important (Williams et al., 2014). If the *Observing* facet is less important at earlier stages of meditation training, the statements may be interpreted differently. Thus, some caution must be used when interpreting the results of this facet of mindfulness. Additional research is necessary in order to compare the

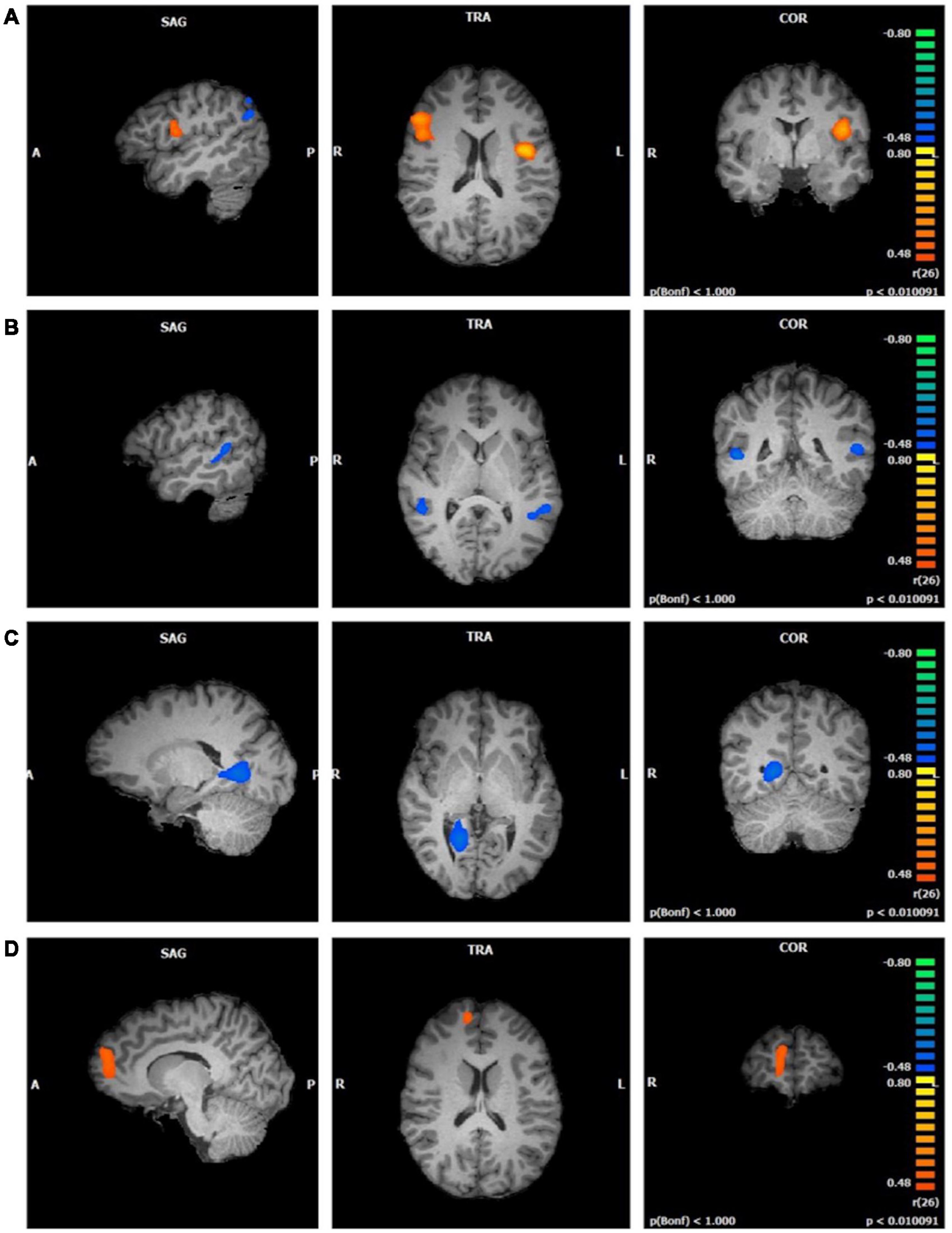

FIGURE 4 | Functional connectivity of attentional network (ATN) clusters correlated with four mindfulness facets ($p < 0.01$, cluster threshold estimator corrected). From top to bottom: **(A)** *Observing*; **(B)** *Describing*; **(C)** *Acting*; **(D)** *Non-Judging*.

cognitive and neural underpinnings of yoga, prayer, and different forms of meditation, and to determine if they affect functional connectivity in a manner similar to trait (or state) mindfulness.

CONCLUSION

The purpose of the current study was to provide novel information about the neural substrates of trait mindfulness, highlighting how individual differences in the functional connectivity of cognitive and attentional resting state networks are related to different facets of this beneficial personality trait. The analyses noted functional connectivity in the ACC and insula, regions that have previously been linked to attentional control and interoception. The analyses also showed interesting mindfulness-dependent variability in the connectivity of the mid-cingulate gyrus, cerebellum, and sensorimotor regions. Together, these results suggest that trait mindfulness is related to the functional connectivity of neural regions involved with cognition, emotion, *and* sensation. Trait mindfulness involves all of these processes on some level, from attending to present-moment internal and external sensations, to reducing rumination and self-referential thought processes, to regulating emotions. Overall, the correlation with functional areas associated with these processes suggests that focusing on the present moment in a non-judgmental fashion may allow for the integration of multisensory modalities to facilitate greater self-awareness.

ETHICS STATEMENT

The University of Winnipeg Human Research Ethics Board and the Bannatyne Human Research Ethics Board provided ethical approval for this study.

AUTHOR CONTRIBUTIONS

SS and JK designed the study. SS was present for the MRI scans and provided the FFMQ to participants. TP analyzed the data and wrote the manuscript, with support from SS and JK.

FUNDING

This research was funded by a grant from the Natural Sciences and Engineering Research Council of Canada (NSERC) to SS.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2019.00112/full#supplementary-material

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Conflict of Interest Statement: 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.

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in Human Neuroscience

ORIGINAL RESEARCH
published: 22 May 2019
doi: 10.3389/fnhum.2019.00169

Gray Matter Correlates of Creativity in Musical Improvisation

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Creativity has been defined as requiring both novelty and effectiveness, but little is known about how this standard definition applies in music. Here, we present results from a pilot study in which we combine behavioral testing in musical improvisation and structural neuroimaging to relate brain structure to performance in a creative musical improvisation task. Thirty-eight subjects completed a novel improvisation continuation task and underwent T1 MRI. Recorded performances were rated by expert jazz instructors for creativity. Voxel-based morphometric analyses on T1 data showed that creativity ratings were negatively associated with gray matter volume in the right inferior temporal gyrus and bilateral hippocampus. The duration of improvisation training, which was significantly correlated with creativity ratings, was negatively associated with gray matter volume in the rolandic operculum. Together, results show that musical improvisation ability and training are associated with gray matter volume in regions that are previously linked to learning and memory formation, perceptual categorization, and sensory integration. The present study takes a first step towards understanding the neuroanatomical basis of musical creativity by relating creative musical improvisation to individual differences in gray matter structure.

Keywords: creativity, improvisation, gray matter, VBM, music

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Edited by:
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University of Miami, United States

Reviewed by:
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Received: *19 January 2019*
Accepted: *08 May 2019*
Published: *22 May 2019*

Citation:
Arkin C, Przysinda E, Pfeifer CW, Zeng T and Loui P (2019) Gray Matter Correlates of Creativity in Musical Improvisation. Front. Hum. Neurosci. 13:169. doi: 10.3389/fnhum.2019.00169

INTRODUCTION

The study of creativity and flow are central to positive psychology and neuroscience. We often know when we are experiencing creative works of art; yet it is impossible to find a single dimension along which to rank all works of creative genius. This is especially true of music. The standard definition of creativity in the psychological literature requires both novelty and effectiveness (Runco and Jaeger, 2012). Despite its clear importance (Guilford, 1950), the topic of creativity remains challenging precisely because novelty, quality, and appropriateness to audience are all difficult to quantify (Baer, 1993).

Efforts to understand creativity have come from multiple methods. Historiometric studies have provided insight into exceptional creativity, also known as "Big C" creativity (Simonton, 2014), and many such studies have focused on composers such as Mozart as paragons of human creativity (Gardner, 1998). Theoretical work posits the cognitive mechanism of "blind variation and selective retention" (Campbell, 1960; Simonton, 2013) as fundamental to the creative process. In this model, information is modified, recombined, and generated pseudorandomly ("blind variation") to give rise to many possible novel ideas; once the possible ideas are generated, the best ideas are retained ("selective retention") and refined to become the creative product (Campbell, 1960; Simonton, 2013). To capture this process of "blind variation," psychometricians have designed divergent thinking tests such as the Torrance Test of Creative Thinking, in which subjects are given short prompts and are expected to generate multiple answers, and subjects' responses are scored on fluency, originality, flexibility, and elaboration (Torrance, 1968b). While the scoring of fluency can be relatively automatic in divergent thinking tests, scoring of originality by raters can be somewhat subjective; thus consensual assessment between multiple raters is preferred (Amabile, 1982). Another issue concerns the extent to which laboratory tasks such as the Torrance Test of Creative Thinking truly capture the process of creativity in real time, and whether the divergent thinking tests are in fact measuring the same construct as that which was studied historiometrically in great musicians and composers (Baer, 2008).

In music, creativity is seen in composition and in performers' interpretations, but also especially in improvisation such as in jazz music, which requires generating musical ideas in real time. For this reason, jazz improvisation has long been viewed as a prominent example of improvisational creativity in the Western culture (Sawyer, 1992). In recent years, the science of music has seen a flourishing of studies that take a neuroscientific approach, and the study of jazz improvisation is no exception. Musical improvisation has been studied as a prototypical form of spontaneous creative behavior.

Time-sensitive measures such as electroencephalography and event-related potentials (EEGs and ERPs), have shown both spectral and temporal differences in brain activity among groups of subjects with varying levels of improvisation training (Vuust et al., 2012; Przysinda et al., 2017; Goldman et al., 2018). Results from ERP studies have shown that people with different levels of improvisation training differ in how they react to unexpected musical events in a very time-sensitive manner: while all groups of participants are sensitive to unexpected musical events, trained jazz musicians notice the unexpectedness earlier, as early as 200 ms after event onset, whereas classical musicians continue to show sensitivity well after jazz improvising musicians at 800 ms (Przysinda et al., 2017). Goldman et al. (2018) showed that experienced improvisers responded more quickly to functional deviants (as opposed to exemplar deviants as defined by music-theoretical function), with the differences around 200 ms and 450 ms after chord onset predicting the behavioral advantage of experienced improvisers (Goldman et al., 2018). Furthermore, EEG studies in creativity generally show that alpha-band activity plays a key role in the creative process, with some additional contributions from the theta and gamma bands (Stevens and Zabelina, 2019). Specifically in music, trained improvisers showed higher right frontal alpha band activity, especially during improvisation (Lopata et al., 2017). Additionally, jazz improvising pianists showed more beta power increase whereas classical pianists showed enhanced theta band activity during the perception of syntactically inappropriate or unexpected chords (Bianco et al., 2018).

The first functional Magnetic Resonance Imaging (fMRI) studies compared spontaneous improvisation against controlled performance on the keyboard, and revealed a network of activations and deactivations in medial prefrontal cortex (MPFC) and dorsolateral prefrontal cortex during jazz improvisation (Limb and Braun, 2008). Since then the majority of neuroimaging studies in musical creativity have used functional MRI to relate behavioral performance during improvisation to brain activity (Donnay et al., 2014; Pinho et al., 2014). As jazz improvisation can be thought of as spontaneous generation of auditory-motor sequences (Berkowitz and Ansari, 2008), neuroimaging studies on jazz improvisation can inform the more general neuroscience of motor behavior. As reviewed in recent literature (Beaty, 2015), results have shown differences related to improvisation training in multiple brain regions and at various time-points throughout perceptual and cognitive processing. Many findings centered around the prefrontal cortex, but the precise findings differ among studies. Within the prefrontal cortex, some studies have observed increased activity in the MPFC and downregulation of the lateral prefrontal cortex during improvisation (Limb and Braun, 2008; Liu et al., 2012). In addition to MPFC, other mesial activity has also been observed during improvisation, including the cingulate cortex and supplementary motor area (Bengtsson et al., 2007; Limb and Braun, 2008; de Manzano and Ullén, 2012; McPherson et al., 2016). The SMA and cingulate cortex belong to different resting state networks and are related to transient and sustained cognitive control respectively (Dosenbach et al., 2008; Christoff et al., 2016); both types of cognitive control are likely involved in musical improvisation and are difficult to disentangle in an improvisation task.

Findings also differ between studies depending on the specific cognitive demands during musical improvisation tasks. One study found higher activation in language-related areas in the lateral prefrontal cortex, specifically the pars triangularis and pars operculum of the left inferior frontal gyrus (Broca's area), especially during socially interactive improvisation ("trading fours"; Donnay et al., 2014). Another study additionally manipulated emotional intent and showed that the valence of the target emotion affected activity as well as functional connectivity in the prefrontal cortex (McPherson et al., 2016). The design of control conditions in these task-based experiments could also explain some differences in results. In functional MRI tasks, the control condition typically also involves the production of auditory-motor sequences, but without spontaneous idea generation: Control tasks have included rote repetition of an overlearned sequence, such as a scale, or a previously memorized melody (Limb and Braun, 2008) or the reproduction of a previously produced performance (Bengtsson et al., 2007). This control task may require more memory, specifically more active maintenance and retrieval strategies, and thus a contrast between improvised and control conditions often reveals deactivations in areas that maintain short-term memory, such as the dorsolateral prefrontal cortex. In addition to these differences in task demands and experiment design, discrepancies necessarily arise in task fMRI studies due to the inherent variability in the mental process of improvisation: at a given moment in the improvisation task, subjects could be utilizing any number of available mental capacities (e.g., visuospatial and/or auditory/phonological components of working memory, autobiographical memory recall, motor planning, attentional selection, and affective communication, just to name a few) to engage in the idea generation and evaluation process. This poses an inherent challenge in task fMRI studies of jazz improvisation (Loui, 2018).

Having identified challenges with task-based neuroimaging data, it becomes clear that a task-independent neuroanatomical comparison could add value to this discussion. Associations between creativity in musical improvisation and individual differences in gray and white matter structure may provide clues as to the fundamental neurobiological underpinnings of musical improvisation ability (Loui, 2018); furthermore, they may offer insights into whether musical improvisation involves shared or distinct networks from non-musical creativity tasks more generally.

Several studies have related neuroanatomical measures to creativity as assessed by non-musical creativity tasks, such as divergent thinking tasks done outside the scanner, and observed associations between creative behavior and regional variations in the posterior cingulate cortex, the lingual gyrus, the angular gyrus, and the orbitofrontal cortex (Jung et al., 2010). Self-report measures of creativity, as measured by the Creativity Achievement Questionnaire (Carson et al., 2005), are inversely correlated with gray matter volume in the cingulate cortex and SMA (Chen et al., 2014), but performance on a divergent thinking task showed positive associations with gray matter volume in the caudate, precuneus, midbrain, and middle frontal gyrus (Takeuchi et al., 2010). More recently, Shi et al. (2017) directly compared gray matter volume between self-report measures of artistic and scientific creativity, and found that artistic creativity was negatively associated with gray matter volume in the SMA and cingulate cortex whereas scientific creativity was positively correlated with the gray matter volume in more lateral prefrontal structures, specifically the left middle frontal gyrus and left inferior occipital cortex. These findings suggest that creativity may be supported by multiple distributed regions in a domain-specific, rather than a domain-general manner. Thus, studies that use domain-specific measures of creativity may add value to our understanding of creativity as a construct.

In musical creativity specifically, a recent study has related cortical surface area and volume from structural MRI data to musical creativity (Bashwiner et al., 2016). They found that cortical surface area in superior frontal gyrus, left planum temporale, and right middle temporal gyrus, and subcortical volume in left amygdala, were correlated with musical creativity ratings. These findings were important as they were first to relate musical creativity to brain structure; however, creativity was assessed by self-report measures and not independently verified. Combining a behavioral task of musical improvisation with MRI measures of individual differences in brain structure will yield direct associations between improvisation ability and brain structure, thus shedding light on the neural correlates of real-time creative behavior while circumventing methodological challenges as reviewed above. Furthermore although these measures of brain structure are task-invariant (i.e., not dependent on task-induced activations), they may change over time as a result of training-induced plasticity even in adults, as shown by numerous studies in the neuroanatomical changes as a function of musical training independent of creativity (Schlaug, 2001, 2015; Pantev et al., 2003, 2009; Bengtsson et al., 2005; Imfeld et al., 2009; Halwani et al., 2011; Elmer et al., 2012, 2013, 2016; Herholz and Zatorre, 2012; Oechslin et al., 2013, 2018; Gärtner et al., 2013; Kleber et al., 2016; Karpati et al., 2017; Moore et al., 2017; Li et al., 2018). Thus, a better understanding of neuroanatomical correlates of musical creativity may enable future interventions and training programs that specifically target the plasticity of these neuroanatomical regions with the goal of promoting musical creativity.

Here, we report the first results from a combined behavioral and neuroimaging study to test the hypothesis that individual differences in creative musical behavior are associated with differences in gray matter structure. We use a behavioral task of musical improvisation to assess real-time creativity in individuals with a broad range of musical training, similar to recent studies from a developmental perspective (Ilari et al., 2017). Expert ratings of musical creativity are used as predictors in a voxel-based morphometry (VBM) study to relate gray matter structure to musical improvisation behavior.

MATERIALS AND METHODS

Subjects

Thirty-eight subjects from Wesleyan University and the Hartt School of Music participated in return for financial compensation or course credit. All subjects gave written informed consent as approved by the Institutional Review Boards of Wesleyan University and the Hartford Hospital. They then completed a survey of their background including demographic information, information on their age of onset and duration of general musical training and training in jazz and in musical improvisation, and self-rating of skills in improvisation. Care was taken to recruit a racially/ethnically diverse and gender-balanced sample that was representative of the student population. While the subjects were racially/ethnically diverse, there was a skew towards male subjects. To control for possible confounds of gender in our results, we incorporate gender as a covariate in all of our analyses. Subjects also completed background tests as part of prescreening procedures for our study. These included the non-verbal subtest of the Shipley Institute of Living, which is a correlate of IQ that is used to rule out intellectual impairment (Shipley, 1940), digit span for short term memory (Baddeley, 2003), and a pitch discrimination threshold-finding task (Loui et al., 2008) to screen for tone-deafness. **Table 1** shows demographics, music training variables, and results on baseline tests.

Stimuli

Twelve musical prompts were composed for this experiment. Each prompt lasted 2.4 s (1 measure = 4 beats at 100 bpm). The prompts varied in either rhythm or pitch.

TABLE 1 | Subject demographics and musical training information.

	Mean ± SD
Gender	Female *n* = 11; Male *n* = 27
Age	21.87 ± 3.02
Handedness	Left *n* = 4; Right *n* = 34
Ethnicity/Race	Asian and Pacific Islander *n* = 6, Asian/Caucasian *n* = 2, Black/African American *n* = 4, Hispanic/Latino *n* = 3, White/Caucasian *n* = 23
Pitch Discrimination Perception (Hz)	6.92 ± 7.94
Digit Span (digits)	7.55 ± 1.61
Shipley (raw score)	17.14 ± 1.73
Age of onset of musical training (years)	8.31 ± 2.56
Duration of musical training (years)	7.36 ± 4.10
Duration of improvisation training (years)	3.59 ± 3.73
Musical instruments played	piano (16), guitar (12), drums (5), clarinet (5), bass (5), violin (4), saxophone (4), voice (3), flute (2), pipa (1), trumpet (1)

Figure 1 shows the 12 musical prompts, and example recordings of the prompts are also available online here: https://doi.org/10.6084/m9.figshare.6590489.v1. All prompts were presented in MIDI grand piano timbre throughout the experiment.

Procedures

Improvisation Continuation Task

Twelve different trials were presented from a computer. Each trial consisted of a listening phase (two measures), a continuation phase (eight measures), and an improvisation phase (eight measures). Visual cues were given on the screen throughout the listening phase (“Listen”), the continuation phase (“Play along”), and the improvisation phase (“Improvise”). In addition, a metronome was presented at 100 bpm to keep time throughout the entire trial.

Subjects were instructed to listen to the clip two times during the listening phase, to play along with the prompt eight times during the continuation phase, and then to improvise in the most creative way they could be based on the prompt given, for another eight measures until the metronome stops. No additional instructions were given on how to improvise, nor were any guidelines given for what constitutes creativity. All subjects completed this task on a Casio PX 150 MIDI keyboard. Subjects who self-identified as playing other instruments additionally performed on their instrument of choice. MIDI data were collected through Max/MSP using the borax function, which recorded the pitch, velocity, duration, and inter-onset interval for each note received by the keyboard. All performances were also recorded using a Zoom Q8 video camera.

MRI

T1 images were acquired from all participants in a 3T Siemens Skyra MRI scanner at the Olin Neuropsychiatry Research Center at the Institute of Living. Anatomical images were collected using a T1-weighted, 3D, magnetization-prepared, rapid-acquisition, gradient echo (MPRAGE) volume acquisition (Axial acquisition, 224 slices, FOV = 256 mm, TE = 2.09 ms, TR = 2,400 ms, flip angle = 8°, voxel resolution = $0.8 \times 0.8 \times 0.8$ mm^3). We also acquired resting state fMRI and DTI images, which will be described in a separate report.

Data Analysis

Improvisation Continuation Task Analysis

Example audio files of subjects’ production are available online at https://doi.org/10.6084/m9.figshare.6590489.v1. Audio was extracted from video recordings and rated for creativity by two professional jazz instructors (Rater 1 and Rater 3) and one experienced jazz improvising musician (Rater 2). Expert raters were asked to listen to each anonymized recording of each improvisation, and to rate the recording on a scale of 1–6 for creativity and imagination, with 1 being “Not creative and/or imaginative” to 6 being “Creative and/or imaginative.” Rater 1 completed the full dataset of 456 ratings (38 subjects * 12 trials each). Rater 2 completed ratings for 10 subjects (12 trials each * 10 subjects = 120 ratings), but stopped after 120 ratings due to lack of interest. Rater 3 completed 432 ratings (36 subjects * 12 trials each); two subjects were tested after Rater 3 already completed the other ratings; thus the last two subjects were not rated by Rater 3. Each rater’s ratings were averaged across the 12 trials performed by each subject to

FIGURE 1 | Musical prompt for the improvisation continuation task.

obtain an average score given by each rater to each subject. We then obtained an averaged creativity rating for each subject by averaging across all available raters' data for that subject.

MRI Analysis

VBM analysis (Ashburner and Friston, 2000) was performed on T1 images to relate gray matter variations to behavioral measures. First, we extracted T1 images of the brain from non-brain voxels using the Brain Extraction Tool (BET) in FSL (Jenkinson et al., 2012). Brain masks were checked to ensure that they accurately covered the entire brain. Then in SPM12, the images were realigned by setting the origin to the anterior commissure. Using the VBM toolbox in SPM12, the brain-extracted images were normalized relative to the canonical image (avg152T1.nii). Images were then segmented into gray matter, white matter, and cerebrospinal fluid. The resulting gray matter images were smoothed using a 12 mm Gaussian kernel. Multiple regressions were run on the behavioral dependent variable of averaged creativity score, with gender and overall brain volume added as covariates of no interest. A whole-brain regression was not significant at the $p < 0.05$ FWE-corrected or FDR-corrected levels. We, therefore, applied a combined threshold with voxel-wise significance level of $p < 0.001$ (uncorrected) and a cluster-correction of $k > 10$ voxels, to capture results that surpass both a voxel-wise and an extent threshold. While the use of uncorrected voxel-wise significance level was relatively liberal, the additional application of the extent threshold served to reduce the likelihood of type 1 errors.

RESULTS

Behavioral Results

Mean creativity rating across the three expert raters was 3.19 (SD = 0.96). Cronbach's Alpha across the three raters was 0.932, confirming high inter-rater reliability. Cronbach's alpha was calculated in SPSS using list-wise deletion to account for missing data resulting from incomplete datasets from raters. Since list-wise deletion does not take into account the subjects that only received two out of three possible ratings, we also separately show the pairwise correlation matrix between each pair of raters. The three raters' average scores were all highly correlated, as shown in the inter-rater correlation matrix in **Table 2**. The available ratings for each subject were averaged across the raters to derive an averaged creativity ratings score, ranging from 1 (Not creative and/or imaginative) to 6 being (Creative and/or imaginative). The resulting averaged creativity score was normally distributed (Kolmogorov-Smirnov test: $D_{(38)} = 0.9$, n.s.).

Multiple regression was used to test if training and performance on background tests predicted creativity. We ran a multiple linear regression analysis on the dependent variable of averaged expert ratings of creativity, with the independent variables of duration of improvisation training and duration of general musical training, as well as scores on pitch discrimination, digit span, and Shipley tests. This regression was significant, with the combined factors explaining 69% of the variance ($R^2 = 0.693$, $p = 0.003$). Duration of improvisational training was the most significant predictor of creativity ratings ($\beta = 0.75$, $p < 0.001$), whereas duration of general musical training did not significantly predict creativity ratings ($\beta = 0.13$, $p = 0.37$). Performance on pitch discrimination ($\beta = -0.212$, $p = 0.156$), Digit span ($\beta = -0.251$, $p = 0.128$), and Shipley ($\beta = 0.112$, $p = 0.46$) baseline tests did not significantly predict creativity ratings.

TABLE 2 | Inter-rater correlation matrix showing correlation coefficients (*r*) for each pair of raters.

	Rater 1	Rater 2
Rater 2	0.931	
Rater 3	0.860	0.804

Voxel-Based Morphometry

A whole-brain regression on gray matter volume with the covariate of averaged creativity ratings showed no significant voxels at the $p < 0.05$ FWE- or FDR-corrected levels. However, there were three significant clusters that surpassed the combined peak and cluster thresholds ($T = 3.53$, $p < 0.001$ uncorrected, extent threshold $k = 10$ voxels). These clusters were identified using the Automated Anatomical Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002) as being in the left and right hippocampus and the right inferior temporal gyrus. Scatterplots showed a negative relationship between averaged creativity ratings and gray matter signal in all three regions: participants whose production was rated as more creative had lower gray matter signal in all three regions (**Figure 2B**).

A whole-brain regression on gray matter volume with the covariate of duration of improvisation training showed a single cluster that surpassed both t and k thresholds, in the right rolandic operculum. Scatterplots again showed a negative relationship between the duration of improvisation training and gray matter signal: participants who had more improvisation training had lower gray matter signal in the rolandic operculum. **Figure 2** shows anatomical locations and sizes of these clusters (**Figure 2A**), and their correlations with averaged creativity ratings and with improvisation duration (**Figure 2B**). **Table 3** shows the clusters in MNI coordinates.

DISCUSSION

In this study, we combine behavioral and voxel-based morphometry methods to relate brain structure to creativity in musical improvisation. Results show that expert ratings of creativity on an improvisation task are associated with differences in gray matter structure and that these associations are distinct from neuroanatomical correlates of training in musical improvisation.

Our musical improvisation continuation task is modeled after previous studies and is designed to be doable by participants of all levels of training (Pinho et al., 2014; Ilari et al., 2017). Like all creative tasks, there is no unique correct answer for each trial, but some utterances are clearly more creative than others. In that sense, our task parallels the more domain-general divergent thinking task (Torrance, 1968a). To quantify creativity in these situations, the most common approach is to rely on expert ratings, such as by professional jazz musicians. Here, we show

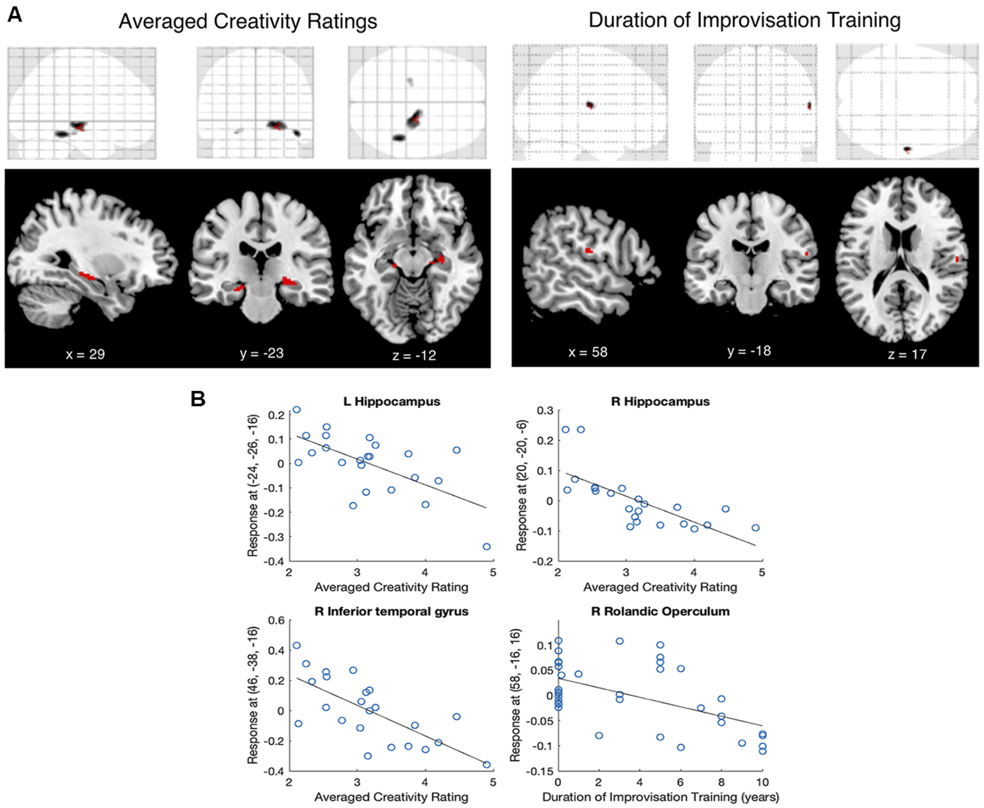

FIGURE 2 | (A) Voxel-based morphometry (VBM) regression on averaged creativity ratings and the duration of improvisation training ($T > 3.53$, $p < 0.001$, $k > 10$). Top row shows glass-brain representations of the whole-brain regressions; Bottom row shows significant clusters overlaid on a T1 template. **(B)** Scatterplots showing relationships between averaged creativity ratings and gray matter signal at left and right hippocampus, between averaged creativity ratings and right inferior temporal gyrus, and between the duration of improvisation training and the right rolandic operculum.

TABLE 3 | Significant clusters (MNI coordinates) from whole-brain regression analysis of variations in gray matter volume with creativity ratings.

Contrast	Region	Hemisphere	T	*k*	*x*	*y*	*z*
Creativity	Hippocampus	R	4.63	179	20	−20	−6
	Inferior temporal gyrus	R	4.58	76	46	−38	−16
	Hippocampus	L	3.84	22	−24	−26	−16
Duration of Improv Training	Rolandic Operculum	R	3.77	15	58	−16	16

that there is consistent agreement between the expert ratings of musical improvisations, suggesting that musical creativity can be reliably assessed and compared between participants in a behavioral paradigm.

Individual differences in gray matter volume as identified in voxel-based morphometry may reflect variations in neuronal cell bodies themselves and/or from differences in relative density of cell bodies which gives rise to gyrification patterns, which may, in turn, facilitate connectivity towards those cell bodies (Ashburner and Friston, 2000). Here, we find that creativity ratings are negatively associated with gray matter volume in the bilateral hippocampus and the right inferior temporal gyrus. These clusters show no overlap with the cluster that is negatively associated with duration of improvisation training, which is in the rolandic operculum. The consistent patterns of negative correlations between gray matter volume and variables of interest have been observed in other studies: as reviewed in the introduction, measures of creative achievement were inversely correlated with gray matter volume in the anterior cingulate and the SMA (Chen et al., 2014; Shi et al., 2017). In a previous study relating gray matter volume to rhythm perception and production, temporal discrimination abilities were found to be inversely correlated with gray matter volume in the cerebellum (Paquette et al., 2017). As voxel-based morphometry is a voxel-wise comparison of the local concentration of gray matter between individuals (Ashburner and Friston, 2000), the results are agnostic to the direction of the difference between participants. Lower gray matter volume in more creative and more highly trained musical improvisers may be due to more densely packed neuronal cell bodies, more neuronal and/or synaptic pruning, and/or differences in the distribution of glial cells leading to a less defined gray-white matter boundary in the significant regions among successful improvisers. While at present we cannot disentangle these possible interpretations, in future studies we plan to use cortical thickness and surface area, subcortical volume, white matter volume, and other methods to tease apart these distinct biological mechanisms in a larger sample.

Creativity ratings were negatively associated with gray matter volume in the hippocampus. The hippocampus is primarily involved in learning and memory formation; recent work has linked this structure to creativity tasks as well. A recent voxel-based morphometry study found that hippocampal volume was correlated with performance on the remote associate's test, a verbal creativity task (Tu et al., 2017). Among amateur and expert musicians, previous work has shown that hippocampal volume is significantly correlated with fluid intelligence as assessed by the Raven's Advanced Progressive Matrices (Oechslin et al., 2013). A jazz guitarist whose left hippocampus was surgically removed due to an arteriovenous malformation, lost his musical capabilities while acquiring profound retrograde amnesia following the surgery. However, through long-term training and associations, he was able to recover completely in his ability to improvise music, despite chronic impairment in verbal memory but not visual memory tasks (Galarza et al., 2014). This suggests that temporal lobe in both hemispheres, including both hippocampi, are involved in musical improvisation, but also that improvisation ability can be recovered even with only one intact hippocampus (Duffau, 2014). Here, the hippocampal clusters that are inversely correlated with creativity ratings span the middle to anterior hippocampus and parahippocampal gyrus in the right hemisphere, and the middle to posterior hippocampus in the left hemisphere. The slight asymmetry between left and right hippocampal findings may highlight known dissociations along the anterior-posterior axis of the hippocampus (Poppenk and Moscovitch, 2011). The anterior hippocampus is more associated with perceptual novelty, imagery, and episodic memory formation (Zeidman and Maguire, 2016), whereas the posterior hippocampus is more associated with indexing familiarity to behaviorally relevant stimuli (Strange et al., 1999). As musical improvisation requires sensitivity to perceptual novelty (Przysinda et al., 2017) as well as familiarity with known repertoire (Pressing, 1998), the functions of both anterior and posterior hippocampus are likely at work in musical improvisation.

The inferior temporal gyrus is part of the "what" pathway in the visual system. Specifically, the cluster that we find to be associated with averaged creativity ratings falls in the gray-white matter boundary between the right posterior inferior temporal gyrus and the fusiform gyrus, in an area that is activated during studies that involve categorization of meaningful stimuli ranging from objects such as tools and chairs (Ishai et al., 1999; Creem-Regehr and Lee, 2005; Rice et al., 2014) to bodies (Downing et al., 2001; Peelen and Downing, 2005) and emotional categories in sign language (Emmorey and McCullough, 2009). These categories, although seemingly disparate, may share the characteristic of having action-related properties, in that they are categories of objects and concepts that can afford action (Mahon et al., 2007). Given the role of right inferior temporal gyrus in access to categories, its association with creativity in musical improvisation likely reflects better access to the relevant action-related categorical information (e.g., notes, chords, melodies) among better performers.

The rolandic operculum is anatomically between the parietal and temporal lobes and includes multisensory integration areas including secondary somatosensory cortex. Activity in the rolandic operculum has been reliably observed during interoception which is the awareness of one's own bodily sensations, such as the awareness of one's own heartbeat (Blefari et al., 2017). In music, activity in the rolandic operculum has been observed during musical improvisation when emotional improvisation is contrasted against simply improvising with pitch (Pinho et al., 2016). Here, we find that people with more improvisation training show lower gray matter volume in the rolandic operculum. In light of findings that the rolandic operculum is important for the sensory integration of interoceptive signals especially during the production of emotional sounds, our interpretation is that this sensory-interoceptive-emotional integration is especially relevant during improvisation training. This is consistent with known educational strategies in teaching jazz improvisation, which emphasize awareness and anticipation of sensory feedback and simultaneously communicating emotions while maintaining flow (Biasutti, 2015).

Surprisingly, our study found no significant associations with creativity ratings or duration of improvisation training in the prefrontal cortex nor in the frontal lobe. This stands in contrast to two VBM studies on creativity outside of music, which showed negative associations between creativity, in particular, artistic creativity, and gray matter volume in the anterior cingulate cortex and the SMA (Chen et al., 2014; Shi et al., 2017). These differences may be explained by our different approaches in that previous studies used the Creativity Achievement Questionnaire (Carson et al., 2005), a self-report measure that asked questions about successes in various creative domains including music but not specific to improvisation, whereas we incorporated improvisation as the primary behavioral measure in our study. VBM associations with real-time creative ability, as assessed in a musical improvisation task, may tap first and foremost into neural substrates for memory, learning, and categorization, rather than neural substrates for sustained and transient cognitive control as may be required for more long-term production of creative products such as musical composition.

Summarizing the VBM findings, gray matter volume in the bilateral hippocampus and the right inferior temporal gyrus, which are involved in learning, memory formation, and object categorization, together reflect differences in musical creativity as assessed by expert ratings on an improvisation task. Performance on the musical improvisation task shows different neuroanatomical correlates from the duration of musical improvisation training, which is negatively correlated with gray matter volume in the rolandic operculum, a region likely involved in sensory integration.

Limitations

This study is first to relate musical improvisation behavior to gray matter correlates in brain structure; however, there are several limitations. First, the sample size is relatively small for a VBM study. This could contribute to the major caveat: that our results do not survive correction for multiple comparisons at the $p < 0.05$ FWE or FDR-corrected levels. Second is that the musician participants in our study are relatively early in their musical careers; thus the relationship between creativity and gray matter may not necessarily extend towards more experienced players. Third, more than two-thirds of the participants in this sample are male; this is similar with other neuroimaging studies on musical improvisation (Limb and Braun, 2008; Liu et al., 2012; Donnay et al., 2014; Pinho et al., 2016) and reflects the higher availability of male participants with improvisation training. Studies on the neural correlates of creativity have shown some evidence for gender asymmetry (Ryman et al., 2014); while our sample is too small to separately relate creativity to male and female brain structure, ongoing efforts are focused on recruiting more females to participate in the study. Finally, the current study focuses on relating performance on the improvisation task to gray matter structure of the brain; other work on white matter is ongoing (Zeng et al., 2018), as is additional work on resting state functional connectivity using resting state functional MRI (Belden et al., 2018). Together, the functional and structural (gray and white matter) differences can contribute to our thinking about structural and functional brain networks that enable creativity, and may possibly serve as targets for future training and intervention.

CONCLUSION

Taken together, we present first results relating individual differences in brain structure to expert ratings of performance in a musical improvisation task. The results show that individual differences in musical creativity, as assessed by an improvisation task, are associated with regions implicated in memory formation and categorical representation, whereas regions implicated in sensory integration are associated with duration of improvisation training. The use of VBM enables the identification of specific regions in the brain that has demonstrated functions, and knowledge of these functions then shed light on how the brain accomplishes the complex creative task of musical improvisation. Future work will expand the current approach to a larger sample size, and also apply other data-driven measures to predict creativity and relate them to brain structure and function. By relating brain structure to the perceived creativity of musical output, the present preliminary results set the stage for further research towards the neural correlates of musical creativity.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of “IRBs of Wesleyan University and Hartford Hospital” with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by Wesleyan University and the Hartford Hospital.

AUTHOR CONTRIBUTIONS

PL conceptualized the idea behind this manuscript, performed data analyses, and wrote the first draft. CA, EP and TZ acquired and preprocessed the behavioral and neuroimaging data. CA and CP analyzed the behavioral and neuroimaging data. All authors revised the manuscript and approved the submission.

FUNDING

This work was supported by the Imagination Institute (the John Templeton Foundation), RFP15-15, and NSF STTR 1720698.

ACKNOWLEDGMENTS

We thank John Baboian from Berklee College of Music, Pheeroan akLaff from Wesleyan University, and Justin Friedman from Wesleyan University for serving as expert raters of our subjects' recorded improvisations, and we thank Pheeroan akLaff for helpful discussions on creativity and musical improvisation.

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Conflict of Interest Statement: 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.

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in Human Neuroscience

ORIGINAL RESEARCH
published: 22 May 2019
doi: 10.3389/fnhum.2019.00170

Martial Arts "*Kendo*" and the Motivation Network During Attention Processing: An fMRI Study

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Japanese martial arts, *Budo*, have been reported to improve cognitive function, especially attention. However, the underlying neural mechanisms of the effect of *Budo* on attention processing has not yet been investigated. *Kendo*, a type of fencing using bamboo swords, is one of the most popular forms of *Budo* worldwide. We investigated the difference in functional connectivity (FC) between *Kendo* players (KPs) and non-KPs (NKPs) during an attention-related auditory oddball paradigm and during rest. The analyses focused on the brain network related to "motivation." Resting-state functional magnetic resonance imaging (rs-fMRI) and task-based fMRI using the oddball paradigm were performed in healthy male volunteers (14 KPs and 11 NKPs). Group differences in FC were tested using CONN-software within the motivation network, which consisted of 22 brain regions defined by a previous response-conflict task-based fMRI study with a reward cue. Daily general physical activities were assessed using the International Physical Activity Questionnaire (IPAQ). We also investigated the impact of major confounders, namely, smoking habits, alcohol consumption, IPAQ score, body mass index (BMI), and reaction time (RT) in the oddball paradigm. Resting-state fMRI revealed that KPs had a significantly lower FC than NKPs between the right nucleus accumbens and right frontal eye field (FEF) within the motivation network. Conversely, KPs exhibited a significantly higher FC than NKPs between the left intraparietal sulcus (IPS) and the left precentral gyrus (PCG) within the network during the auditory oddball paradigm [statistical thresholds, False Discovery Rate (FDR) < 0.05]. These results remained significant after controlling for major covariates. Our results suggest that attenuated motivation network integrity at rest together with enhanced motivation network integrity during attentional demands might underlie the instantaneous concentration abilities of KPs.

Keywords: ***Budo***, ***Kendo***, **motivation network, functional connectivity, attention**

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Received: *25 January 2019*
Accepted: *08 May 2019*
Published: *22 May 2019*

Citation:
Fujiwara H, Ueno T, Yoshimura S, Kobayashi K, Miyagi T, Oishi N and Murai T (2019) Martial Arts "Kendo" and the Motivation Network During Attention Processing: An fMRI Study. Front. Hum. Neurosci. 13:170. doi: 10.3389/fnhum.2019.00170

INTRODUCTION

Physical exercise is widely believed to be beneficial to health. These benefits are felt by walking, gymnastics, and sports as hobbies. In addition to the physical benefits of exercise on cardiovascular, respiratory, and metabolic systems (Paffenbarger et al., 1984; Biddle et al., 2011), several reports have suggested that engagement in sports positively influences mental well-being. For example, habitual exercise has been found to alleviate depression and anxiety and reduce stress (Hassmén et al., 2000; Callaghan, 2004), and single bouts of exercise have been reported to suppress the urge to drink alcohol (Ussher et al., 2004). Engaging in sport also has beneficial effects on cognitive function (Etnier et al., 1997; Northey et al., 2018), particularly attention. Using a selective attention task, Abernethy and Russell (1987) reported outstanding attentional capacities of athletes. Kida et al. (2005) found that professional baseball players had shorter reaction times (RTs) to target stimuli during a Go/NoGo task. Furthermore, in this study, a 2-year longitudinal follow-up showed a further shortening of RTs, which indicates that practice positively influenced performance (Kida et al., 2005).

The potential benefits of martial arts (known as *Budo* in Japan) for both physical and mental health have received particular attention (Woodward, 2009; Bu et al., 2010; Zheng et al., 2015). Although the various forms of *Budo* are often regarded as sports, one of the characteristics of *Budo* that sets it apart from other sports is its emphasis on the mind and heart, which the Japanese martial arts tradition has partially adopted from concepts of Zen Buddhism. *Budo* emphasizes the importance of a calm, unmoving, and undisturbed mind; these aspects are described as Fudoshin (unmoving mind) or Mu (empty mind; Oosterling, 2011). In contrast to the contemplative meditation of the sitting Zen, *Budo* is regarded as "Zen in action" (Oosterling, 2011), and physical training is an essential component. Previous studies have reported outstanding attentional capacities of *Budo* players (Sanchez-Lopez et al., 2014). Integrative mind-body training, such as meditation and martial arts, is known to enhance performance on attentional tasks (Brefczynski-Lewis et al., 2007; Johnstone and Marí-Beffa, 2018). Furthermore, a positive effect of *Budo* on the improvement of attention-deficit/hyperactive disorder symptoms has been reported (Woodward, 2009). Despite evidence for these positive impacts of *Budo* on attention, the underlying neural mechanism has only been investigated by one study. That study reported a difference between skilled and novice players in event-related potentials during a continuous performance test, which is an index of attention processing, over the frontal and limbic lobes (Sanchez-Lopez et al., 2016).

The mechanisms underlying *Budo*-associated benefits on mental health, including an improvement of cognitive function, is not yet known. Investigating the effect of *Budo* on "motivation" can help to address this question, because cognitive functions, including attention, are considered to be influenced by motivation (Robinson et al., 2012). Thus, in the current study, we focused on the motivation network as a possible neural mechanism that could explain the superior attentional skills of *Budo* players. As mentioned above, a calm and undisturbed mind is required to become a *Budo* expert. Furthermore, as is required in any sport, instantaneous concentration is also essential. According to the Drive Theory (Anselme, 2010), motivation acts as a "drive" that provides an organism with the energy required to trigger, maintain, and direct goal-related behaviors, and with a kind of homeostatic trait. The motivational drive continuously influences on our daily behaviors, that is, instantaneous enhancement of motivation in the face of critical aims/goals, followed by its attenuation after satisfaction. We predicted that this "resting vs. attentionally-driven" state switching/change of motivation can be trained and becomes more efficient through the mind-body training of *Budo*.

Recent neuroimaging studies have suggested that brain functional connectivity (FC) can be used to characterize neural circuits that underpin human cognitive functions, including attention processing assessed by visual oddball paradigm (Li et al., 2016), and health-benefits of non-pathological internet use on motivational function (Fujiwara et al., 2018). Furthermore, FC changes in circumstances such as mental fatigue (after engaging in cognitive tasks for a prolonged period, Li et al., 2016; car driving drowsiness, Harvy et al., 2019) have been reported in EEG studies, in addition to FC abnormalities revealed by functional magnetic resonance imaging (fMRI) in mental illnesses such as schizophrenia (Li et al., 2018).

To test our hypothesis, we focused on *Kendo*, which is a type of fencing with bamboo swords that is practiced by over four million people (International Kendo Federation, 2014). We investigated the difference in FC between *Kendo* players (KPs) and non-*Kendo* players (NKPs) within the motivation network (Kinnison et al., 2012; Fujiwara et al., 2018) during both resting state and an attention-related paradigm. Brain regions within the motivation network have been identified using a motivation-related paradigm (Padmala and Pessoa, 2011). The network consists of 22 regions of interest (ROIs) that are well-synchronized in terms of their activity; identified ROIs include the bilateral intraparietal sulcus (IPS), medial prefrontal cortex (MPFC), frontal eye field (FEF), middle frontal gyrus (MFG), anterior insula (aIns), midbrain (MB), putamen (Put), caudate (Caud), nucleus accumbens (NAcc), left inferior parietal lobule (IPL), right rostral anterior cingulate cortex (rACC), supplementary motor area (SMA), and left precentral gyrus (PCG). In addition to the MB and basal ganglia, which constitute the core of the reward system, these ROIs include several cortical regions that are well-synchronized with the core regions. We hypothesized that KPs have: (1) attenuated FC during resting state; and (2) enhanced FC during tasks with an increased attentional-load.

MATERIALS AND METHODS

Participants

Participants were age-matched KPs ($n = 15$) and NKPs ($n = 15$), who were all healthy men. KPs were defined as individuals who were Dan-grade players (i.e., individuals with a career of *Kendo* for over 10 years) who practiced *Kendo* at least twice a week. Two well-trained psychiatrists confirmed that none of the participants had any psychiatric disorder or severe medical or neurological illness. Estimated intelligence quotients were measured using the Japanese Version of the Adult Reading Test (JART; Matsuoka et al., 2006), and all participants fell within the normal range. After the experimental procedures had been fully explained, all participants provided written informed consent before study participation.

The study was approved by the Ethics Committee of the Kyoto University Graduate School and Faculty of Medicine and was conducted in accordance with the Declaration of Helsinki.

The Assessment of General Physical Activity and Other Life Habits

The International Physical Activity Questionnaire

The International Physical Activity Questionnaire (IPAQ; the 7-item short version, Craig et al., 2003) is a self-rating questionnaire that is used to measure the average amount of physical activity over a week. This questionnaire was developed as a tool for cross-national monitoring of physical activity in adults, and the reliability and validity of the short form of Japanese IPAQ have been confirmed previously (Murase et al., 2002). The indices of the questionnaire are as follows: the average exercise intensity = multiplication of METs and duration of exercise [metabolic equivalents (METs) minutes/day] and those of energy consumption (kcal/day)[1].

Body Mass Index

Body mass index (BMI) was calculated using the following formula: body weight (kg)/ the square of height (m^2).

The Index of Smoking and Alcohol Consumption

Smoking and alcohol consumption may potentially influence attention and motivation/reward system; these habits were therefore assessed using the Fagerström Test for Nicotine Dependence (FTND, Heatherton et al., 1991) and the Alcohol Use Disorder Identification Test (CORE-AUDIT, Babor et al., 1992; Hiro and Shima, 1996).

MRI Acquisition

The fMRI acquisition started with a 360-s resting-state scan (Rest) using a single-shot gradient-echo echo planar imaging (EPI) pulse sequence on a 3-Tesla MRI unit (Tim-Trio; Siemens, Erlangen, Germany) with a 40-mT/m gradient and a receiver-only 32-channel phased-array head coil. During resting-state data acquisition, we instructed participants to visually concentrate on a fixation cross in the center of the screen and to avoid thinking about anything specific. Next, they received instructions on how to complete the oddball task for 25 s. They then performed the auditory oddball task for 390 s. The task included 30 target trials and 150 non-target trials. Participants heard two different sounds, as follows: 30 pink-noise sounds as target stimuli and 150 pure 400-Hz tones as standard stimuli. Tones were presented in a randomized order. The sounds were generated using Audacity 2.1.1. software[2]. All stimuli were presented using E-prime 2.0 software (Psylab, USA) for 200 ms with a randomized inter stimulus interval (ISI) of 1–3 s in 100 ms units. During the task, participants were instructed to differentiate between target and non-target tones by pressing a button as fast and accurately as possible after target stimulus presentation. The total acquisition time for the fMRI was 775 s. Head movement was minimized within the head coil with the use of foam rubber pads.

Structural MRI data were also acquired using 3-dimensional magnetization-prepared rapid gradient-echo (3D-MPRAGE) sequences. The parameters for the 3D-MPRAGE images were as follows: echo time (TE), 3.4 ms; repetition time (TR), 2000 ms; inversion time, 990 ms; field of view (FOV), 225 × 240 mm; matrix size, 240 × 256; resolution, $0.9375 \times 0.9375 \times 1.0\ \text{mm}^3$; and 208 total axial sections without intersection gaps. Parameters for the fMRI were as follows: TE, 30 ms; TR, 2500 ms; flip angle, 80°; FOV, 212 × 212 mm; matrix size, 64 × 64; in-plane spatial resolution, $3.3125 \times 3.3125\ \text{mm}^2$; 40 total axial slices; and slice thickness, 3.2 mm with 0.8-mm gaps in ascending order. A dual-echo gradient-echo dataset for B0-field mapping was also acquired for distortion correction.

Image Preprocessing

The fMRI dataset was corrected for EPI distortion using FMRIB's Utility for Geometrically Unwarping EPIs (FUGUE), which is part of the FSL software package (FMRIB's software library ver. 5.0.9)[3] and which unwarps the EPI images based on fieldmap data. Artifact components and motion-related fluctuations were then removed from the images using FMRIB's ICA-based X-noiseifier (FIX; Griffanti et al., 2014).

The preprocessed fMRI and structural MRI data were then processed using the CONN-fMRI FC toolbox (ver.17e)[4] with the statistical parametric mapping software package SPM12 (Wellcome Trust Centre for Neuroimaging)[5]. First, all functional images were realigned and unwarped, slice-timing corrected, coregistered with structural data, spatially normalized into the standard MNI space (Montreal Neurological Institute, Canada), outlier detected (ART-based scrubbing), and smoothed using a Gaussian kernel with a full-width-at-half maximum (FWHM) of 8 mm. All preprocessing steps were conducted using a default preprocessing pipeline for volume-based analysis (to MNI-space). Structural data were segmented into gray matter, white matter (WM), and cerebrospinal fluid (CSF), and normalized in the same default preprocessing pipeline. Principal components of signals from WM and CSF, as well as translational and rotational movement parameters (with another six parameters representing their first-order temporal derivatives), were removed using covariate regression analysis by CONN. Using the implemented CompCor strategy (Behzadi et al., 2007), the effect of nuisance covariates, including fluctuations in fMRI signals from WM, CSF, and their derivatives, as well as realignment parameter noise, were reduced. As recommended, band-pass filtering was performed with a frequency window of 0.008–0.09 Hz. This preprocessing step was found to increase retest reliability. Before running FIX, movement during fMRI was evaluated using frame-

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[1] https://sites.google.com/site/theipaq/scoring-protocol

[2] https://www.audacityteam.org/

[3] http://www.fmrib.ox.ac.uk/fsl

[4] www.nitrc.org/projects/conn

[5] http://www.fil.ion.ucl.ac.uk/spm

wise displacement, which quantifies head motion between each volume of functional data (Power et al., 2012). Participants were excluded if the number of volumes in which head position was 0.5 mm different from adjacent volumes was more than 20% (Fujiwara et al., 2018). In actuality, no participants were excluded according to this criterion. Furthermore, there was no significant difference in frame-wise displacement between the KPs and NKPs (0.154 ± 0.062 vs. 0.145 ± 0.050, $p = 0.72$).

Functional Connectivity Analysis

The Analysis Within the Motivation Network

We conducted a region of interest (ROI)-to-ROI FC analysis. We specified 22 spherical clusters with 10-mm diameters and peak-coordinates based on motivation-related fMRI studies (Kinnison et al., 2012; Fujiwara et al., 2018). The ROIs were located in the bilateral IPS (IPS_R: $x = 24$, $y = -54$, $z = 40$, IPS_L: −27, −52, 41), MPFC (MPFC_R: 6, 8, 39, MPFC_L: −8, 7, 39), FEF (FEF_R: 34, −11, 48, FEF_L: −31, −12, 50), MFG (MFG_R: 26, 46, 25, MFG_L: −28, 35, 29), aIns (aIns_R: 31, 17, 11, aIns_L: −35, 26, 5), Midbrain (MB_R: 7, −15, −8, MB_L: −10, −18, −8), Put (Put_R: 17, 9, −2, Put_L: −19, 9, 2), Caud (Caud_R: 10, 9, 2, Caud_L: −10, 9, 2), NAcc (NAcc_R: 13, 6, −7, NAcc_L: −13, 6, −7), left IPL (IPL_L: −28, −42, 41), right rACC (rACC_R: 13, 39, 8), right SMA (SMA_R: 0, −6, 57), and PCG (PCG_L: −48, −4, 37). For each subject, the preprocessed fMRI time series of all voxels in the 22 ROIs was extracted and averaged. ROI-to-ROI FC was defined as the Fisher-transformed bivariate correlation coefficients for each pair of the 22 regions, which resulted in a 22 × 22 correlation matrix (231 FCs) in each subject.

Due to the exploratory nature of this study, corrections for multiple comparisons were performed using the False Discovery Rate (FDR), but not using Bonferroni correction (statistical significance $p < 0.0023$) based on the number of ROIs within the motivation network.

The Analysis Within the Attention Network

Since we adopted an attention-related paradigm, an analysis within the attention network was conducted to test whether the KP was different from NKP group in attention, referring ventral/dorsal attention network (VAN/DAN; Yeo et al., 2011) as an additional analysis.

Statistical Analysis

Subject-specific connectivity matrices for each ROI estimated from the CONN toolbox were used as a second-level analysis. We performed a one-way analysis of covariance (ANCOVA) with group (KP vs. NKP) as an independent variable, FC as a dependent variable, and age as a covariate of no interest. Significant connections were identified by calculating the FDR-corrected two-sided p-values < 0.05.

A two-tailed t-test was applied for group comparisons of demographic data, average RT to the target stimuli in the oddball paradigm, and measures of physical exercise.

To test the effects of smoking and alcohol consumption, general physical exercise, and oddball task RTs on the FC differences between KP and NKP groups, additional analyses were performed in two steps, including a correlational analysis to investigate the association of FTND, CORE-AUDIT, IPAQ, BMI, and RT with FC, and an ANCOVA using group as an independent variable, FC as a dependent variable, and (1) FTND, CORE-AUDIT, (2) IPAQ, BMI, (3) RT, and (4) all covariates of (1), (2) and (3), as covariates. A one-sample Kolmogorov–Smirnov test revealed that the data were mixed in their distribution. Therefore, to test the correlations mentioned above, Pearson's correlation coefficients were used if an initial exploration of the dataset indicated normal distribution of the data, and Spearman's rank-correlation coefficients were used if the data were not normally distributed.

RESULTS

Demographic Information, General Physical Activity, and Behavioral Data

According to structural MRI findings, one and four subjects were excluded from the KP and NKP group, respectively, because of subtle organic brain abnormalities (ischemic changes or arachnoid cyst). Data from a final total of 14 KPs and 11 NKPs were analyzed. Demographic information, IPAQ scores, BMI, and behavioral data of the oddball paradigm are summarized in **Table 1**. There were no significant between-group differences in smoking (one person was currently a smoker in each group, and six/five KPs/NKPs were past smokers), alcohol consumption, IPAQ score, or BMI.

TABLE 1 | Participant demographics and behavioral data.

	***Kendo* player (n = 14)**		**Non-*Kendo* player (n = 11)**		
Variables	***M***	***SD***	***M***	***SD***	***p***
Age	39.9	13.0	38.8	13.2	0.836
FTND	0.3	1.1	0.2	0.6	0.776
CORE_AUDIT	7.0	5.0	7.5	7.2	0.824
IPAQ (METs. minutes/day)	439.6	372.3	315.9	202.3	0.336
IPAQ (kcal/day)	483.7	512.7	384.3	268.2	0.584
BMI	23.3	6.4	24.1	3.6	0.708
Auditory oddball paradigm					
Number of omission errors	0.1	0.3	0.0	0.0	0.387
Number of commission errors	0.3	0.6	0.3	0.5	0.285
Reaction time (ms)	171.2	42.9	244.9	91.8	0.028*

FTND, Fagerström test for nicotine dependance; CORE_AUDIT, The alcohol use disorder identification test; IPAQ, International Physical Activity Questionnaire; BMI, body mass index.
$^*p < 0.05$.

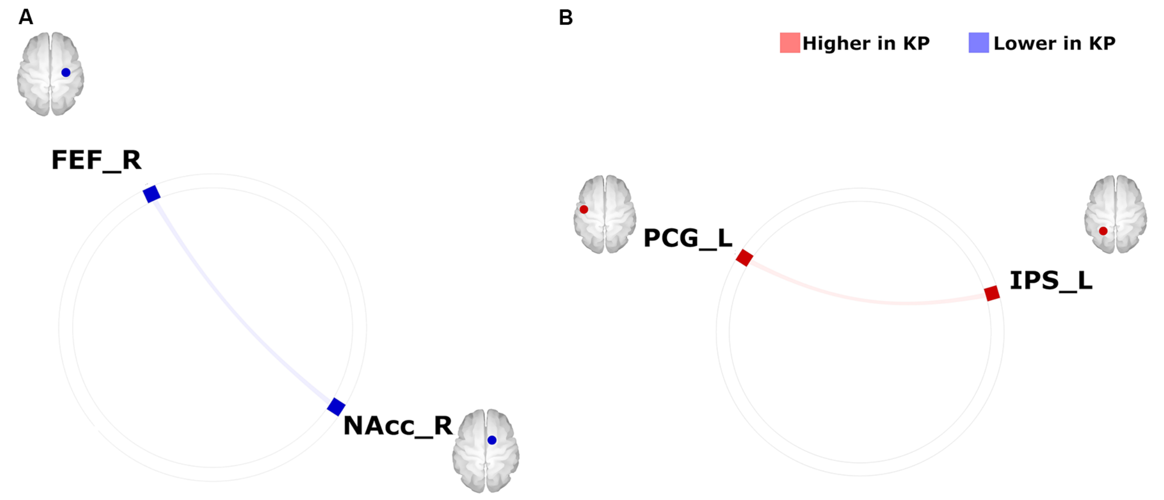

FIGURE 1 | Group differences in FC within the motivation network on **(A)** resting-state-functional magnetic resonance imaging (rs-fMRI) and **(B)** task-based fMRI during an auditory oddball paradigm (KPs < NKPs/ KPs > NKPs). FEF, frontal eye field; FC, functional connectivity; NAcc, nucleus accumbens; PCG, precentral gyrus; IPS, intraparietal sulcus; L, left; R, right; KP, *Kendo* players; NKP, Non-*Kendo* players.

Regarding behavioral data of the oddball paradigm, the error rate was not significantly different between the two groups. RTs to the stimuli were significantly shorter in KPs than in NKPs (**Table 1**).

Group Differences in FC Within the Motivation Network

Between-group differences (KPs vs. NKPs) in FC between two regions of the motivation network are shown in **Figure 1**. The CONN-toolbox analysis revealed the following: (1) KPs exhibited a significantly lower FC between the right NAcc and right FEF ($T_{(22)} = -4.44$, $p = 0.004$) compared with NKPs during rs-fMRI (**Figure 1**); and (2) KPs had a significantly higher FC between the left PCG and left IPS ($T_{(22)} = 4.33$, $p = 0.006$) than NKPs during the oddball paradigm (all statistical thresholds were FDR < 0.05). No other between-group differences in FC were found.

Correlations Between FC and Other Variables

The RT to the target stimuli was negatively correlated with FC between the left IPS and left PCG within the motivation network. None of the other variables, that is, FTND, CORE-AUDIT, IPAQ score, and BMI, were correlated with FCs at either resting state or during the oddball task (**Table 2**).

Group Comparisons of FC

An ANCOVA was performed using the following variables as covariates: (1) FTND and CORE-AUDIT as life habits that affect attention and motivation; (2) IPAQ score and BMI as indicators of general physical activity; (3) RT; and (4) all covariates of (1), (2) and (3), as a factor that has a significant effect on the between-group differences in FC (**Table 3**). The ANCOVA revealed that, compared with the NKP group, KPs had a significantly lower FC between the right FEF and right NAcc during rest and higher FC between the left IPS and left PCG during the oddball task after controlling for covariates (1), (2), (3) and (4; **Table 3**). According to the ANCOVA analyses, there were no significant effects of covariates (FTND scores, CORE_AUDIT, IPAQ score, BMI, and RTs) on the differences of FC.

Comparison of FC Within the Attention Network

No differences were found between the KP and NKP groups in FC during either resting state or the oddball paradigms in the analysis within the VAN/DAN.

DISCUSSION

In the current study, we predicted that "resting vs. attentionally-driven" switching/change of motivation can be trained and becomes more efficient through the mind-body training of *Budo*. The main finding of this study was that one of the FCs (FEF-NAcc) within the motivation network was smaller during rest in KPs vs. NKPs, while one of the FCs (PCG-IPS) was larger during the higher attentional load required during the oddball task in KPs vs. NKPs. This result is in line with our initial hypothesis and indicates that KPs can recruit the motivation network in a more timely manner, depending on the attentional demand.

This is the first study to investigate the neural correlates of the effect of *Kendo* on motivation, focusing on FC within the motivation network during both resting state and an attention-related task. We also investigated the effects of confounding factors on between-group differences in FC, including smoking, alcohol consumption, and general physical activity. As a result, no effect of the potential confounding factors on the difference in FCs was found.

Budo has elements of both Zen and actual physical training. The emphasis on having a calm/empty mind, much like

TABLE 2 | Correlations between functional connectivity (FC) and other variables that may be associated with attention.

	FC_FEF_NAcc		**FC_IPS_PCG**	
	Statistic	***p***	**Statistic**	***p***
FTND	$\rho = 0.11$	0.609	$\rho = 0.01$	0.972
CORE_AUDIT	$\rho = 0.01$	0.965	$\rho = -0.28$	0.182
IPAQ (METs. minutes/day)	$\rho = -0.25$	0.235	$\rho = 0.18$	0.388
IPAQ (kcal/day)	$r = -0.21$	0.235	$r = 0.16$	0.458
BMI	$\rho = 0.18$	0.402	$\rho = -0.01$	0.955
Reaction time to Odd (ms)	$\rho = 0.30$	0.140	$\rho = -0.48$	0.015*

*FTND, Fagerström test for nicotine dependance; CORE_AUDIT, The alcohol use disorder identification test; IPAQ, International Physical Activity Questionnaire; BMI, body mass index; Odd, auditory oddball paradigm; FC_FEF_NAcc, functional connectivity between the frontal eye field and nucleus accumbens; FC_IPS_PCG, functional connectivity between the intraparietal sulcus and precentral gyrus. *Uncorrected* $p < 0.05$.

TABLE 3 | Group comparison of FC by analysis of covariance (ANCOVA) controlling for confounding factors.

	Group effect of FC_FEF_NAcc		**Group effect of FC_IPS_PCG**	
Covariates	**Statistic**	***p***	**Statistic**	***p***
FTND, CORE_AUDIT	$F_{(1,21)} = 6.927$	0.002	$F_{(1,21)} = 6.850$	0.002
IPAQ (MET-minutes/week), IPAQ (kcal/day), BMI	$F_{(1,20)} = 4.909$	0.008	$F_{(1,20)} = 3.427$	0.031
Reaction time to Odd (ms)	$F_{(1,22)} = 9.998$	0.001	$F_{(1,23)} = 9.592$	0.001
FTND, CORE_AUDIT, IPAQ(MET-minutes/week), IPAQ (kcal/day), BMI and Reaction time to Odd (ms)	$F_{(1,16)} = 11.971$	0.003	$F_{(1,16)} = 7.146$	0.017

FTND, Fagerström test for nicotine dependance; CORE_AUDIT, The alcohol use disorder identification test; IPAQ, International Physical Activity Questionnaire; BMI, body mass index; Odd, auditory oddball paradigm; FC_FEF_NAcc, functional connectivity between the frontal eye field and nucleus accumbens; FC_IPS_PCG, functional connectivity between the intraparietal sulcus and precentral gyrus.

Zen, distinguishes *Budo* from other sports. This Zen spirit is substantiated in the training style of *Budo*. For example, in the case of *Kendo*, a regular training starts and concludes with a short period of meditation called "mokuso," during which individuals sit silently with their eyes closed (Labbate, 2011). Sport, in general, is likely to have positive effects on attentional processing. This might be due to increased recruitment of the motivation network when motivational drive is needed in response to attentional loads. In the case of *Budo*, and particularly with regard to its element of Zen, decreased recruitment of the motivation network during rest might represent a kind of preparation stage for efficient attentional processing, which could represent a "resting vs. attentionally-driven" contrast in terms of the integrity of the motivation network. This contrast between two states, that is, a resting vs. attentionally-driven state in motivation is consistent with a key concept of Zen, Fudoshin (unmoved mind), which was conceived by Takuan Soho, a Zen master priest (1573–1645). According to his writing "*The Unfettered Mind: Writings from a Zen Master to a Master Swordsman*" (Wilson and Takuan, 2012), an "unmoved mind" is a calm mental state, but with the potential to flexibly move at a moment's notice; these ideas have been interpreted in different ways. This resting vs. attentionally-driven contrast might explain another key concept of Zen, "Shinshin-ichinyo" (mind-body unity; Nakao and Ohara, 2014). An integrated mind-body training (which includes aspects of Zen, as well as those of physical exercise) by *Kendo* practice could lead to the development of the mind/body in a unified manner.

Only RTs of the oddball paradigm were correlated with FCs, during both rs-fMRI and task-based fMRI. These results suggest that smoking, alcohol, and exercise habits are not associated with FC differences between KPs and NKPs. RTs were shorter in the KP group than the NKP group and were negatively correlated with FC differences between the PCG and IPS during the oddball paradigm. This suggests that faster RTs indicate a stronger neural network integrity between the PCG and IPS. The between-group differences in FC were still significant after controlling for these potential confounding variables. The lack of any between-group difference in attention network integrity might be due to the simple structure of the oddball paradigm and the low cognitive demands in attention processing while performing this very basic task. In this sense, significant between-group differences in FC of the motivation network but not of the attention network in the current study would indicate a difference between KPs and NKPs in cognitive rewarding/motivational drive rather than a difference in attention processing at low cognitive demands.

Although the current results support the idea that *Kendo* brings health benefits, in the sense that strengthens the motivation network favorably, physical exercise, in general, might have negative impacts on mental health when training is excessive, such as "overtraining syndrome" (Kreher and Schwartz, 2012) or exercise dependance/sports addiction (Hausenblas and Downs, 2002). Given this potential effect on mental health, further investigations should be carried out to determine the appropriate quantity, quality, frequency, and intensity of *Kendo* training.

The current study has several technical limitations that should be considered. First, all participants were all male. Therefore, the results of the study cannot be generalized to women. Second, the sample size was relatively small. This could have resulted in a higher risk of type II errors, and so the results should be interpreted with caution. Future work could replicate the current study with a larger sample size. Third, we adopted a cross-sectional design. Considering the potential disadvantages of analyzing data from one time point, it is still unknown whether *Kendo* practice changes FCs in the motivation network or whether KPs have an innate trait of high FC in this network. A longitudinal follow-up study will be necessary to clarify the causal relationship between *Kendo* practice and FC changes within the motivation network and to clarify the specificity of *Kendo* effects on FC, while also considering the effects of other potential confounding variables not included in the present study. Fourth, due to the nature of exploratory studies, Bonferroni correction was not applied in FC analysis for multiple comparisons. However, this could have resulted in type 1 errors. Fifth, we did not examine the differences between any other sports or martial arts. Further studies are needed to clarify whether *Budo*/*Kendo* has specific effects or whether the results can be generalized to other fitness practices.

Finally, in addition to the above-mentioned limitations, the lack of behavioral correlates of brain parameters complicates the interpretation of our results. FC between the left IPS and left PDG during the oddball paradigm was negatively correlated with RTs, which might suggest that higher connectivity in the motivation network is advantageous in realizing higher attentional performance. However, the functional significance of the attenuated connectivity at rest in KPs is unclear, as no behavioral correlates were observed; nonetheless, our interpretation is that reduced connectivity at rest might help us attain favorable psychological states such as serenity. Follow-up studies that include relevant psychological or cognitive measures will be necessary to investigate this. In addition, physiological measures of the autonomic nervous system, such as heart rate and its variability, might also be useful.

In conclusion, we examined the effects of *Kendo* during rest and the oddball paradigm, focusing on the connectivity of the motivation network. We found a lower FC in rs-fMRI and a higher FC during attention-related paradigms. Our results suggest that the contrast between lower activities within the motivation network at resting state and the enhanced ones during the attentional task in KPs are indicative of a difference between KPs and NKPs in terms of motivational drive in attention processing. However, the results should be regarded as preliminary in light of the limitations mentioned above. Further studies with larger sample and a longitudinal study design are needed to verify the present findings. The integrated training of both mind and body, which is substantiated in *Budo*, including *Kendo*, might be applicable to a wide range of health-promoting programs for enhancing cognition and could also inform therapeutic programs for various psychiatric conditions, such as attention-deficit/hyperactive disorder.

ETHICS STATEMENT

The study was approved by the Ethics Committee of the Kyoto University Graduate School and Faculty of Medicine and was conducted in accordance with the Declaration of Helsinki.

AUTHOR CONTRIBUTIONS

HF conceived, designed, and conducted the experiments, acquired and analyzed the data, and drafted the manuscript. TMu, TU, and HF contributed to the conception of the study, interpretation of data, and revisions for critically important intellectual content. KK, SY, TMi, and NO contributed to the design and data acquisition, interpretation of data, and drafting the manuscript. All authors approved the final manuscript for submission and agree to be accountable for all aspects of the work, including the assurance that questions related to the accuracy or integrity of any part are appropriately investigated and resolved.

FUNDING

This project was funded by Grant-in-Aid for Scientific Research on Innovative Areas (Ministry of Education, Culture Sports, Science and Technology, Japan, project numbers: 16H06402, 16H06395, and 16H06397), Grant-in-Aid for Scientific Research (C; Japan Society for The Promotion of Science, 16K01790), Daiwa Securities Health Foundation, the Nakatomi Foundation, and the Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT), Program of the Council for Science, Technology and Innovation (Cabinet Office, Government of Japan, 2015-PM11-08-01).

ACKNOWLEDGMENTS

We thank Nia Cason, PhD, from Edanz Group (www.edanzediting.com/ac) for editing a draft of this manuscript.

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

ORIGINAL RESEARCH
published: 11 June 2019
doi: 10.3389/fnhum.2019.00181

Ability-Based Emotional Intelligence Is Associated With Greater Cardiac Vagal Control and Reactivity

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Several distinct models of emotional intelligence (EI) have been developed over the past two decades. The ability model conceptualizes EI as a narrow set of interconnected, objectively measured, cognitive-emotional abilities, including the ability to perceive, manage, facilitate, and understand the emotions of the self and others. By contrast, trait or mixed models focus on subjective ratings of emotional/social competencies. Theoretically, EI is associated with neurobiological processes involved in emotional regulation and reactivity. The neurovisceral integration (NVI) model proposes a positive relationship between cardiac vagal control (CVC) and cognitive-emotional abilities similar to those encompassed by EI. The current study examined the association between CVC and EI. Because ability EI is directly tied to actual performance on emotional tasks, we hypothesized that individuals with higher ability-based EI scores would show greater levels of CVC at rest, and in response to a stressful task. Because mixed-models of EI are not linked directly to observable emotional behavior, we predicted no association with CVC. Consistent with expectations, individuals with higher levels of ability EI, but not mixed EI, had higher levels of CVC. We also found that individuals with greater levels of CVC who demonstrated reactivity to a stress induction had significantly higher EI compared to individuals that did not respond to the stress induction. Our findings support the theoretically expected overlap between constructs within the NVI model and ability EI model, however, the observed effect size was small, and the associations between EI and CVC should not be taken to indicate a causal connection. Results suggest that variance in the ability to understand emotional processes in oneself and to reason about one's visceral experience may facilitate better CVC. Future work manipulating either CVC or EI may prove informative in teasing apart the causal role driving their observed relationship.

Keywords: cardiac vagal control, emotional intelligence, mixed emotional intelligence, ability emotional intelligence, heart rate variability, stress, autonomic control, emotion regulation

OPEN ACCESS

Edited by:
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Received: *31 January 2019*
Accepted: *20 May 2019*
Published: *11 June 2019*

Citation:
Vanuk JR, Alkozei A, Raikes AC, Allen JJB and Killgore WDS (2019) Ability-Based Emotional Intelligence Is Associated With Greater Cardiac Vagal Control and Reactivity. Front. Hum. Neurosci. 13:181. doi: 10.3389/fnhum.2019.00181

INTRODUCTION

Emotion and cognition represent a dynamic system involved in a reciprocal relationship. Their interplay is proposed to facilitate social adaptation, thus facilitating the optimization of health, and behavior (Lazarus, 1991). The facilitation and balance between emotion and cognition are thought to be a unique set of abilities, separate from general intelligence (IQ), and conceptualized as emotional intelligence (EI) (Salovey and Mayer, 1990). EI has been defined in a number of ways but is generically described as the awareness and understanding of emotional information relating to oneself and others, and the ability to use that information to facilitate goal-oriented behavior (Payne, 1985; Mayer and Geher, 1996; Goleman, 2006; Smith et al., 2018). The concept of EI has been defined by multiple authors, to index the degree to which emotion relates to adaptive human behavior and social engagement (Bar-On, 2004; Extremera and Fernández-Berrocal, 2005; Pérez et al., 2005; Seal et al., 2009).

Two main models for quantifying EI for research purposes have emerged from previous work and are proposed as either purely "performance ability" or "trait" based (Bar-On, 1997; Mayer et al., 2008). The ability model postulates EI as a narrow construct and uses objective performance-based testing as a means of quantification, whereas trait models theorize that it is a broader skill set and have become known as mixed-models of EI (Mayer et al., 2002; Bar-On, 2004; Gutiérrez-Cobo et al., 2016). The Mayer-Salovey-Caruso Emotional Intelligence Test (MSCEIT) is the most widely used performance-based ability model test and encompasses a variety of skills and abilities related to emotional processing, such as the ability to use emotions purposefully, distinguish emotional cues, and deliberately use emotions when having to make decisions (Mayer et al., 2001; Brackett et al., 2006). The model proposes a hierarchy of performance based on the quality of responses to a variety of emotion-focused problems. As an ability measure, the MSCEIT comprises a series of tasks that assess discrete emotional skills such as the ability to recognize emotions in visual stimuli such as faces and photographs, the ability to regulate and manage emotions in various contexts, and the ability to solve emotional problems. On the other hand, the Bar-On emotional quotient inventory (EQ-i) is one of the most widely used self-report instruments assessing mixed model EI (Bar-On, 2004). The Bar-On model, and other mixed approaches, generally conceive of EI as a set of stable social and emotional competencies of which the individual is self-aware and that are assessed via self-report statements (Petrides and Furnham, 2001). An alternative conceptualization of EI that has gained attention for its potential to foster a more holistic theory of EI calls for a multi-level model and the integration of a behavioral level of EI relating it to social and professional outcomes (Boyatzis, 2018). A multi-level approach will undoubtedly propel our understanding of EI as a unique and specific construct relating to cognition and behavior. However, the time and resource demands of the qualitative methodology inherent to this type of assessment of EI capacities has been a barrier to its larger scale dissemination and application in research. As such, practitioners wishing to assess EI find themselves having to consider not only theoretical orientations but the resources necessary to adequately assess the capacity (Boyatzis, 2018). Despite more than two decades of intensive research, there continues to be a wide-ranging debate about the construct validity of the various models of EI and how such models relate to cognition (Mayer et al., 2001; Locke, 2005; Alkozei et al., 2018).

It is well accepted that effective emotion regulation strategies contribute to wellbeing and positive mental health outcomes. Higher levels of EI are particularly strong predictors of mental health outcomes and also associated with better physical health (Martins et al., 2010; Fernández-Abascal and Martín-Díaz, 2015). Interestingly, mixed and ability measures of EI are often poorly correlated with one another and predict different aspects of health (Webb et al., 2013). For example, higher mixed EI has been associated with increased well-being, yet attempts to replicate this association with ability tests have been unsuccessful (Furnham and Petrides, 2003; Zeidner and Olnick-Shemesh, 2010). Higher levels of mixed EI may also protect against emotion dysregulation and facilitate greater quality in social interactions (Lopes et al., 2005). Individuals with higher levels of mixed EI demonstrate increased resilience against decrements in personally relevant moral-judgment decisions while sleep deprived, without significant changes for other moral domains (Killgore et al., 2007). Both mixed and ability model scores demonstrate a positive association with accuracy in recognizing emotional facial expressions (Petrides and Furnham, 2003; Wojciechowski et al., 2014). There is a high correlation between mixed EI and job performance, however, well-established measures of knowledge, skills, abilities, and other characteristics offer significant incremental prediction beyond measures of mixed EI (Joseph et al., 2015). The mixed findings for the two models underscore the notion that associations between EI as a quantified measure are dependent on several factors, including cognition, the testing modality, and the degree of emotional content inherent to the endeavor. A growing body of work demonstrates a distinction between cognitive tasks that are emotionally neutral, as opposed to those containing affective stimuli, conceptualized as utilizing "hot" or "cool" cognitive processes (Metcalfe and Mischel, 1999). A recent systematic review of studies showed that ability, but not mixed, EI correlated positively with task performance that required "hot" cognitive processes, while studies investigating the relationship between EI metrics, and "cool" cognitive processes failed to produce any positive associations (Gutiérrez-Cobo et al., 2016). Based on their findings, the authors concluded that current ability and mixed model conceptualizations of EI are only relevant for tasks that require affective processing and that the MSCEIT is the only current ability or mixed model based EI measure that reliably predicts increased performance on affective cognitive tasks.

Emotional functioning depends on a dynamic interplay of the central nervous system and the autonomic nervous system. A fundamental component of the parasympathetic branch of the autonomic nervous system critical to mind-body interactions is cardiac vagal control (CVC), which provides a reliable marker for emotional health (Porges, 1995). Measures of CVC, such as heart rate variability (HRV), are considered representative of interindividual differences in parasympathetic efferent control of cardiac rate, which when high promotes adaptive emotional responding and regulation that underlie physical, and mental health (van Ravenswaaij-Arts et al., 1993; Acharya et al., 2007; Beauchaine and Thayer, 2015). Optimal cardiac reactivity demonstrates tightly coupled reciprocal responsiveness between the sympathetic and parasympathetic systems in reaction to environmental demands (Mccabe et al., 2000). The Polyvagal theory posits that CVC is responsible for higher-order functions in mammals, from a phylogenetic perspective, by facilitating emotion regulation, and promoting social engagement (Porges, 1995). Individual differences in CVC reactivity predict vulnerability to stress, along with positive outcomes in communication, attention, and the regulation of emotion (Suess et al., 1994; Porges, 1995; Thayer and Lane, 2000; Appelhans and Luecken, 2006). A substantial body of work demonstrates associations between low levels of resting and reactive CVC with multiple forms of internalizing and externalizing psychopathology (Kemp and Quintana, 2013; Shahrestani et al., 2014; Beauchaine, 2015). Greater CVC reactivity buffers against the development of psychopathology and health problems (El-Sheikh et al., 2001). Increases in CVC are related to optimal outcomes in the treatment of major depression and have been suggested as a target for anxiety interventions (Chambers and Allen, 2002; Chalmers et al., 2014).

Cardiac vagal control is important in a wide range of situations that demand effective cognitive-emotional regulation through coordination of biological systems. The degree of influence CVC has over the central autonomic network is thought to rely on prefrontal inhibition, and the neurovisceral integration (NVI) model proposes that the dynamic system contributing to autonomic control involves a negative feedback system guided by attention regulation and affective processing (Thayer and Lane, 2000). The central autonomic network demonstrates a positive relationship between CVC modulation and increased cognitive-emotional abilities that are similar to EI and is predictive of positive behavioral health outcomes in mood disorders, such as depression (Friedman, 2007). Since its initial conception, the NVI model has gained considerable empirical support relevant to positive behavioral health outcomes, and recent work has extended NVI model to a hierarchical model involved in predictive cognitive coding computations (Smith et al., 2017). Cognitive coding computations are critical during early development and are vital to learning and the comprehension of knowledge (Clark and Paivio, 1991). Children with higher levels of resting HRV have higher capacities for sustained attention and higher attention span/persistence in early childhood; which contribute to cognitive development and higher educational attainment (Suess et al., 1994; McClelland et al., 2013). Increased performance in high-stress environments such as sports competition is also linked to greater ability to regulate emotions, as well as resting CVC and its modulation (Crombie et al., 2009; Plews et al., 2012). The use of biofeedback to enhance CVC control is related to improvements in emotional health in the workplace as well as better performance in competitive environments where high levels of stress are inherent (McCraty et al., 2003; Holden, 2006). Favorable results related to increases in resting CVC recovery following a stressor after targeted biofeedback training have been shown to occur and contribute to positive outcomes related to anxiety and emotion regulation (McCraty et al., 1999; Thurber et al., 2010).

Chronic stress and the inability to regulate emotions are associated with maladaptive physiology, mental health, and have a critical impact on multiple aspects of well-being (Chrousos, 2000). Higher levels of ability-based EI predict greater CVC reactivity during more intense emotional experiences (Rash and Prkachin, 2013). Self-report mixed EI metrics also predict positive outcomes and better cardiac responsiveness during stress (Bar-On et al., 2006). Athletes with higher levels of mixed EI have lower levels of CVC reactivity during high-stress competitive environments (Laborde et al., 2011). However, this must be considered in light of the fact that athletes demonstrate atypical autonomic reactivity compared to less physically fit individuals and have significantly higher levels of self-esteem and social connectedness (Koivula et al., 2002; Plews et al., 2012). In conclusion, studies investigating the relationship between the different conceptualizations of EI, CVC, and its reactivity to stress demonstrate consistent positive associations between EI and CVC; but no study to date has investigated this relationship incorporating two of the most widely used and validated measures of mixed and ability EI simultaneously.

To address the current gap in literature associating CVC and EI, we examined the influence of both ability EI and mixed EI on CVC during rest and in response to a potentially stressful task. Since CVC reactivity is linked to flexibility in emotion regulation and ability-based metrics are most representative of cognitive control, likely extending to EI, then individual differences in EI are expected to be related to CVC modulation during stress. In light of prior evidence, three general hypotheses were tested. First, we hypothesized that individuals with higher levels of ability EI would have greater levels of CVC at rest, and if so by the perceiving and understanding domains that are less likely to incorporate acute CVC reactivity. Second, we hypothesized that individuals with higher levels of ability EI would have greater decreases in CVC in response to stress and greater subsequent increases during recovery, and if so, these would be driven by the managing and using domains, which may be more likely to be utilized in contexts requiring CVC reactivity. Finally, we hypothesized that cardiac metrics that are less specifically sensitive to vagally mediated influences (i.e., sensitive to some extent also to sympathetic influences) would not demonstrate the same associations with EI as CVC metrics that reflect primarily parasympathetic influence.

MATERIALS AND METHODS

Participants

One hundred thirty-five healthy adults (87 females) were recruited from the local community via internet, newspaper, radio, and flyer advertisements for the present study. A power analysis modeled on previous work investigating CVC and emotional dispositions suggested that effect sizes were small to medium (Pearson's r ranged from 0.21 to 0.38) (Oveis et al., 2009). Therefore, for the proposed study, we applied the mean effect size ($r = 0.29$) to estimate power to detect individual differences. That power analysis showed that with $\alpha = 0.05$ (2-tailed), a sample of $n = 88$ should provide adequate power ($1-\beta = 0.8$) to detect individual differences to be established by CVC characteristics, which was less than the minimum number of individuals to be recruited for a subsequent study sharing a recruitment effort with the present study. Participants were between the ages of 18–40. Because of the high reading and cognitive demands of the tasks, participants were required to have an English reading proficiency of 8th grade or higher as defined by the WRAT4 Reading subtest and were also screened to exclude individuals with impaired reading comprehension, and altered mental status or capacity, due to medications, substances, cognitive status, injury, or medical conditions that could influence the outcome of psychological assessment.

Participants were excluded from analyses if they took medication with a mechanism of action that influences cardiac reactivity (21 participants, see **Supplementary Appendix A** for a list of medications) or had unusable EKG data (8 participants). Four participants failed to have their EQi recorded and were also removed from analyses. The final sample for analyses included 102 individuals (64 females, mean age = 22.8 years, *SD* = 4.4). All participants had a high school diploma or equivalent, 91.2% of participants completed some college, 28.4% of participants had a Bachelor's degree or higher. 54.9% of participants were Caucasian, 21.6% were Hispanic/Latino, 12.7% were Asian/Pacific Islander, 4.9% were African American, and 5.9% reported ethnicity as "other."

All participants provided written informed consent before enrollment. The study protocol was approved by the Institutional Review Boards of the University of Arizona and the U.S. Army Human Research Protections Office.

Apparatus and Materials

Psychological Assessment

The Mayer-Salovey-Caruso Emotional Intelligence Test II (MSCEIT) was used to assess ability-based EI and evaluates a number of specific skills and abilities related to reasoning about and regulating emotional processes (Mayer et al., 2003). The MSCEIT is a 141-item performance test requiring subjects to identify emotions in faces and designs, to specify emotions or feelings that interfere with or facilitate specific thought processes, demonstrate an understanding of how various emotions combine to create higher-order emotions and how these blends may change over time, as well as demonstrate knowledge of how specific emotional management strategies will lead to various consequences in oneself and others. The test yields a total EI score, two area scores (experiencing and strategic), and four branch scores (perceiving, using, understanding, and managing); derived from eight task-level scores. The area scores are specific to the ability to recognize emotions and determine how they interact with a thought or understand emotional meanings relative to others and manage them. The branch scores are specific to the ability to identify emotions, facilitate thought using emotions, understand emotions, and manage emotions. The MSCEIT has been found to have adequate reliability (split-half reliability overall = 0.91) and good discriminant and convergent validity (Mayer et al., 2002).

Mixed EI was assessed using the *Bar-On EQ-I 2* (EQi), a self-report inventory designed to evaluate the construct of EI and the underlying factors that contribute to emotionally intelligent behavior (Bar-On et al., 2006). The EQi is a 133-item self-report measure using short sentences (e.g., "I am good at reading other people's emotions") and a 5-point Likert response scale ranging from (1) "very seldom or not true of me" to (5) "very often true of me or true of me." The measure provides several scores, including a general metric of total EI and five composite scales (self-perception, self-expression, interpersonal, decision making, stress management), assessing various features of mixed EI. The EQi has been found to have good discriminant and convergent validity, as well as very high reliability (internal consistency = 0.97) (Bar-On, 2004).

Physiological Assessment

Physiological data were recorded using a Zephyr Biopatch[1] with conductive adhesive hydrogel foam electrodes. The device was placed at the sternum, and the ECG signal was sampled at 1000 Hz, which is above the minimum suggested sampling frequency (Camm et al., 1996). Off-line analysis was performed by extracting the inter-beat interval (IBI) series from the raw digitized ECG signal using QRSTool Software (Allen et al., 2007).

Procedure

After providing informed consent, participants underwent an ECG reactivity assessment that entailed two five-minute resting periods separated by a 90-s cognitive challenge as a stress induction (serial subtraction) (Tomaka et al., 1994; Seraganian et al., 1997). During resting periods, participants were instructed to sit quietly without talking or moving while focusing on a fixation cross positioned in front of them. During the stress induction, participants were asked to count backward by 17, starting from 1,025, as quickly as possible. Participants were provided pre-recorded auditory feedback contingent on their performance via an E-Prime program[2], controlled by a research technician. To maximize the stress induction, participants were instructed to begin again if they made an error in their subtraction, or that they needed to go faster and to start again if they reached predetermined points without error. Participants completed all psychological measures, including the MSCEIT and EQi, subsequent to the ECG reactivity assessment.

Physiological Data Reduction and Variable Selection

The extracted IBI series were hand corrected by a trained and experienced technician to eliminate artifacts such as ectopic, erroneous, and missed beats (Berntson et al., 1990). Data were processed using Matlab (version 2015B[3]) with parameters modeled on those of CMetX Cardiac Metric Software (Allen et al., 2007), with the additional incorporation of a moving window. The moving window used 30-s segments that shifted by 3-s at a time. Estimates of multiple metrics of cardiac chronotropy were derived using the extracted time series. The moving window approach ensures that variance estimates from a non-stationary time series (as is almost always the case with interbeat-interval data) are not inflated by recording length. The mean value across all 30-s epochs was taken for each metric as the final value to be used in analyses.

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[1] https://www.zephyranywhere.com/media/download/zephyr-performance-biopatch-hp-brochure.pdf

[2] https://pstnet.com/products/e-prime/

[3] https://www.mathworks.com

CVC Variable Selection and Estimates

Increased influence of the vagus nerve on heart rate leads to larger variance in the time interval between heartbeats; a phenomenon classified HRV. HRV is widely accepted as representative of CVC and is sensitive to both the parasympathetic and sympathetic influences of the autonomic nervous system, but it reflects predominantly parasympathetic influences when individuals are at rest (Allen et al., 2007; Kromenacker et al., 2018). The root mean square of successive differences (RMSSD) is another time-domain measure proposed to quantify the parasympathetic nervous system's impact on HRV (Von Neumann, 1941; Malik et al., 1996). The Polyvagal theory proposes respiratory sinus arrhythmia (RSA) as a measure of CVC, indexing the magnitude of respiratory-linked changes in HRV (Porges, 1995). Individual differences in RMSSD are associated with similar outcomes as RSA, such as susceptibility to cardiovascular disease, but more sensitive to low-frequency HRV contributions that can represent a combination of parasympathetic and sympathetic influences on HRV (Berntson et al., 2005; Thayer et al., 2010; Kromenacker et al., 2018). While RSA is the gold standard in the non-invasive quantification of parasympathetic control, it is still an imperfect index of CVC, as it is susceptible to the influence of respiration (Grossman et al., 1991; Allen et al., 2007). RMSSD is less sensitive to the impact of slow respiration and individuals breathing outside the targeted range, but debate remains regarding the underlying influence on this time domain metric (Hill et al., 2009). Previous work shows high correlations between RSA and RMSSD (*r*'s = 0.85–0.91*)* but RSA has higher correlations with HRV ($r = 0.90$) than RMSSD ($r = 0.84$) (Berntson et al., 2005; Kleiger et al., 2005; Allen et al., 2007).

Respiratory sinus arrhythmia was estimated by calculating HRV in the high-frequency band that captures respiratory-related changes in the timing of heart beats (0.12–0.4 Hz). The IBI series was converted to a time series sampled at 10 Hz with linear interpolation and a 241-point optimal finite impulse response digital filter designed using FWTGEN V3.8 (Cook and Miller, 1992) with half amplitude frequencies of 0.12–0.4 Hz. RSA is the natural log of the variance of this filtered time series. HRV is the natural log of the variance of the unfiltered time series. RMSSD was also quantified as a measure of CVC, to be utilized in the event the RSA metric was compromised by individuals with a peak frequency of respiration below 0.12 Hz. An estimate of RMSSD was derived using the root mean square of successive differences in the IBI time series across each moving window. An index of respiration rate was obtained using a fast Fourier transform on the IBI series, and the dominant frequency in the power spectrum of the respiration waveform was inspected to ensure the rate did not fall below 0.12 Hz, which invalidates the estimate of RSA for such segments (Grossman and Taylor, 2007). During the resting baseline period, 77.2% of individuals had max power frequencies that fell below 0.12 Hz. Due to this problem, which invalidated the RSA measure in the majority of subjects, all analyses targeting CVC were conducted using RMSSD rather than RSA. CVC estimates represent mean levels during each unique condition (i.e., during the baseline resting period, during the stressor, and during the post-stress recovery resting period).

MSCEIT Scoring

Raw data from the MSCEIT were scored by the Multi-Health-Systems using consensus scoring adjusted for age and gender. Consensus scoring is based on the concept that general consensus should identify the optimal answer to the majority of emotion-based questions, as emotions are evolved signals that require the majority of the group to understand and accept as valid/accurate (Mayer et al., 2003).

Statistical Analysis

All statistical tests used an *a priori* significance level of $p \leq 0.05$. Inspection of skewness, kurtosis, and the Shapiro-Wilk test indicated non-normal distributions among multiple variables. Due to deviations from normality and the presence of heteroscedasticity, log transformations of variables of interest were employed. However, as some variables of interest still failed to achieve normality assumptions, optimal model parameters were identified using akaike's information criterion (AIC) penalized-likelihood criteria, and the optimal model parameters reported utilized employed fixed variances and separate covariances with restricted maximum likelihood estimation.

Software and packages utilized

All statistical analyses were performed using R (version 3.5.1[4]). Correlation analyses were performed using the *hmisc* package (Harrell, 2018). Linear regression model assumptions were interrogated and ensured to have been met using the *gvlma* package (Pena and Slate, 2014). Linear models were analyzed utilizing the *nlme* and *predictmeans* packages (Luo et al., 2014; Pinheiro et al., 2014). Penalized likelihood criteria were analyzed using the *glmnet* package (Friedman et al., 2010). Hierarchical agglomerative clustering was conducted using the *FactoMineR* package (Lê et al., 2008; Wickham, 2016). Stepwise variable selection was implemented using the stepAIC function in the MASS package (Ripley, 2002). Figures and tables were generated using the *corrplot* and *ggplot2* packages (Wei and Simko, 2013; Lüdecke, 2018).

Zero-order correlation analysis

Bivariate Spearman correlations were performed across all subjects for age, total EI scores, and cardiovascular variables for resting baseline, stress reactivity and recovery indices (change in RMSSD from the prior level). EI subscale correlations are presented in the **Supplementary Material S3**.

EI predicting baseline CVC

A simple linear regression model was used to predict baseline cardiac metrics, based on the total score of each EI measure. Outcomes and predictors were log transformed [$y' = \log(y)$] after the initial model failed to meet the model assumptions of skewness, kurtosis, and heteroscedasticity. Model assumptions were satisfied utilizing the log-transformed variables. To identify which EI subscale drove potential significant effects, a multiple linear regression model was fit using all sub scale scores from the unique EI metric and an automated forward and backward stepwise variable selection method simplified the model to limit multi-collinearity between predictors.

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[4] https://www.r-project.org

Physiological response to serial subtraction

A linear mixed model for repeated measures over time using generalized least squares was used to investigate changes in RMSSD in response to the serial subtraction task and subsequent recovery following the stress induction.

EI predicting change in CVC across conditions

The identified optimal parameters for the linear mixed models assessing RMSSD across time were used to investigate the main effect and interactions for EI measures and RMSSD levels across the stress induction and recovery conditions using RMSSD as the dependent variable and condition, total ability EI, and total mixed EI scores as predictors. AIC penalized-likelihood criteria was used to determine if the addition of the EI total scores in a main effect or interaction model had a significant influence beyond the simpler model with only condition (e.g., resting baseline, stress induction, and resting recovery levels), as a predictor.

Investigating potential influential covariates

Akaike's information criterion penalized-likelihood criteria was used to determine if covariates of interest had a significant influence on the models with a least absolute shrinkage and selection operator (LASSO) regression analysis using baseline RMSSD as an outcome variable and gender, age, caffeine consumption that day, and time of day as predictors. Regression models were rerun, accounting for the identified covariates of influence, to investigate potential increases in the total variance accounted for within the models and compared to the simpler model using AIC penalized-likelihood criteria.

Exploring individual differences in CVC in response to stress and recovery

To investigate potential group level effects associated with individual differences in CVC, a principal components analysis (PCA) in conjunction with hierarchical agglomerative clustering was employed across RMSSD at rest, stress induction, and recovery. Initial analyses investigating between-group effects were conducted using *t*-tests. However, residuals were not normally distributed, so non-parametric two-tailed Mann-Whitney *U* tests were utilized for group-level analyses examining associations CVC responsiveness to stress induction and EI variables.

Secondary analyses

Additional secondary analyses on HRV and HR are presented in the **Supplementary Materials**, including statistical methods and results. See **Supplementary Material S1** and **Supplementary Tables S2, S3, S6, S7**.

RESULTS

Descriptive Statistics and Correlations

Table 1 presents descriptive statistics, means, and associated standard deviations for the demographic, EI, and physiological variables.

TABLE 1 | Descriptive statistics of the sample.

Measure	Mean	St. Dev.
Age	22.78	4.39
Baseline RMSSD	32.74	19.64
Stress induction RMSSD	26.81	13.40
Stress recovery RMSSD	33.61	17.94
Baseline HRV	7.26	0.98
Stress induction HRV	7.49	0.84
Stress recovery HRV	7.30	0.90
Baseline HR	84.63	11.15
Stress induction HR	95.20	13.91
Stress recovery HR	83.27	11.48
EQi total	102.79	12.62
EQi interpersonal branch	105.78	13.62
EQi decision making branch	101.85	12.80
EQi stress management branch	104.84	12.30
EQi self perception branch	101.46	13.46
EQi self expression branch	97.64	14.10
MSCEIT total	107.97	12.52
MSCEIT perceiving branch	110.16	12.81
MSCEIT using branch	106.93	13.48
MSCEIT understanding branch	111.84	18.92
MSCEIT managing branch	100.97	11.79

RMSSD, root mean square of successive differences; HRV, heart rate variability; HR, heart rate; EQi, Bar-On EQ-I 2; MSCEIT, Mayer-Salovey-Caruso Emotional Intelligence Test II; St. Dev., standard deviation.

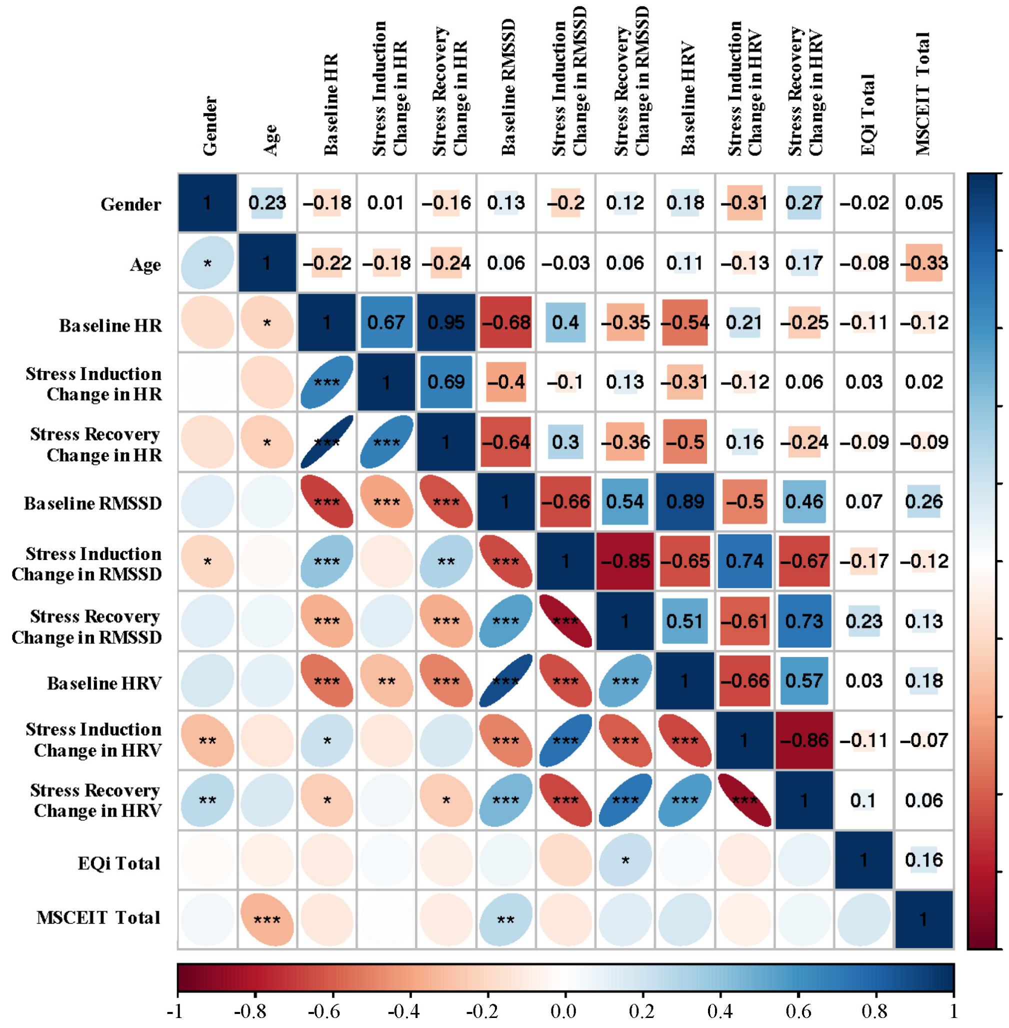
Full Sample Zero-Order Correlations

Figure 1 presents bivariate correlations assessing relationships among RMSSD, HRV, and HR at baseline resting levels, and stress reactivity and recovery indices (change in RMSSD from the prior level), with age, depression, and total EI scores across the total sample. Baseline RMSSD showed positive associations with the MSCEIT total score. Total mixed EI had a positive association with change in RMSSD from stress induction to recovery. No associations were observed for HRV or HR at baseline, change after stress, or after recovery. Age had a negative association with the MSCEIT total score, as well as baseline and recovery levels of HR; however, age had a high degree of positive skew. None of the observed associations remained significant after Bonferroni correction for multiple comparisons.

EI Predicting Baseline CVC

EI and RMSSD

Total ability EI was a significant predictor for baseline RMSSD, $F(1,99) = 4.60$, $p = 0.03$, (**Figure 2A**). The observed effect was driven by the understanding branch of ability EI, $F(1,100) = 3.89$, $p = 0.05$, which was not significantly associated with baseline RMSSD as an independent predictor. In contrast to ability EI, total mixed EI was not a significant predictor of baseline RMSSD, $F(1,99) = 0.26$, $p = 0.61$ (**Figure 2B**). HRV and HR during the baseline resting condition were not significant predictors of EI (**Figure 2C–E**). See **Supplementary Table S1** for RMSSD model coefficients, sums of squares, and partial eta-squared.



	Gender	Age	Baseline HR	Stress Induction Change in HR	Stress Recovery Change in HR	Baseline RMSSD	Stress Induction Change in RMSSD	Stress Recovery Change in RMSSD	Baseline HRV	Stress Induction Change in HRV	Stress Recovery Change in HRV	EQi Total	MSCEIT Total
Gender	1	0.23	−0.18	0.01	−0.16	0.13	−0.2	0.12	0.18	−0.31	0.27	−0.02	0.05
Age	*	1	−0.22	−0.18	−0.24	0.06	−0.03	0.06	0.11	−0.13	0.17	−0.08	−0.33
Baseline HR		*	1	0.67	0.95	−0.68	0.4	−0.35	−0.54	0.21	−0.25	−0.11	−0.12
Stress Induction Change in HR			***	1	0.69	−0.4	−0.1	0.13	−0.31	−0.12	0.06	0.03	0.02
Stress Recovery Change in HR		*	***	***	1	−0.64	0.3	−0.36	−0.5	0.16	−0.24	−0.09	−0.09
Baseline RMSSD			***	***	***	1	−0.66	0.54	0.89	−0.5	0.46	0.07	0.26
Stress Induction Change in RMSSD	*		***		**	***	1	−0.85	−0.65	0.74	−0.67	−0.17	−0.12
Stress Recovery Change in RMSSD			***		***	***	***	1	0.51	−0.61	0.73	0.23	0.13
Baseline HRV			***	**	***	***	***	***	1	−0.66	0.57	0.03	0.18
Stress Induction Change in HRV	**		*			***	***	***	***	1	−0.86	−0.11	−0.07
Stress Recovery Change in HRV	**		*		*	***	***	***	***	***	1	0.1	0.06
EQi Total								*				1	0.16
MSCEIT Total		***				**							1

FIGURE 1 | Bivariate Spearman correlations performed across all subjects with correlation coefficients in the upper portion of the matrix and significant correlations identified in the lower portion of the matrix. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. RMSSD, root mean square of successive differences; HRV, heart rate variability; EQi, Bar-On EQ-I 2; MSCEIT, Mayer-Salovey-Caruso Emotional Intelligence Test II.

Physiological Response to Serial Subtraction

A linear mixed model was utilized to assess the response to the serial subtraction task and subsequent recovery following the stress induction. As expected, the model demonstrated that participants showed significant reductions in RMSSD during the stress induction and significant increases during recovery relative to baseline levels, $F(2,303) = 9.55$, $p < 0.0001$. See **Supplementary Table S4** for model coefficients, sums of squares, and partial eta-squared.

EI Predicting Change in CVC Across Conditions

Total ability EI and total mixed EI scores were both incorporated into the physiological response to serial subtraction linear mixed model to assess whether EI could account for changes in RMSSD during stress induction or recovery conditions; beyond the associations observed for RMSSD during the baseline resting condition. There was no significant main effect of total ability EI and RMSSD with condition, $F(1,301) = 2.03$, $p = 0.08$ or total mixed EI and RMSSD with condition, $F(1,301) = 0.80$, $p = 0.54$. No significant interactions between EI and stress induction or recovery conditions were observed for ability EI, $F(2,294) = 0.86$, $p = 0.42$, or mixed EI, $F(2,294) = 1.95$, $p = 0.14$. The addition of total EI scores was not favored over the simpler model only including RMSSD and condition, for the main effect $L.Ratio = 3.24$, $p = 0.20$, or interaction $L.Ratio = 11.85$, $p = 0.22$. See **Supplementary Table S5** for model coefficients, standard errors, and beta values.

Investigating the Potential Influence of Covariates

Gender and caffeine use were tested as potentially influential covariates affecting CVC during rest, based on prior literature (Allen et al., 2007). The combination of both covariates

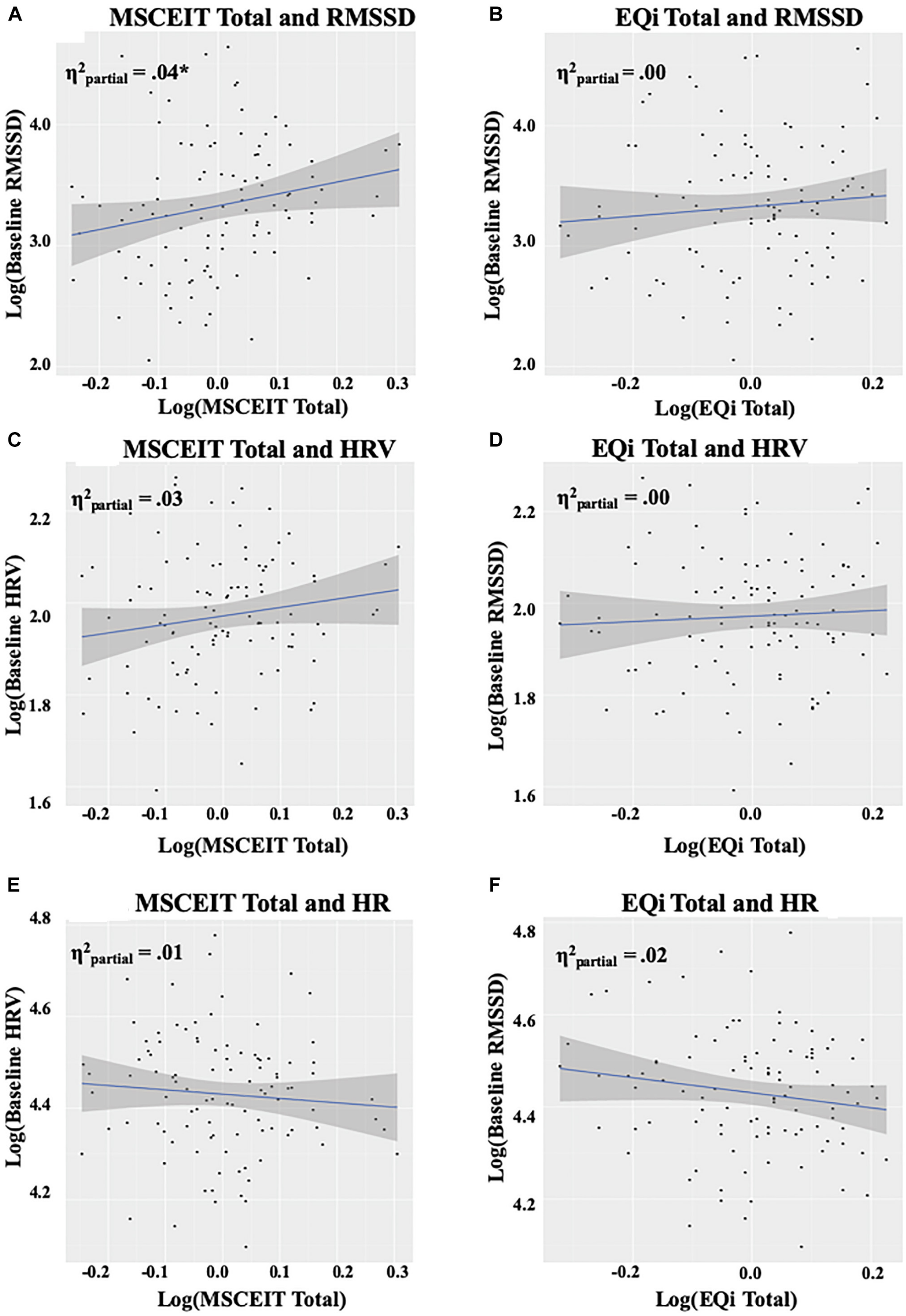


FIGURE 2 | Panels **(A,B)** depict the relationship between EI measures and RMSSD at baseline, panels **(C,D)** depict the relationship between EI measures and HRV at baseline, and panels **(E,F)** depict the relationship between EI measures and HR at baseline. The intercept reflects levels at baseline, and the shaded area represents the 95% confidence interval. Plots and values are displayed on a log scale reflecting the data transformations utilized to meet model assumptions. RMSSD, root mean square of successive differences; HRV, heart rate variability; HR, heart rate; EQi, Bar-On EQ-I 2; MSCEIT, Mayer-Salovey-Caruso Emotional Intelligence Test II; η^2_{partial}, partial eta-squared. *$p < 0.05$.

was not favored over the simpler model main effect model only including RMSSD and EI, *nor was their* addition independently. See **Supplementary Material S2** for model comparison statistics.

Exploring Individual Differences in CVC in Response to Stress and Recovery

CVC Reactivity Cluster Identification

The principal components analysis identified two components that accounted for 97.93% of the cumulative percentage of variance in RMSSD across conditions. Hierarchical agglomerative clustering classified three unique groups based on CVC (**Figure 3A**). Due to the large variance in the sample sizes between the clusters identified ($n = 53$, $n = 39$, and $n = 10$), the two unique groups that had similar decreases in RMSSD during stress and subsequent increases during the recovery were collapsed to form two groups with comparable sample sizes to assess differences in CVC responsiveness [i.e., CVC-non-responders ($n = 53$) and CVC-responders ($n = 49$)] (**Figure 3B**). **Table 2** presents initial group descriptive statistics, means, and associated standard deviations for the demographic, EI, and physiological variables. **Table 3** presents the collapsed groups descriptive statistics, means, and associated standard deviations for the demographic, EI, and physiological variables.

CVC Responsiveness to Stress Predicting EI

Compared to CVC-non-responders, individuals that experienced decreases in RMSSD during the stress induction condition and subsequent increases during recovery had significantly higher levels of total ability EI (W = 891, $p = 0.01$). The association was not driven by a specific subscale. There were no significant differences between groups for total mixed EI (W = 1105.5, $p = 0.26$). See **Supplementary Table S8** for model coefficients, group means, and standard deviations.

DISCUSSION

In this study, we investigated the relationship between EI, as measured by two alternate theoretical models, and CVC under resting and reactive conditions. Based on prior findings, we hypothesized that higher ability EI would be associated with higher levels of CVC. Overall, we found support for this hypothesis, although with some qualifications. We discuss these findings and their implications in detail below.

Primary Hypotheses

First, we hypothesized that individuals with higher levels of ability EI would have greater levels of CVC at rest. This hypothesis was supported, as individuals with higher levels of CVC at rest indeed had significantly higher levels of total ability EI, whereas no association was found with total mixed EI. Contradictory to expectations, higher levels of understanding emotions and the ability to perceive emotions were not significantly associated with resting CVC, even though understanding emotions was found to drive the association with total ability EI. This may be because the ability to perceive emotions is more specific to affective processing and the ability to self-regulate in environments eliciting more personally relevant emotion-specific contexts (Rash and Prkachin, 2013). The only other study investigating ability EI and CVC did not find any association with total EI at rest (Rash and Prkachin, 2013). However, participants in that study may have been aware that the experiment involved a personally relevant experiential sadness induction, as they had to provide a personalized sadness narrative before their laboratory visit. This may have led to affect specific introspective thoughts during the resting period. Our study had greater statistical power than the Rash & Prkachin study and, therefore, may be more representative of the typical resting condition utilized in CVC reactivity assessments (Rash and Prkachin, 2013). Thus, we conclude that individuals with greater demonstrated ability EI, perhaps by those who show a more sophisticated understanding of emotions, the factors that influence them, and how they may

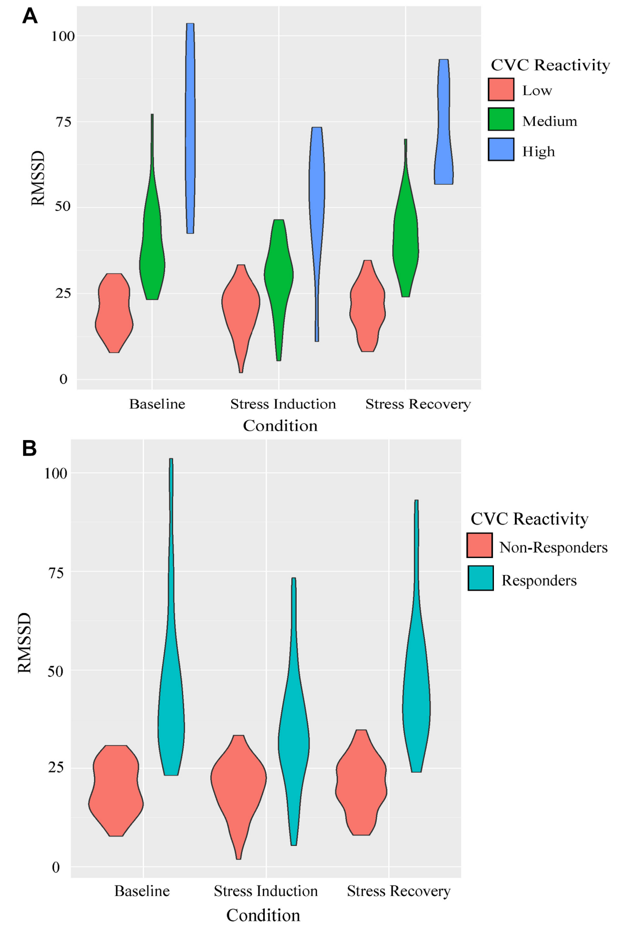


FIGURE 3 | Parameters of RMSSD estimates across conditions for the CVC reactivity groups presented as violin plots. Outlines illustrate kernel probability density, i.e., the width of the shaded area represents the proportion of the data located there. Panel **(A)** represents the initial groupings identified using hierarchical cluster analysis. Panel **(B)** represents the collapsed grouping discriminating CVC reactivity to the stress induction for Mann-Whitney U analyses.

TABLE 2 | Descriptive statistics of groups identified using hierarchical agglomerative clustering.

	CVC low responders		CVC middle responders		CVC high responders	
Measure	**Mean**	**St. Dev.**	**Mean**	**St. Dev.**	**Mean**	**St. Dev.**
Age	22.72	4.59	23.16	4.62	21.80	2.10
Baseline RMSSD	19.76	6.21	39.69	11.83	73.44	21.49
Stress induction RMSSD	20.03	6.92	29.49	10.07	51.51	18.15
Stress recovery RMSSD	20.79	6.77	41.42	9.81	70.36	14.19
EQi total	101.21	13.30	105.97	10.83	100.70	13.94
MSCEIT total	104.81	11.59	112.24	13.43	107.44	9.75

RMSSD, root mean square of successive differences; HRV, heart rate variability; HR, heart rate; EQi, Bar-On EQ-I 2; MSCEIT, Mayer-Salovey-Caruso Emotional Intelligence Test II.

TABLE 3 | Descriptive statistics of the collapsed grouping utilized for group level analyses.

	CVC responders		CVC non-responders	
Measure	**Mean**	**St. Dev.**	**Mean**	**St. Dev.**
Age	22.88	4.24	22.72	4.59
Baseline RMSSD	46.72	19.76	19.76	6.21
Stress induction RMSSD	34.08	14.99	20.03	6.92
Stress recovery RMSSD	47.45	15.98	20.79	6.77
EQi total	104.88	11.58	101.21	13.30
MSCEIT total	111.24	12.81	104.81	11.59

RMSSD, root mean square of successive differences; HRV, heart rate variability; HR, heart rate; EQi, Bar-On EQ-I 2; MSCEIT, Mayer-Salovey-Caruso Emotional Intelligence Test II.

evolve over time and during the course of social interactions, also show a greater capacity to regulate cardiac vagal responsiveness.

Second, we hypothesized that individuals who have higher levels of ability EI would have greater decreases in CVC in response to stress and show subsequent increases during recovery. This hypothesis was not supported by initial statistical models. Participants with greater modulation in CVC across the stress induction period (RMSSD decrease) and subsequent recovery (RMSSD increase) did not have higher levels of total ability EI or mixed EI. Baseline differences in CVC appear to drive the observed association with EI since no interactions with stress induction or recovery conditions were found. Although sympathetic and parasympathetic outflows tend to have a close-fitting reciprocal relationship, modes of autonomic control are not always linear (Berntson et al., 1991). Higher resting CVC is associated with situationally appropriate emotional responding and can mitigate the experience of negative emotional arousal in response to stress (Fabes and Eisenberg, 1997). This may represent an adaptive response where activation of parasympathetic systems attenuates sympathetic dominance when individuals experience stressors. From these findings, we conclude that individuals with higher ability EI demonstrate a greater level of resting CVC.

Exploratory Analyses

As part of the present study, we also sought to clarify how the predictive validity of EI on CVC compares to other cardiac metrics. The observed associations between ability EI and RMSSD, but not HRV or HR, suggest that parasympathetic influences on autonomic control are responsible for the majority of observed associations with ability-based EI. RMSSD is a metric that results in a differential gain function such that it weights more heavily the high-frequency vagal influence whereas HRV is a metric that results in a flat gain function that will capture frequencies that represent a combination of sympathetic and parasympathetic influences (Allen et al., 2007).

We also sought to determine how categorization based on individual differences in CVC reactivity would predict ability EI and mixed EI. Individual categorization based on responsiveness to the stress induction confirmed the relationship observed in the linear regression models. Individuals identified as responders to the stress induction had significantly higher ability EI scores compared to CVC non-responders; while no difference between groups was observed for mixed EI scores. Intriguingly, no specific domain of ability EI displayed significant positive associations with CVC responders. These findings suggest that during stressful experiences, individuals with higher baseline levels of CVC and greater cardiovascular responses, which reflect higher baseline parasympathetic control, greater withdrawal during stressors and greater increases during the subsequent recovery, may have a greater capacity to modulate CVC and in a manner that facilitates the ability to cope with emotional demands.

Considerations

Our findings are consistent with the only other study that investigated direct associations between HRV as a metric representative of autonomic control and quantified EI (Rash and Prkachin, 2013). Two other studies examining CVC and EI used less known mixed-model-based metrics to quantify EI, which may have contributed to their varied findings, and failure to distinguish associations between EI and baseline CVC (Laborde et al., 2011; Plews et al., 2012). EI as a measurable construct remains highly debated, and the call for an increased focus on refinement in its assessment may lead to greater clarity about the association between EI and CVC (Fiori and Antonakis, 2011). The substantial body of work associating CVC and emotional regulation emphasizes the notion that if EI is validly conceived and measured, at least some aspects should have significant associations with autonomic processes. While the amount of variance accounted for in our significant baseline model using RMSSD (*partial* $\eta^2 = 0.04$) was relatively small, the findings are consistent with the amount of unique variance accounted for by the association between RSA and ability EI in the only other study examining CVC and the MSCEIT (Rash and Prkachin, 2013). The theoretical construct of EI also remains heavily debated, and a multi-level theoretical approach incorporating actual behavioral outcomes will be critical to the construct in achieving its potential for psychometric validity (Boyatzis, 2018). In light of this, we believe that our study offers a unique and valuable insight into the relationship between CVC and EI that will help propel future investigations relating these two constructs (Ioannidis, 2005). Based on the Polyvagal theory, the relationship between higher CVC and reactivity is associated with adaptive and beneficial behavioral responding, which based on the evidence presented, is associated with higher levels of EI. Whether higher CVC leads to higher EI or higher EI results in higher and more responsive CVC is, at present, an empirical question, and one that might be fruitfully examined in a longitudinal developmental study, or in a study training CVC and EI to observe the time-dependent changes in each.

The interplay between emotion and feeling are critical components in the maintenance of health and the facilitation of perception, decision making, and learning; and an inability to integrate the two processes often leads to maladaptive behavior (Damasio, 2001). Decreased CVC is associated with both mild and more severe forms of psychopathology and is becoming a more widely accepted biomarker for susceptibility to emotion dysregulation (Thayer et al., 2012). The cognitive system contributing to autonomic control, as defined by the NVI model, is especially sensitive to negative feedback (Thayer and Lane, 2000). Lower resting CVC is associated with perceived difficulties in emotion regulation, specific to decrements in emotional clarity and impulse control (Williams et al., 2015). Attention regulation and affective processing are necessary to counter sympathetic activation during non-optimal contexts and facilitate social interaction as described by the Polyvagal theory (Porges, 1995). There is also an association between stress-related illness, blunted autonomic regulation, and negative family-of-origin relationship experiences (Luecken et al., 2005). This further highlights the impact of biopsychosocial development on physiologic and emotion regulation capacities that should theoretically relate to the construct of EI. Higher levels of cognitive-emotional abilities contribute to emotion regulation abilities that drive positive behavioral outcomes. A recent systematic review of 135 papers concluded resting CVC is associated with flexible emotional responding and emotion regulation strategies, as well as supports CVC as an objective marker of emotion regulation (Balzarotti et al., 2017). The interplay between decrements in physiological resources (e.g., during sleep deprivation, environmental extremes, emotional stress, and physical hardship), and degradation of cognitive function contribute to potentially detrimental decision making and allude to the need for novel interventions to mitigate the impact of stress on cognitive systems.

The use of biofeedback to augment CVC and its reactivity under stressful conditions is widely used and increasingly has focused on domains ranging from workplace office environments to fitness centers (McCraty et al., 2003; Düking et al., 2017). Interventions targeting emotional processes, such as mindfulness-attention training, can lead to positive outcomes in well-being, and have a substantial impact on emotion-specific neurocognitive processing (Shapiro et al., 2008; Desbordes et al., 2012). Recent work has also demonstrated that EI is malleable and susceptible to increases with targeted training (Alkozei et al., 2018; Mattingly and Kraiger, 2018). The current findings suggest there is a need for further study into the use of training interventions targeting CVC and EI in conjunction as a useful non-pharmacological method for improving well-being; perhaps mitigating symptomology associated with decreases in emotional processing on both an impermanent and pathological level in a manner that promotes well-being.

LIMITATIONS

Several limitations should be considered when interpreting the results of this study. We have interpreted the decrease in RMSSD during stress and subsequent increase during recovery as evidence of an optimal adaptive emotion regulation process, relative to the experience of stress. While the stress induction indeed produced a significant decrease in CVC across the sample of participants, a subset of individuals experienced increases in autonomic control during the stress induction or no change at all. It is possible that some individuals did not take the task seriously and did not actively engage in the serial subtraction task. Using a multi-faceted stress induction, such as the serial subtraction task in conjunction with a cold pressor or the Trier Social Stress Test, as well as variations in stressors more specific to different emotions may be more appropriate in future work to assess the relationship between EI and the experience of stress. The use of an affect induction, such as sadness, would also provide valuable information on individual differences in the associations between CVC, stress, affect, and EI.

Recent work has demonstrated the usual reciprocal relationship between the sympathetic and parasympathetic systems, representing the widely accepted fluctuations in autonomic control in response to stress, is dependent on individuals' cumulative exposure to risk, and resting sympathetic activation (Giuliano et al., 2017). It is possible that the exposure to stress and adversity may have moderated the response to the serial subtraction task and contributed to the observed individual differences in CVC. Further exploration of the influence of cumulative life experiences on CVC and EI is necessary. Of note, we did not collect data on body mass index or specific to anxiety/depression in the present study, which have both been shown to impact HRV. It is conceivable that these unmeasured factors may have also influenced the statistical models and would be appropriate to examine in future work. Participants also completed EI assessment measures after the stress reactivity assessment, leaving the potential for the residual effects of the stress induction to affect individual's performance on the subsequent measurement of EI, and measurements assessing the behavioral level of EI were also not collected. Lastly, multiple biological systems and factors influence autonomic control, and the associations observed between EI and CVC should not be taken to indicate a causal connection (Bauman et al., 2002).

CONCLUSION

The present study examined the association between the mixed and ability models of EI and their relation to CVC at rest and in response to a stressor. These findings help clarify the relationship between individual differences in the two most widely used metrics of EI for the mixed and ability models and their associations with CVC. Higher levels of total ability EI and the ability to understand the complexities of emotions were associated with an index of cardiac parasympathetic control at rest. Larger reductions in parasympathetic control during stress and the ability to recover were also found to be associated with higher total ability EI and driven by the ability to understand emotions. These results suggest that differences in the ability to understand emotional processes in oneself and reason about one's visceral experience may facilitate better cognitive and emotional processing. Additional research is needed to clarify the degree to which affect influences the relationship between stress and EI, as well as whether improvements in EI can also lead to subsequent increases in CVC or vice versa.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the Institutional Review Board (IRB) of the University of Arizona and the United States Army Human Research Protection Office (HRPO). All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Institutional Review Board (IRB) of the University of Arizona and the United States Army Human Research Protection Office (HRPO).

AUTHOR CONTRIBUTIONS

JV analyzed the data and wrote the initial draft of the manuscript. AA contributed to writing the initial draft of the manuscript. AR contributed to the statistical analysis and writing of the manuscript. JA aided in study design, as well as, contributed to data processing, statistical analysis, and writing of the manuscript. WK designed and supervised all aspects of the study and contributed to the writing of the manuscript.

FUNDING

Funding for the research program facilitating the collection of the data analyzed for this work was supported by the Joint Warfighter Medical Research Program, award number W81XWH-16-1-0062.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2019.00181/full#supplementary-material

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

ORIGINAL RESEARCH
published: 27 June 2019
doi: 10.3389/fnhum.2019.00208

The Effects of Different Stages of Mindfulness Meditation Training on Emotion Regulation

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This study examined mood enhancement effects from 4-week focusing attention (FA) meditation and 4-week open monitoring (OM) meditation in an 8-week mindfulness training program designed for ordinary individuals. Forty participants were randomly assigned to a training group or a control group. All participants were asked to perform cognitive tasks and subjective scale tests at three time points (pre-, mid-, and post-tests). Compared with the participants in the control group, the participants in the meditation training group showed significantly decreased anxiety, depression, and rumination scores; significantly increased mindfulness scores; and significantly reduced reaction times (RTs) in the incongruent condition for the Stroop task. The present study demonstrated that 8-week mindfulness meditation training could effectively enhance the level of mindfulness and improve emotional states. Moreover, FA meditation could partially improve individual levels of mindfulness and effectively improve mood, while OM meditation could further improve individual levels of mindfulness and maintain a positive mood.

Keywords: mindfulness meditation, focusing attention, open monitoring, emotion regulation, Stroop task

OPEN ACCESS

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Received: *12 March 2019*
Accepted: *03 June 2019*
Published: *27 June 2019*

Citation:
Zhang Q, Wang Z, Wang X, Liu L, Zhang J and Zhou R (2019) The Effects of Different Stages of Mindfulness Meditation Training on Emotion Regulation. Front. Hum. Neurosci. 13:208. doi: 10.3389/fnhum.2019.00208

INTRODUCTION

Mindfulness can be defined as nonjudgmental attention to the present moment (Kabat-Zinn, 1994). Mind wandering was defined as a lack of relation to the current task (Klinger and Cox, 1987; Killingsworth and Gilbert, 2010). Irving (2016) proposed that mind wandering is unguided attention. The main techniques of mindfulness intervention include meditation, body scanning, walking meditation, breathing, and mindfulness yoga (Kabat-Zinn, 2003). Different mindfulness skills are some of the possible specific practices that allow people to understand the core of mindfulness (Kabat-Zinn, 2003). Tang and Posner (2013) proposed that these various mindfulness skills had a common goal, which is being in a state of placidity and awareness of what is occurring within the phenomenological field. More than the conceptual and emotional classifications, mindfulness training requires increasing acceptance of whatever happens and reducing mental judgments.

In recent years, numerous studies have provided empirical evidence for the effectiveness of mindfulness meditation on emotion regulation (e.g., Nyklícek and Kuijpers, 2008; Chambers et al., 2009; Mathew et al., 2010; Geschwind et al., 2011). Researchers have proposed that mindfulness practitioners could be happier and more satisfied (Shapiro et al., 1998, 2008; Ivanovski and Malhi, 2007); be less anxious, less depressive, and have a greater chance of experiencing the feeling of equanimity (Baer et al., 2006); weaken addiction disorder (Bowen et al., 2006); and be healthier (Davidson et al., 2003) than nonmindfulness practitioners. Moreover, some studies have provided evidence that mindfulness training increased cognitive capacity (Brefczynski-Lewis et al., 2007; Jha et al., 2007; Ortner et al., 2007; Tang et al., 2007; McCracken and Yang, 2008) and improved social cognition (Low et al., 2008).

Emotion regulation has been defined as processes through which persons regulate their emotions consciously or unconsciously (Rottenberg and Gross, 2006). Emotional regulation involves many research topics, such as emotional regulation strategies, processes, and outcomes. Individuals use different strategies to modify the intensity or type of emotional experience (Gross, 1998). Successful emotional regulation increases health, improves relationships, and promotes job performance (John and Gross, 2010). Individuals who cannot effectively manage their emotion for a long time may evolve into diagnosable depression or anxiety (Mennin et al., 2007).

However, studies to date on the mechanisms of action underlying mindfulness are inconclusive, and more research is needed. Shapiro et al. (2006) expounded on three mechanisms of mindfulness: intention, attention, and attitude. They posited that intention, attention, and attitude are not separate but are interwoven aspects of mindfulness training and that effective mindfulness training is accompanied by the transformation of these three elements. They proposed that the core potential working mechanism of mindfulness is reperceiving, which promotes the transformation of thinking. Hölzel et al. (2011) suggested that mindfulness training includes a series of different but interrelated compositions which can enhance self-regulation. They proposed four effective compositions: (1) attention regulation, sustaining attention on the chosen object (whenever distracted, returning attention to the object); (2) body awareness, focusing on an object with an internal experience: sensory experiences of breathing, emotions, or other body sensations; (3) emotional regulation, approaching ongoing emotional reactions in a different way and exposing oneself to whatever is present in the field of awareness, letting oneself feel it, and refraining from internal automatic reactivity; and (4) changing the perspective of oneself, separating from a static self-cognition. In addition, they indicated that these four components are similar to the Theravada Buddhist scriptures "Satipatthana Sutta" (mind, body, perception, and law; Hölzel et al., 2011).

"Satipatthana Sutta" is one of the most important references for classic Buddhist mindfulness practice, which requires practitioners not only to have an intention such as compassion for all beings but also stipulating a stringent step-by-step sequence of mindfulness practice. Chiesa (2011) concluded that early stages of mindfulness training are linked with developing the capacity for focusing attention (FA), selecting attention, and executing attention. Later stages of mindfulness training focus on open monitoring (OM) meditation, improving vigilance attention, and keeping attention. Lutz et al. (2008) described two kinds of mindfulness meditation that include FA meditation and OM meditation. FA and OM are also called concentration and mindfulness (Cahn and Polich, 2006). On the one hand, FA meditation requires participants to focus their attention on a chosen object; on the other hand, OM meditation requires participants to monitor the content of their experience in a nonreactive manner from moment to moment. Lutz et al. (2008) conducted a detailed comparison of these two kinds of mindfulness meditation and found that the two kinds of mindfulness meditation had considerable differences in content and features. FA typically requires a relatively narrow field for focusing, such as breathing, while reducing attention to other distracting stimuli. OM, however, needs to make no effort to maintain focus on specific objects. Other researchers have examined the difference between FA and OM (Sears and Kraus, 2009; Perlman et al., 2010). However, few studies have examined the relationship between the training effect and the training order of these two states.

Arch and Craske (2006) found that the focusing breathing group reported lower negative affect and did a more appropriate response to negative stimuli than the unfocused attention and worry group. Perlman et al. (2010) posited that OM has a better effect on individual pain tolerance than FA. However, their study did not provide further exploration of training effects concerning FA and OM. In a similar study, Sears and Kraus (2009) explored the relationship among three groups: FA meditation, OM meditation, and a longer meditation combining both FA and OM meditation. They found that the training effect of the integration group was better than that of the other two groups, indicating that attention and OM in mindfulness training relate to each other and jointly created a better training effect. It should be noted that their study did not differentiate between the longitudinal training sequence effects of FA and OM meditation in the integration group.

Based on the previous findings and Buddhist scripture explanations that FA and OM are interrelated and have a hierarchical relationship (Travis and Shear, 2010), we reasoned that a novice should not directly practice OM before the novice practices FA because going directly to the OM stage would not be effective for beginners. We also thought that FA and OM were equally important. Meditation practitioners might lose the intrinsic meaning of mindfulness if they were not in accordance with the hierarchical relationship of FA and OM.

The present study posited that FA and OM had different working mechanisms and that FA and OM were two kinds of processes for a beginner and emphasized different contents and sequences. Therefore, the purpose of the present study was to investigate the effect of mindfulness training beginning with 4 weeks of FA meditation training, immediately followed by 4 weeks of OM meditation training on emotion regulation.

The emotion regulation effects between the 4-week FA meditation and the 4-week OM meditation training were examined. Mind wandering is defined as the transfer of executive control from the attainment of personal goals, often without intention or even awareness of the transfer (Schooler et al., 2004). Mind wandering is the opposite of mindfulness (Smallwood and Schooler, 2006). The level of mind wandering can be used as a measure of mindfulness (Davidson, 2010). We used the Stroop task to measure mind wandering. Meanwhile, Moore and Malinowski (2009) concluded that increased mindfulness are related to improved attentional functions and found that mindfulness meditators performed better at the Stroop task in their study. Moore et al. (2012) further found that mindfulness practices could significantly change neuronal activity related to executive control functions in the Stroop task. We hypothesized that an 8-week mindfulness meditation program would increase mindfulness levels, that FA would significantly decrease depression and anxiety, and that OM would facilitate mindfulness and continue to maintain improvement of the emotional state following FA.

MATERIALS AND METHODS

Participants

The participants consisted of 12 males and 28 females. The mean age of the sample was 22.5 years (range = 19–32 years old). All subjects were healthy and had no smoking or drinking habits. None of the participants had previously practiced mindfulness or other types of meditation. They were randomly assigned into two groups: the training group and the waitlist control group. The participants in the training group took part in mindfulness training for 8 weeks. The participants in the control group were waitlisted for the later training. During the 8-week mindfulness training, four participants in the training group did not finish the training, and thus, there were a total of 16 participant data in the training group and 20 participant data in the control group for data analysis. The experimental procedures were approved by the Institutional Review Board of the State Key Laboratory of Cognitive Neurosciences and Learning of Beijing Normal University.

Procedure

Participants in the present study were voluntary, and all of them signed an informed consent form for the training and the use of their data. Participants in both the 8-week mindfulness training and the waiting control groups were first introduced to the experiment tasks, which included the questionnaires and the Stroop task. They then completed the experiment tasks at pre- (baseline, the week prior to mindfulness training), mid- (during the 4th and 5th weeks), and post-training (after the 8-week training). The participants in the training group completed 8 weeks of mindfulness training, while the participants in the control group just waited for 8 weeks without mindfulness training. All participants also completed the tasks same as in the baseline during the 4th and 5th weeks, as well as after 8 weeks. After the 8-week training, the participants in the control group participated in the mindfulness training.

Measures

Questionnaire Materials used in the present study.

Freiburg Mindfulness Inventory

Freiburg Mindfulness Inventory (FMI) assesses nonjudgmental present awareness and acceptance of mindfulness. All statements were rated on a four-point scale (1 = seldom; 4 = always). The total score is a summation of all items, ranging from 13 to 52, with higher scores indicating a better mindfulness level (Chen and Zhou, 2014).

Positive and Negative Affect Scale

Positive and Negative Affect Scale (PANAS) consists of two subscales in total of 20 items with each subscale consisting of 10 items. One subscale measures positive emotion such as enthusiasm, and the other scale measures negative emotion such as hostility. Each question is rated on a five-point scale that ranges from 1 (never) to 5 (often). The Cronbach's alpha coefficient of the Chinese version is 0.82 (Huang and Yang, 2003). The participants were asked to fill out the questionnaire according to the experience over the past 1–2 weeks. The total score of the Positive Affect Scale was a summation of the positive items ranging from 10 to 50, with the higher score indicating more positive. The total score of the Negative Affect Scale was a summation of the negative items ranging from 10 to 50, with the higher score indicating more negative.

The Beck Anxiety Inventory (Chinese version)

The Beck Anxiety Inventory (BAI) is a measure of anxiety (Beck et al., 1988). The instrument consists of 21 statements rated on a four-point scale (0 = not at all; 3 = severely, I could barely stand it). The Cronbach's alpha coefficient for the Chinese version of the BAI was 0.95 (Zheng et al., 2002). The summation of all items resulted in a total score, which was converted into a standardized score by the function Y = int (1.19×), with the higher score indicating more severe anxiety.

The Beck Depression Inventory (Chinese version)

The Beck Depression Inventory (BDI) consists of 21 statements that measure depression (Beck et al., 2009). Each of them was measured on a four-point scale ranging from 0 (not at all) to 3 (severely; I could barely stand it). The Chinese version of the BDI has been shown to be reliable with a Cronbach's alpha coefficient of 0.89 and a split-half reliability of 0.88 (Zhang et al., 1990). The participants were asked to fill out the questionnaire according to the experience over the past week. The total score was the summation of all items ranging from 0 to 63, with the higher score indicating more severe depression.

Rumination-Reflection Questionnaire

The Rumination-Reflection Questionnaire (RRQ) consists of two subscales (Campbell et al., 1996). The Rumination scale measures the recurrent negative self-focus associated with threat or uncertainty. The Reflection scale measures the positive self-focus associated with epistemic interest in the self. Each item is rated on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The Cronbach's alpha coefficient of the Chinese version was 0.86 (Yuan et al., 2010). The subscale average score is higher, indicating more rumination or reflection.

Cognitive Test: The Stroop Task

The Stroop task requires participants to perform a task of the font color or word meaning inference with the Stroop interference. The task comprised a series of color words including "RED," "YELLOW," "BLUE," and "GREEN" in Chinese characters, which were presented in a matched font color (congruent trial) or a nonmatched font color (incongruent trial). The participants were asked to respond to the specific color of the characters by pressing the specific button as fast and correctly as they could. In the practice block, participants learned to press "D" for red, "F" for yellow, "J" for green, and "K" for blue. Not until the accuracy rate of the participants reached more than 90% in the 24 practice trials could the participants be allowed to enter the experiment trials for using the reaction time (RT) as the only independent variable (Stroop, 1935). There were a total of 154 experiment trials. The half of the trials were congruent color–word pair, while the other half were incongruent color–word pair.

Mindfulness Intervention

The mindfulness training method in the present study was adopted from the book *Mindfulness: A Practical Guide to Finding Peace in a Frantic World* written by Williams and Penman (2011). The training method was a comprehensive program created by Williams and Penman based on the theory of mindfulness-based stress reduction (MBSR) and mindfulness-based cognitive therapy (MBCT). The program consisted of the 4 weeks of FA meditation practice and then 4 weeks of OM meditation practice. The specific forms of the mindfulness training are in **Table 1**.

The mindfulness training program lasted 8 weeks. The training was conducted at 19:00–21:00 PM every Monday for 8 weeks in a psychology laboratory. Participants in the training group were instructed to conduct home mindfulness practice guided by the online training program during the remaining 6 days of the week, 20–30 min per day and to fill the recording sheets. All participants in the training group agreed to complete the home mindfulness practice and record their daily practice on the sheets during the 8 weeks of training.

RESULTS

Pre-intervention Analyses

A univariate analysis of variance (ANOVA) was conducted on the mean scores between the mindfulness training and the control group before the mindfulness intervention. There was no significant difference in the mindfulness (scored by FMI) between the training and control groups. In the pre-test, the training group and the control group had no significant differences in positive and negative affect (scored by PANAS), anxiety (scored by BAI), depression (scored by BDI), and rumination (scored by RRQ). However, we found that the mindfulness training and control groups had significant difference in reflection (scored by RRQ; $F_{(1,34)} = 6.46$, $p = 0.016$, $\eta^2 = 0.160$), with the training group significantly higher than the control group. In the cognitive test, there were no significant difference in the congruent and incongruent color–word tasks (scored by the Stroop Task). The pre-intervention analyses indicated that the emotional and cognitive levels of participants from two groups were similar. **Table 2** shows the descriptive statistics of each score on the three tests for the two groups.

Comparison of Pre-, Mid-, and Post-test Between the Mindfulness Training and Control Groups

The group (training vs. control group) × time (pre- vs. mid-test, post-test) ANOVA analyses were performed for the score of BAI, BDI, FMI, RRQ, PANAS, and Stroop task, respectively.

Mindfulness

For FMI, the time point × group interaction effect was significant, $F_{(2,68)} = 5.05$, $p = 0.009$, $\eta^2 = 0.129$. Simple effect analyses showed a significant difference on the FMI scores among testing sessions ($F_{(2,68)} = 8.56$, $p < 0.001$) in the training group, with the score of the mid-test and post-test being significantly higher than the pre-test (pre-test vs. mid-test, $p = 0.010$; pre-test vs. post-test, $p = 0.001$), whereas there was no significant difference among sessions in the control group.

Positive and Negative Affect

For PANAS, the results indicated a significant time point × group interaction effect in the positive affect subscale, $F_{(2,68)} = 3.66$, $p = 0.031$, $\eta^2 = 0.097$; further simple effect analyses showed that both groups were not significantly different in the three times. On the negative affect subscale, both the main effect and interaction were not significant.

Anxiety and Depression

For BAI, the results indicated a significant time × group interaction effect, $F_{(2,68)} = 3.65$, $p = 0.031$, $\eta^2 = 0.097$. Simple effect analyses of three times data (pre-test, mid-test, and post-test) showed that the BAI score was significantly different in the three tests ($F_{(2,68)} = 5.79$, $p = 0.005$) in the training group, with the score of the mid-test and post-test being significantly lower than that of the pre-test (pre-test vs. mid-test, $p = 0.002$; pre-test vs. post-test, $p = 0.023$). However, no significant difference was found in the control group.

For BDI, there was a significant time × group interaction effect, $F_{(2,68)} = 5.70$, $p = 0.005$, $\eta^2 = 0.144$. Simple effect analyses showed a significant difference on the BDI scores among testing sessions ($F_{(2,68)} = 11.01$, $p < 0.001$) in the training group, with the score of the mid-test and post-test being significantly lower than that of the pre-test (pre-test vs. mid-test, $p = 0.001$; pre-test vs. post-test, $p = 0.001$), whereas there was no significant difference among sessions in the control group.

TABLE 1 | The specific tasks of mindfulness training program.

Week	Topic	Practices
Week 1	waking up from the autopilot	eat raisin under mindfulness; wake up from routine; habit buster; weekly mindfulness.
Week 2	keeping the body in mind	body scan practice at least 15 min at least twice a day; perform mindfully on another routine activity;habit buster and go for a walk for at least 15 min at least once a week.
Week 3	the mouse in the maze	8 min of movement mindfulness meditation; 8 min of breath and body meditation; 3-min breathing space meditation and practice it twice a day; a habit buster: valuing the television.
Week 4	moving beyond the rumor mill	8-min breath and body meditation; 8-min sound and thought meditation; 3-min breathing space meditation and practice it twice a day.
Week 5	turning toward difficulties	8-min breath and body meditation; 8-min sound and thought mediation; 10-min exploring difficulty meditation; 3-min breathing space meditation.
Week 6	trapped in the past or living in the present	10-min befriending meditation; 3-min breathing space meditation.
Week 7	when did you stop dancing	carry out your own formal meditation practice.
Week 8	your wild and precious life	start the day with mindfulness; use breathing space to punctuate the day; maintain mindfulness practice; befriend your feelings; take a breathing space when you feel tired, frustrated, anxious, anger, or any other powerful motion; mindfulness activities; increase your level of mindfulness exercise; remember the breath.

TABLE 2 | The descriptive results of the questionnaire and Stroop data at the pre-test, mid-test, and post-test for the training and control groups.

Outcome	Training group (n = 16)			Control group (n = 20)			p-value
	Pre-test M (SD)	Mid-test M (SD)	Post-test M (SD)	Pre-test M (SD)	Mid-test M (SD)	Post-test M (SD)	
FMI	28.75 (4.80)	32.38 (6.18)	34.31 (6.18)	32.00 (4.84)	31.80 (5.95)	31.85 (5.21)	0.009
PANAS Positive	22.81 (4.79)	24.81 (8.08)	25.69 (8.79)	26.20 (8.82)	25.80 (8.82)	24.10 (8.47)	0.031
PANAS Negative	16.94 (7.62)	14.56 (6.50)	15.19 (5.97)	15.95 (4.51)	16.90 (5.59)	16.00 (5.10)	>0.05
BAI	33.88 (12.22)	29.00 (8.77)	30.00 (8.89)	33.20 (8.06)	33.70 (9.95)	31.05 (7.61)	>0.031
BDI	9.06 (8.68)	4.31 (4.81)	4.13 (5.78)	7.90 (5.41)	8.50 (6.31)	6.30 (5.62)	0.005
Rumination	43.06 (7.71)	39.13 (8.14)	38.31 (9.58)	42.00 (5.27)	41.35 (8.63)	42.60 (7.58)	0.008
Reflection	43.31 (6.28)	43.63 (6.22)	44.19 (8.84)	37.90 (6.41)*	37.80 (9.36)	38.55 (8.46)	>0.05
Stroop Congruent	736.56 (172.04)	648.55 (108.01)	660.20 (105.11)	698.05 (101.08)	658.09 (106.29)	671.71 (146.04)	>0.05
Stroop Incongruent	952.51 (254.56)	823.41 (145.80)	849.25 (163.22)	831.75 (136.27)	818.65 (190.19)	808.52 (175.34)	0.042

**Indicates a significant difference between the training and the control groups in the pre-test. What we reported on the p-value were p-values of the time point × group interaction effect.*

Rumination–Reflection

On the rumination facet, the time point × group interaction effect was significant ($F_{(2,68)} = 5.13$, $p = 0.008$, $\eta^2 = 0.131$), and simple effect analyses showed that the rumination score in each testing time was significantly different ($F_{(2,68)} = 8.19$, $p = 0.001$) in the training group, with the score of the mid-test and post-test being significantly lower than that of the pre-test (pre-test vs. mid-test, $p = 0.005$; pre-test vs. post-test, $p = 0.001$); however, there was no significant difference among sessions in the control group. On the reflection facet, the group main effect was significant ($F_{(1,34)} = 5.38$, $p = 0.026$, $\eta^2 = 0.137$); however, the time point × group interaction effect was not significant.

Stroop Task

For the Stroop task, in the congruent condition, a significant main effect of time was found ($F_{(2,68)} = 5.35$, $p = 0.007$, $\eta^2 = 0.136$), showing that the RTs in the mid-test and post-test were significantly lower than that of the pre-test (pre-test vs. mid-test, $p = 0.003$; pre-test vs. post-test, $p = 0.045$). The time point × group interaction effect was not significant. In the incongruent condition, the results indicated a significant time point × group interaction effect, $F_{(2,68)} = 3.33$, $p = 0.042$, $\eta^2 = 0.089$. Simple effects showed that the RTs were significantly different ($F_{(2,68)} = 7.94$, $p = 0.001$) among sessions in the training group, with the RTs of the mid-test and post-test being significantly lower than that of the pre-test (pre-test vs. mid-test, $p = 0.001$; pre-test vs. post-test, $p = 0.013$), whereas there was no significant difference among sessions in the control group.

DISCUSSION

The present study provided empirical evidence that an 8-week mindfulness meditation training program could effectively improve the level of individual mindfulness and the regulation of anxiety, depression, and rumination. Moreover, this study also confirmed that the change of mindfulness level and mood was a dynamic process and FA meditation could partially improve mindfulness level and mood, while OM meditation could further enhance mindfulness level and maintain the effect on mood regulation. It is important to indicate that the mindfulness training methods used in the present study effectively enhanced the mindfulness level. Our findig that the mindfulness training method was effective in improving mindfulness is consistent with findings obtained from previous studies (Nyklícek and Kuijpers, 2008; Farb et al., 2010; Robins et al., 2012).

The present study found that 8-week mindfulness meditation training could effectively regulate mood and reduce anxiety and depression. This finding has been observed in several previous mindfulness studies (Baer et al., 2006; Sears and Kraus, 2009). For example, Sears and Kraus (2009) found that anxiety scores decreased in the FA and OM integrated groups, which is consistent with our study results. However, there was no significant difference in the anxiety scores measured from FA training, which is not consistent with our study. It should be noted that anxiety level in our study was reduced significantly due to the FA training in the first 4 weeks. Further studies are needed to replicate this finding and understand the underlying mechanisms.

Past studies have examined the effectiveness of FA and OM meditation, but no studies have investigated the training effect and order of these two states. For example, Perlman et al. (2010) compared the individual pain tolerance effect of the two stages of FA and OM and found that the effect of OM meditation was better than FA meditation in pain management, without exploring other training effects of FA and OM. In another study, Sears and Kraus (2009) divided participants into three groups: brief meditation focused on attention, brief meditation focused on loving–kindness, and longer meditation combining the attention and loving kindness aspects of mindfulness. Their study found that the third group demonstrated the best effect, which is similar to the finding from the present study. However, Sears and Kraus's (2009) study did not distinguish whether the sequences of longitudinal research in the third group could cause different results.

The present study also indicated that the RT for the Stroop incongruent tasks was reduced, which reflected the improvement in individuals' attention levels during mindfulness training. Eight-week mindfulness meditation training also reduced the RT of the individual under the incongruent condition, but not for the congruent condition. This finding was consistent with several previous studies. Moore and Malinowski (2009) reported that compared with the control group, the error rate for the Stroop task had a negative correlation with the increase of the mindfulness level in the meditation group. Their study suggested that meditation training improved the subjects' ability to complete the Stroop task. However, the subjects in their study were all Buddhist meditators, and the data collection method was a paper test that cannot reach the ideal accuracy. Furthermore, their study did not record RT, which is a reliable indicator for attention level enhanced by mindfulness training. In a similar study, Wenk-Sormaz (2005) discovered that participating in meditation practice could result in a lower interference effect for the Stroop task compared to the control group, indicating that the participants in the meditation group had a stronger anti-interference ability. However, Wenk-Sormaz's experiment only compared the post-test results of the two groups without comparing the changing results from pre-test to post-test; therefore, the data collected were not sufficiently comprehensive. Similar to our results, Wang et al. (2012) found that mindfulness training improved performance on the Stroop task, mainly in the incongruent condition. However, the major task of the mindfulness training in their experiment was consciously observing one's own breathing and inner experience of the moment, which involved FA mindfulness and neglected OM mindfulness. We think that the nonsignificant change in RT in the previous studies was most likely attributable to the insufficient training time in which participants were not required to practice every day, except a 10- to 15-min collective exercise per week (Sears and Kraus, 2009). However, the present study required the participants to submit their training records of weekly exercise. In short, compared to previous studies, the present study provided evidence that the combined FA and OM mindfulness training was an effective method to increase participants' attention and mindfulness by using a methodology that measured the RT and mindfulness at the time of pre-test, mid-test, and post-test.

According to the previous studies and Buddhist scripture, FA and OM meditation are interrelated and have a hierarchical relationship (Peng and Hu, 2011). For participants who have no previous meditation experience, we strongly recommend that they practice FA meditation before OM meditation. In our study, participants with no mindfulness training still obtained a significant positive change in their emotion and cognition in the FA meditation training stage, and OM meditation training further reduced the level of anxiety and depression and improved the participants' mindfulness level. After 4 weeks of mindfulness training, the experimental results from the present study revealed that compared with the control group, the meditation training group showed enhanced mindfulness levels, reduced RT on the incongruent Stroop tasks, and decreased depression, anxiety, and rumination. After 8 weeks of mindfulness training, the results demonstrated that, compared with the control group, the meditation training group showed further increased mindfulness, reduced RT on the incongruent Stroop tasks, and reduced anxiety, depression, and rumination. This experimental result demonstrated the importance of the FA and OM meditation training sequence. These results also provide empirical evidence that mindfulness training is a gradual process with a specific sequence. Although some monks can naturally achieve the OM state, even without practicing the FA state, for ordinary people, the training effect is cumulative, and it is not easy to directly achieve the OM meditation state just using a simple training program without professional and systematic practices.

In summary, the experimental results in the present study demonstrated that participants showed a gradual improvement in mindfulness during the 8-week training program. For these beginners, FA meditation could significantly reduce the levels of anxiety and depression. Furthermore, OM meditation could further improve mindfulness state and maintain a good mood. However, the pure OM could not be separated in this study. Our study failed to answer the difference in the effect of pure OM and FA, as well as the difference in their working mechanism. This study would be helpful to compare the longitudinal development of FA and OM mindfulness in future studies. Many additional indicators can be used to investigate the training effect, such as event-related potential (ERP), functional magnetic resonance imaging (fMRI), and other physiological indicators. Furthermore, whether FA and OM meditation have different benefits on different abilities is worthwhile to explore, and future studies should also compare the different stages of mindfulness training with relevant information contained in Buddhist classical scriptures. This kind of research based on traditional Buddhist culture may be beneficial in the development of mindfulness training methods.

DATA AVAILABILITY

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

ETHICS STATEMENT

The experimental procedures were approved by the Institutional Review Board of the State Key Laboratory of Cognitive Neurosciences and Learning of Beijing Normal University.

AUTHOR CONTRIBUTIONS

QZ and RZ prepared the manuscript. ZW was in charge of training the participants. XW and RZ came up with this idea and research design. XW, LL and JZ collected the data. XW and LL analyzed the data.

FUNDING

This research was funded by Fundamental Research Funds for the Central Universities (14370303), Tsinghua University Research fund of positive psychology (0020344-2015-01-008), and the Key Project of Philosophy and Social Science Research in Colleges and Universities in Jiangsu Province (2015JDXM001).

ACKNOWLEDGMENTS

We thank professor Tian Po Oei's (School of Psychology, The University of Queensland, Australia) valuable suggestion and comments. We would like to express our gratitude for his support.

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Conflict of Interest Statement: 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.

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ORIGINAL RESEARCH
published: 09 July 2019
doi: 10.3389/fnhum.2019.00222

Learning to Look at the Bright Side of Life: Attention Bias Modification Training Enhances Optimism Bias

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Identifying neurocognitive mechanisms underlying optimism bias is essential to understand its benefits for well-being and mental health. The combined cognitive biases hypothesis suggests that biases (e.g., in expectancies and attention) interact and mutually enforce each other. Whereas, in line with this hypothesis, optimistic expectancies have been shown to guide attention to positive information, reverse causal effects have not been investigated yet. Revealing such bidirectional optimism-attention interactions both on a behavioral and neural level could explain how cognitive biases contribute to a self-sustaining upward spiral of positivity. In this behavioral study, we hypothesized that extensive training to direct attention to positive information enhances optimism bias. To test this hypothesis, for 2 weeks, 149 participants underwent either daily online 80-trial attention bias modification training (ABMT) toward accepting faces and away from rejecting faces or neutral control training. Participants in the ABMT group were instructed to click as quickly as possible on the accepting face among 15 rejecting faces randomly displayed on a 4-by-4 matrix; participants in the control group were instructed to click on the five-petaled flower depicted among 15 seven-petaled flowers. Comparative optimism bias and state optimism were measured *via* questionnaires before training, after one training week, and after two training weeks. ABMT enhanced comparative optimism bias, whereas control training did not. Our findings reveal that ABMT toward positive social information causally influences comparative optimism bias and may, thereby trigger the biases' benefits for well-being and mental health. These results can (a) stimulate future neurophysiological research in the area of positive psychology; and (b) reveal an innovative low-cost and easy-to-access intervention that may support psychotherapy in times of rising numbers of patients with psychological disorders.

Keywords: attention bias modification training, cognitive bias modification, comparative optimism bias, expectancy bias, positive attention bias

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Received: *31 January 2019*
Accepted: *17 June 2019*
Published: *09 July 2019*

Citation:
Kress L and Aue T (2019) Learning to Look at the Bright Side of Life: Attention Bias Modification Training Enhances Optimism Bias.
Front. Hum. Neurosci. 13:222.
doi: 10.3389/fnhum.2019.00222

INTRODUCTION

People are usually overly optimistic about their future (optimism bias; Weinstein, 1980) and preferably attend to positive information around them (attention bias; Pool et al., 2016). Both behaviors relate to benefits in everyday life (maintaining motivation) and clinical domains (protecting mental health; Joormann and Gotlib, 2007; Sharot, 2011). However, we know little about how optimism and attention bias interact (Kress and Aue, 2017). If we knew that the positivity biases mutually enforced each other (bidirectional interplay), instigating a self-perpetuating upward spiral of positive emotions (Garland et al., 2010), we could more easily employ the biases' benefits in everyday life and clinical applications.

Theories such as the combined cognitive biases hypothesis suggest that cognitive biases (e.g., in expectancies and attention) interact and mutually enforce each other (Hirsch et al., 2006; Aue and Okon-Singer, 2015; Kress and Aue, 2017). From the combined cognitive biases hypothesis, we have recently proposed that optimism bias and positive attention bias dynamically interact and recruit a common underlying neural network. This network may comprise specific activations in the anterior and posterior cingulate cortices with functional connections to the limbic system (e.g., amygdala; see Kress and Aue, 2017, for further details). Furthermore, we proposed potential mechanisms of neural communication that might support the bidirectional interplay between optimism and positive attention bias.

Some of these theoretical considerations are supported by first empirical findings showing that optimistic expectancies indeed guide visual attention toward rewarding information (Kress et al., 2018). Large-scale neural networks comprising fronto-parietal brain regions in addition to the insula seem to underlie this mechanism (Kress et al., under revision). Notably, however, if bidirectional optimism-attention interactions exist, the reverse causal influence (and, later on, its underlying neural processes) must be demonstrated as well (Kress and Aue, 2017).

Attention bias modification training (ABMT: repeated training to attend to specific target stimuli and ignore others) may help investigators to study such causal influences of attention on optimism because it promises to modify attention (bias) and affect emotions (MacLeod and Mathews, 2012). Recent neural evidence suggests that ABMT reduces amygdala and insula activation toward emotional (threatening) stimuli (Månsson et al., 2013; Taylor et al., 2014). Furthermore, ABMT has been shown to increase frontal control and may thereby reduce anxiety symptoms (Browning et al., 2010; Taylor et al., 2014). Even though these results are promising, recent meta-analyses have revealed several methodological challenges related to ABMT (e.g., Cristea et al., 2015; Heeren et al., 2015b; Grafton et al., 2017; see Jones and Sharpe, 2017, for an overview).

Most studies in these meta-analyses used threat-avoidance ABMT to reduce pre-existing attention biases to threat in anxiety. Yet, these pre-existing biases are not consistently shown and can therefore not be modified in some ABMT studies (Mogg et al., 2017).

From the controversies concerning the appropriateness of threat-avoidance ABMT, a novel approach (positive-search ABMT) has been considered more promising in eliciting beneficial emotional outcomes: Positive-search ABMT works more reliably in home settings and elicits emotional benefits without exclusively relying on changes in attention bias (Mogg et al., 2017). Furthermore, the process trained in positive-search ABMT (i.e., finding a positive stimulus among negative stimuli) may be more adaptive and transferrable to real-life situations than processes trained in traditional threat-avoidance ABMT (e.g., reacting to a dot appearing after a neutral stimulus). For instance, the particular positive-search ABMT used in the current behavioral study has been developed to improve people's ability to inhibit social rejection and approach social acceptance information by training them to find the smiling face in a crowd of frowning faces (Dandeneau and Baldwin, 2004). This training to direct attention to adaptive information may be most effective to boost optimism bias.

People's attention was biased away from negative and toward positive social information after completing positive-search ABMT in most (Dandeneau and Baldwin, 2004, 2009; Dandeneau et al., 2007; Waters et al., 2013; De Voogd et al., 2014, 2016) but not all (Waters et al., 2015) studies assessing attentional changes following training. More important, positive-search ABMT elicited diverse beneficial emotional outcomes (lower perceived stress, enhanced self-esteem/positive self-regulation: Dandeneau et al., 2007; Dandeneau and Baldwin, 2009; reduced anxiety/social phobia: Waters et al., 2013, 2015, 2016; De Voogd et al., 2014; but see De Voogd et al., 2016, for null findings). These beneficial outcomes, in turn, are also associated with optimism bias for positive future events (e.g., self-esteem and self-regulation; Hoorens, 1996; Armor and Taylor, 1998). Thus, positive-search ABMT constitutes a promising tool to examine the effects of positive attention processes on optimism bias.

For two reasons, we decided to focus on optimism bias for positive future events in the current study, both relating to evidence in the literature that optimism biases for positive and negative future events represent different aspects with independent motivating factors (Weinstein, 1980; Hoorens, 1996). First, self-enhancement has been suggested to be an important motivating factor for optimism bias for positive future events but not for optimism bias for negative future events (which may be related to different motivating factors such as impression management; Hoorens, 1996). The positive-search ABMT used in the current study has been developed to enhance positive social cognition and self-regulation, thereby permitting the examination of cognitive mechanisms of self-enhancing positivity. Second, the positive-search ABMT used here has shown to enhance self-esteem (Dandeneau et al., 2007; Dandeneau and Baldwin, 2009). Because higher self-esteem was particularly associated with elevated optimism bias for positive future events but less so with optimism bias for negative future events (Hoorens, 1996), we hypothesized that the positive-search ABMT may be particularly effective in enhancing optimism bias for positive events.

The present work investigates whether repeatedly directing attention toward positive or away from negative social information during training causally influences optimism bias. Participants were randomly assigned to ABMT or control training. Before training, after one training week, and after two training weeks, all participants completed the Comparative Optimism Scale (COS; Weinstein, 1980; measuring optimism bias *via* social comparison) and the Future Expectancy Scale (FEX; Peters et al., 2015; measuring current optimistic states that are not necessarily biased but likely instigate optimism bias; see Garland et al., 2010, for details on how momentary emotional experiences trigger durable changes in emotional systems/affective styles). Because optimistic states vary across situations, ABMT that directs attention to positive aspects of a situation may trigger such state optimism.

Whereas comparative optimism bias was measured to uncover the importance of social/self-enhancing components in relation to attention processes, state optimism was measured to examine whether attention processes elicit optimistic states that then instigate the biases' formation. By measuring these different aspects, the current study can uncover crucial determining factors for the influence of attention processes on optimism bias (social comparisons and/or transient optimistic states). If repeatedly directing attention to positive information through training enhances optimism bias, then people's level of comparative optimism bias and/or state optimism should increase after participating in positive-search ABMT but not after the control training.

Even though prior literature proposes that ABMT affects people's responses to emotional and motivational cues (Beard et al., 2012)—such as when forming expectations about positive, motivationally salient future events—ABMT does not seem to directly affect people's mood (Dandeneau and Baldwin, 2004; Dandeneau et al., 2007; Beard et al., 2012). To replicate this finding and rule out the possibility that potential training effects on optimism bias arose because of changes in mood, we assessed participants' mood with the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988) as a secondary outcome in the current study.

MATERIALS AND METHODS

Participants

From a recent systematic review of meta-analyses on the efficacy of ABMT on emotional outcomes, we anticipated a small effect of ABMT on optimism bias (Jones and Sharpe, 2017; because effect sizes varied considerably, we chose the most modest assumption of a small effect). A minimum sample size of 128 to detect such small effect ($\eta_p^2 = 0.02$) was determined with a power analysis ($\alpha = 0.05$, power = 0.95). Because we expected high dropout rates over the two training weeks, 20 additional participants were tested. Thus, 149 healthy participants with normal or corrected-to-normal vision, who did not report using psychoactive substances, took part in this online study. Sixteen participants were excluded from data analysis because of technical errors in data logging ($N = 2$), or because they did not complete the training on more than 2 days ($N = 14$), leaving a final sample of 133 participants (experimental group: $N = 71$, 26 male, age: $M_{\text{Exp}} = 22.17$ years, $SD_{\text{Exp}} = 3.92$ years; control group: $N = 62$, 16 male, age: $M_{\text{Con}} = 23.35$ years, $SD_{\text{Con}} = 3.16$ years). Participants were randomly assigned to a group and did not show baseline differences in any of the reported outcome measures (i.e., optimism or mood; all $ps \geq 0.283$). However, the experimental group displayed slightly lower trait optimism scores than the control group did (i.e., Life Orientation Test-Revised (LOT-R) sum scores; Scheier et al., 1994: $t_{(131)} = - 0.920$, $p = 0.057$, $M_{\text{Exp}} = 22.61$, $SD_{\text{Exp}} = 3.89$, and $M_{\text{Con}} = 23.89$, $SD_{\text{Con}} = 3.78$). Participants gave written informed consent according to the guidelines of the ethical standards of the Declaration of Helsinki and were told that they could end the experiment at any time. All procedures were approved by the ethical review board of the Faculty of Human Sciences at the University of Bern.

Attention Training Tasks

Stimuli in the experimental training task (ABMT) comprised colored photographs of a smiling/accepting and a frowning face of 16 different people (half female) that were taken from a larger stimulus set collected at Mark Baldwin's "Social Cognition and Social Intelligence Lab" at McGill University. Stimuli were presented on a 4-by-4 matrix that appeared in the top middle of the participants' computer screen. Each matrix displayed one accepting face (target stimulus) and 15 frowning faces (distractor stimuli; see **Figure 1**)[1]. Participants were instructed to click as quickly as possible with their computer mouse on the accepting face. Stimuli appeared at a random location within the matrix in each of the 80 training trials. Every trial was presented until the participant had clicked on the target and the next trial followed (no inter-trial interval). Difficulty of the training task did not adapt to participants' performance and participants did not receive feedback on their performance during the task.

Stimuli in the control task comprised black and white drawings of five- and seven-petaled flowers. The procedure in the control task was identical to that of the experimental task, except that each matrix displayed one five-petaled and 15 seven-petaled flowers and participants were instructed to click on the five-petaled flower as quickly as possible. Thus, the task controlled for activity of engaging in a visual search (while not directing attention toward smiling or away from frowning faces).

Procedure

Participants were told that the study's purpose was to investigate training to improve responsiveness. For 2 weeks, they performed daily 5-min online training on their computer and indicated whether they had performed the training completely, partly, or not at all on an online questionnaire. Moreover, participants completed personality questionnaires (see **Supplementary Appendix A**) before, 1 week after, and 2 weeks after training began (to prevent suggestibility effects, participants were not informed about different training versions or that effects on optimism were being investigated). Participants received a daily e-mail message containing links to their version of the training and questionnaires. If participants had not answered the questionnaires by that evening, they were reminded. After the last training, participants were debriefed.

Dependent Variables

Primary Outcome (Optimism Regarding Future Positive Events)

On the COS (Weinstein, 1980), participants indicated the likelihood of themselves, compared to another person of the

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[1] The attention bias modification training and control training used in the current study can be accessed *via* the following links: ABMT- http://baldwinlab.mcgill.ca/labmaterials/materials_16fa_c_80.html; Control training- http://baldwinlab.mcgill.ca/labmaterials/materials_16fl_80.html

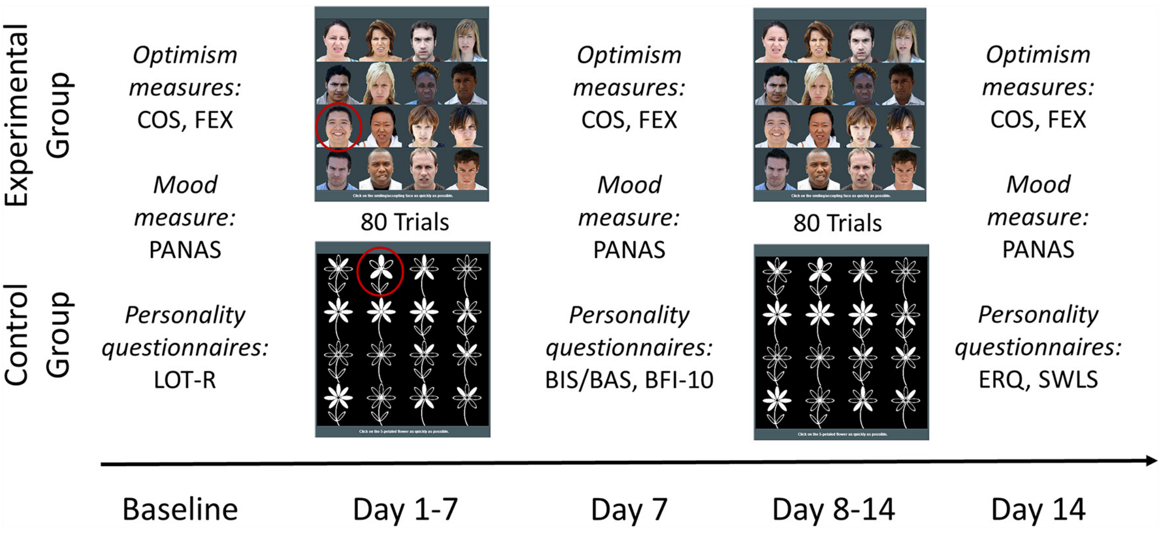

FIGURE 1 | Schematic sequence of the experimental procedure. At baseline, all participants completed the Comparative Optimism Scale (COS; Weinstein, 1980) and Future Expectancy Scale (FEX; Peters et al., 2015) as optimism bias measures (primary outcome), the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988) as a mood measure (secondary outcome), and the Life Orientation Test-Revised (LOT-R; Scheier et al., 1994). For the following 14 days, participants completed daily 80-trial attention bias modification training (ABMT) or control attention training. During ABMT, participants were instructed to click as quickly as possible on the smiling face (here circled in red) among 15 frowning faces in a 4-by-4 matrix; during control training, participants were instructed to click as quickly as possible on the 5-petaled flower (here circled in red) among 15 7-petaled flowers (based on Dandeneau and Baldwin, 2004). On day 7, all participants completed the optimism bias/mood measures, the Behavioral Inhibition System/Behavioral Activation System Scales (BIS/BAS; Carver and White, 1994) and the 10-Item Big Five Inventory (BFI-10; Rammstedt, 2007). On day 14, all participants completed the optimism bias/mood measures, the Emotion Regulation Questionnaire (ERQ; Gross and John, 2003), and the Satisfaction with Life Scale (SWLS; Diener et al., 1985). BIS/BAS, BFI-10, ERQ, and SWLS have been conducted for a larger project on individual differences associated with optimism bias.

same age and gender, to experience 18 positive (e.g., "Marrying someone wealthy") and 23 negative future life events (e.g., "Having a heart attack") on a scale ranging from -3 (much less likely) to 3 (much more likely)[2]. On the FEX (Peters et al., 2015), measuring state optimism, participants indicated the likelihood of experiencing 10 positive (e.g., "You will get a lot of satisfaction out of life") and 10 negative future events (e.g., "You will have health problems") on a 7-point Likert scale ranging from 1 ("not at all likely to occur") to 7 ("very likely to occur"). Sub-scores representing comparative optimism bias and state optimism about future positive events were computed by using mean scores of participants' answers to positive items of the COS and FEX. Reliability was acceptable for the positive subscale of the COS (Cronbach's α = 0.71) and good for the positive subscale of the FEX (Cronbach's α = 0.85) in the current sample.

Secondary Outcome (Mood)

On the PANAS (Watson et al., 1988), participants indicated how strongly they experienced 10 positive (e.g., "excited") and 10 negative feelings (e.g., "distressed") at the moment on a 5-point scale ranging from 1 ("not at all") to 5 ("very much"). Sub-scores representing positive and negative mood were computed by using sum scores of participants' answers to positive and negative items of the PANAS. In the current sample, reliability was good for both the positive (Cronbach's α = 0.85) and the negative subscale of the PANAS (Cronbach's α = 0.81).

Exploratory Outcomes (Optimism Regarding Future Negative Events)

Additionally, sub-scores representing comparative optimism bias and state optimism about future negative events were computed by using mean scores of participants' answers to negative items of the COS and FEX for an exploratory analysis. Reliability was good for the negative subscale of the COS (Cronbach's α = 0.88) and acceptable for the negative subscale of the FEX (Cronbach's α = 0.78) in the current sample.

Data Analysis

Primary Outcome (Optimism Regarding Future Positive Events)

We hypothesized that performing positive-search ABMT increases comparative optimism bias and state optimism for future positive events, whereas performing neutral control training does not. We performed two 3 × 2 analyses of variance (ANOVAs) with the within-subject factor time (baseline, one training week, two training weeks) and the between-subject factor group (experimental, control) on positive sub-scores of COS (Weinstein, 1980) and FEX (Peters et al., 2015). Support for our hypothesis should be reflected in significant time × group interactions. To ensure that potential effects on comparative optimism bias and state optimism

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[2] The German in-house translation of the COS (Weinstein, 1980) used in the current study can be found in **Supplementary Appendix B**.

cannot be explained by group differences in trait optimism, participants' trait optimism scores were included as a covariate in the analyses.

Secondary Outcome (Mood)

We also performed two 3 × 2 ANOVAs with the within-subject factor time (baseline, one training week, two training weeks) and the between-subject factor group (experimental, control) on positive and negative sub-scores of the PANAS (Watson et al., 1988). However, we did not hypothesize, in consistency with earlier findings, an effect of either the positive-search ABMT or the neutral control training on positive or negative mood.

Exploratory Outcomes (Optimism Regarding Future Negative Events)

We further explored whether performing the positive-search ABMT or the neutral control task influenced comparative optimism bias and state optimism regarding future negative events. In this context, we also wanted to test the degree to which effects observed for positive events are comparable to those observed for negative events (for both optimism bias and state optimism). Therefore, we performed two 3 × 2 × 2 ANOVAs with the within-subject factors time (baseline, one training week, two training weeks) and valence (future positive events, future negative events) and the between-subject factor group (experimental, control). Participants' trait optimism scores were included as a covariate in the analyses. We additionally performed two 3 × 2 ANOVAs with the within-subject factor time (baseline, one training week, two training weeks) and the between-subject factor group (experimental, control) on negative sub-scores of COS (Weinstein, 1980) and FEX (Peters et al., 2015). Again, participants' trait optimism scores were included as a covariate in the analyses.

Significant interactions were further investigated by *post hoc* (Sidak corrected) pairwise comparisons. An α-level of 0.05 (two-tailed) was applied to all analyses. Reported effect sizes are partial eta-squared and noted as η_p^2. If the sphericity assumption was violated, Greenhouse-Geisser corrected values are reported.

RESULTS

Training Adherence

On average[3], participants completed 13 of 14 training sessions and training adherence did not differ between the experimental and control groups ($t_{(145)} = 0.770$, $p = 0.442$, $M_{\text{Exp}} = 13.05$, $SD_{\text{Exp}} = 2.41$, and $M_{\text{Con}} = 12.76$, $SD_{\text{Con}} = 2.22$). Of the 147 participants who initially enrolled in the study and had no technical errors during data collection, 81 (55.1%) completed all 14 training sessions, 38 (25.9%) completed 13 of 14 training sessions, 13 (8.8%) completed 12 of 14 training sessions, and one completed 11 of 14 training sessions and started the other three training sessions without finishing (totaling the 133 participants included in the analysis). The remaining 14 participants (9.5%) completed 1 ($N = 2$), 2 ($N = 2$), 4 ($N = 1$), 8 ($N = 1$), 9 ($N = 1$), or 11 ($N = 8$) of the 14 training sessions.

Primary Outcome (Optimism Regarding Future Positive Events)

Comparative optimism bias regarding future positive events did not generally differ between groups, $F_{(1,130)} = 1.119$, $p = 0.292$, $\eta_p^2 = 0.009$, or change over time, when we controlled for variations in trait optimism, $F_{(2,227)} = 0.295$, $p = 0.714$, $\eta_p^2 = 0.002$. Notably, the predicted time × group interaction was significant when we controlled for variations in trait optimism, $F_{(2,227)} = 4.339$, $p = 0.018$, $\eta_p^2 = 0.032$. In line with our hypothesis, comparative optimism bias regarding future positive events increased from before to after two training weeks and showed a trend to increase from before to after one training week and from after one to after two training weeks when people performed daily ABMT (baseline vs. two training weeks: $p = 0.001$, baseline vs. one training week: $p = 0.070$, one training week vs. two training weeks: $p = 0.066$, as revealed by *post hoc* pairwise comparisons). Comparative optimism bias regarding future positive events did not change when people performed neutral control training (baseline vs. two training weeks: $p = 1.000$, baseline vs. one training week: $p = 0.976$, one training week vs. two training weeks: $p = 0.958$; see **Figure 2A**).

By contrast, state optimism regarding future positive events did not differ between groups, main effect of group,

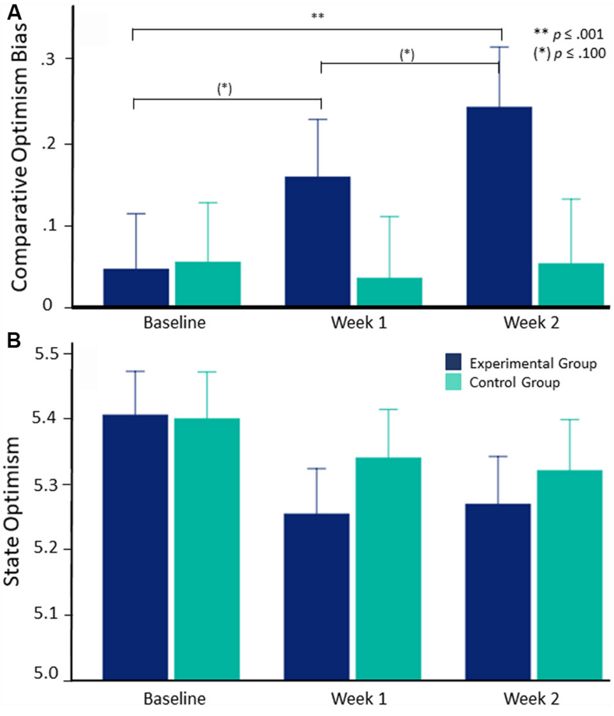

FIGURE 2 | Change in comparative optimism bias and state optimism from baseline to after two training weeks in the experimental/control group. Error bars depict standard errors. **(A)** Comparative optimism bias significantly increases over the 2-week training period in the experimental group but does not change in the control group when we control for trait optimism. **(B)** State optimism does not differ between groups or change over time when we control for trait optimism.

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[3] The raw data of this study can be found in **Supplementary Appendix C**.

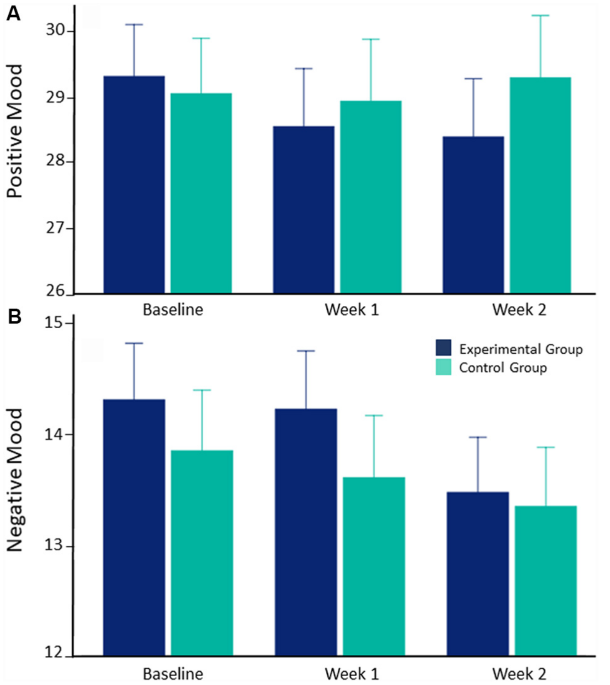

FIGURE 3 | Change in positive and negative mood from baseline to after two training weeks in the experimental/control group. Error bars depict standard errors. **(A)** Positive mood does not change over the 2-week training period in the experimental or control group. **(B)** Negative mood does not change over the 2-week training period in the experimental or control group.

$F_{(1,130)} = 0.218$, $p = 0.641$, $\eta_p^2 = 0.002$; time × group interaction, $F_{(2,226)} = 0.758$, $p = 0.453$, $\eta_p^2 = 0.006$, or change over time when we controlled for variations in trait optimism, $F_{(2,226)} = 0.482$, $p = 0.591$, $\eta_p^2 = 0.004$ (**Figure 2B**).

Secondary Outcome (Mood)

Positive mood did not differ between groups, main effect of group, $F_{(1,131)} = 0.095$, $p = 0.759$, $\eta_p^2 = 0.001$; time × group interaction, $F_{(2,262)} = 0.671$, $p = 0.512$, $\eta_p^2 = 0.005$, or change over time, $F_{(2,262)} = 0.418$, $p = 0.659$, $\eta_p^2 = 0.003$ (**Figure 3A**). Similarly, negative mood did not differ between groups, main effect of group, $F_{(1,131)} = 0.377$, $p = 0.540$, $\eta_p^2 = 0.003$; time × group interaction, $F_{(2,232)} = 0.313$, $p = 0.705$, $\eta_p^2 = 0.002$, or change over time, $F_{(2,232)} = 2.423$, $p = 0.091$, $\eta_p^2 = 0.018$ (**Figure 3B**).

Exploratory Outcomes (Optimism Regarding Future Negative Events)

An exploratory analysis revealed that when valence was added as an additional factor in the analysis, there was only a marginally significant time × valence × group interaction, $F_{(2,220)} = 2.903$, $p = 0.066$, $\eta_p^2 = 0.022$, regarding comparative optimism bias for future events when we controlled for variations in trait optimism. Furthermore, comparative optimism bias regarding future negative events did not differ between groups, main effect of group, $F_{(1,130)} = 0.2.326$, $p = 0.130$, $\eta_p^2 = 0.018$; time × group interaction, $F_{(2,222)} = 0.023$, $p = 0.964$, $\eta_p^2 = 0.000$, or change over time, $F_{(2,222)} = 0.040$, $p = 0.961$, $\eta_p^2 = 0.000$, when we controlled for variations in trait optimism.

There was no significant time × valence × group interaction, $F_{(2,208)} = 1.290$, $p = 0.277$, $\eta_p^2 = 0.010$, regarding state optimism regarding future events when we controlled for variations in trait optimism. State optimism regarding future negative events was significantly lower in the experimental group than in the control group when we controlled for trait optimism, main effect of group $F_{(1,130)} = 4.997$, $p = 0.027$, $\eta_p^2 = 0.037$. However, there was no time × group interaction, $F_{(2,225)} = 0.674$, $p = 0.265$, $\eta_p^2 = 0.010$, and state optimism regarding future negative events did not change over time, $F_{(2,225)} = 1.062$, $p = 0.340$, $\eta_p^2 = 0.008$, when we controlled for variations in trait optimism.

DISCUSSION

The present experiment demonstrates that repeatedly directing attention toward smiling faces and away from frowning faces over 2 weeks enhances comparative optimism bias for future positive events, whereas performing neutral control attention training does not (Weinstein, 1980). Adherence to the online attention training used in the present study was generally high (about 90% of participants completed all or the great majority of training sessions). Furthermore, enhanced optimism bias was specific to future positive events and could not be attributed to peoples' mood (i.e., positive and negative feelings did not change over the training period) or be explained by individual differences in trait optimism (which was controlled for in the analyses).

Thus, training a cognitive habit to pay attention to positive social information not only increases self-esteem and reduces stress, but also enhances optimism bias, an important protective factor for mental health (Dandeneau et al., 2007; Sharot, 2011). What is more, this finding supports the combined cognitive biases hypothesis and implies that (a) expectancy biases are an essential part of the hypothesis (despite being rarely considered in past research; Aue and Okon-Singer, 2015); and (b) cognitive bias interactions are not only present in psychological disorders, but also extend to positivity biases in healthy individuals (Kress and Aue, 2017).

Notably, performing the ABMT does not increase state optimism, but has specific effects on comparative optimism bias. There are two possible explanations for this distinction. First, items of the FEX (Peters et al., 2015) used to measure state optimism are more general than items of the COS (Weinstein, 1980) and might therefore uncover temporary variations in dispositional optimism (i.e., a general positive life orientation that is not necessarily biased, such as the belief that good things will happen) rather than in optimism bias (i.e., biased expectancies about the likelihood of specific future life events, such as being more likely than other people to live past 85 years). Even though dispositional optimism might increase one's readiness to display optimism bias, the two phenomena represent separate concepts (Shepperd et al., 2015).

Second, it is possible that the ABMT used in the current study specifically influenced self-enhancing aspects of comparative optimism bias related to social comparison (Hoorens, 1996). The ABMT has been shown to increase self-esteem (Dandeneau and Baldwin, 2004), which plays an important role in social comparison (Jones and Buckingham, 2005) and may, therefore, mediate the relation between positive attention processes and comparative optimism bias. Furthermore, the ABMT's social stimuli may have had specific effects on the strong social component of comparative optimism bias (i.e., social comparison). A more general ABMT (e.g., using specific words that do not convey a strong social component) might also influence state optimism. To draw final conclusions on such mediating factors, future research should directly examine the relationship between social and non-social ABMT, different measures of optimism bias, and self-esteem.

Notably, we found that, in accordance with the postulate that optimism biases for positive and negative future events represent different aspects with independent motivating factors (Weinstein, 1980; Hoorens, 1996), the influence of the ABMT on comparative optimism was limited to the positive events[4]. Our exploratory analyses for the negative events revealed solely a main effect of group regarding state optimism. However, because this effect remained stable across the three time points considered (i.e., existed already before the experiment), the effect cannot be attributed to the training. It remains to be determined whether other attention modification procedures (e.g., those that train the individual to shift attention away from negative stimuli) are more effective in modifying optimism bias for negative events.

Furthermore, specific mechanisms driving the behavioral effect reported in the current study could be revealed by investigating its underlying neural correlates. Prior investigations of the neural correlates underlying threat-avoidance ABMT, in which people train to direct their attention *away* from negative, maladaptive information, have shown that ABMT may *reduce* activity in limbic brain areas such as the amygdala and insula (Månsson et al., 2013; Taylor et al., 2014) and enhance frontal control (Browning et al., 2010; Taylor et al., 2014). In contrast, positive-search ABMT, in which people train to direct their attention *toward* positive, adaptive information, could make positive social information (i.e., happy faces) more salient and therefore *increase* amygdala and insula activity. Because people usually base their expectancies about the future on information they currently have at hand, we have previously suggested that biased attention toward positive environmental information could strengthen optimism bias and that this process is supported by specific activations in parietal and cingulate cortices (Kress and Aue, 2017). By increasing the saliency of positive, adaptive information, positive-search ABMT could facilitate bottom-up attentional shifts to similar adaptive information in people's environment, and—over time—strengthen optimism bias regarding the future. Of note, the brain's saliency network (comprising the insula and the dorsal anterior cingulate cortex) and the executive control network (especially its more parietal brain areas) have already been shown to play a crucial role in the reverse causal effect, namely, when optimistic expectancies guide attention to positive information (Kress et al., under revision).

Three methodological features of this work might limit the conclusions to be drawn. First, we chose online training in the current study to make sure the training could be easily administered on a large scale (which is the eventual purpose of such cognitive training) and would, therefore, be more useful in both a clinical and non-clinical setting (Holmes et al., 2018). Unfortunately, we were not able to monitor how often participants performed the online training; thus, information on training adherence was based on participants' self-report. However, social desirability bias is usually reduced when questionnaires are self-administered online (Nederhof, 1985) and there is no reason to suspect that social desirability bias would differ between participants in the experimental and control conditions. What is more, if study adherence had been lower than proclaimed by the participants, the observed differences between the experimental conditions should have been even larger. Thus, the main finding observed in the current study (i.e., the influence of the positive ABMT training on comparative optimism bias) should not be limited by self-reported adherence data.

Second, the control training used in the current study did not contain face stimuli (as did the ABMT) and therefore does not control for exposure to faces (and potential associated social effects). For better comparison with earlier findings, we decided to use the same conditions as in prior research on positive-search ABMT (Dandeneau and Baldwin, 2004, 2009; Dandeneau et al., 2007; De Voogd et al., 2014, 2016). Of note, Dandeneau et al. (2007) did include an additional control condition in which participants were asked to look at a matrix of frowning faces similar to the one used in the ABMT. Whereas the ABMT did modulate attention to acceptance/rejection information, pure stimulus exposure did not, making it unlikely that exposure to face stimuli drove beneficial effects on optimism bias in the current study. Yet, to securely rule out this alternative interpretation, future research could include an additional "social" control condition, in which participants are exposed to face stimuli but have to search for a different feature (e.g., the face with brown hair/eyes rather than the smiling face).

The third potential shortcoming relates to the fact that we did not assess whether and how ABMT changed attention processes in the current study (e.g., whether attention bias or attentional control changed throughout the training). Because previous research has already shown that the specific positive-search ABMT used in the current study changes attention bias (Dandeneau et al., 2007), we focused on the training's outcome (i.e., whether extensively training a cognitive habit to direct attention to positive information enhances self-reported optimism bias) instead of the exact attentional mechanisms causing this outcome. Thus, even though it is most likely that the attentional processes targeted by the training

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[4] Note, however, that there was only a marginally significant three-way interaction between the factors time, valence of the event, and group in the three-factorial ANOVA comparing effects for positive vs. negative events; thus the specificity of the ABMT's effects on comparative optimism bias for positive future events needs to be further investigated.

instigated changes in optimism bias, we cannot exclude the possibility that other mechanisms contributed to the reported training effects.

One such mechanism could be stimulus exposure. As mentioned above, because the control training used in the current study did not contain face stimuli, it is possible that changes in optimism bias caused by the ABMT were partly due to stimulus exposure to frowning and smiling faces. However, the ABMT contained an overwhelming majority of frowning faces (each array consisted of 15 frowning faces and only one smiling face), which should from a theoretical point of view reduce rather than increase optimism (Kress and Aue, 2017). Moreover, prior research that used the exact same training protocol as the current study revealed that effects on self-reported outcome measures (e.g., self-esteem) are not merely due to stimulus exposure but instead rely on active attentional mechanisms (Dandeneau et al., 2007). Yet, it is crucial that future research replicates the current findings and additionally includes attention measures to shed light on the exact mechanisms leading to the training's effects on optimism bias.

The specificity of traditional threat-avoidance ABMT in modifying attention bias and emotional outcomes has been discussed controversially because (1) control trainings have often elicited similar changes, and (2) threat-avoidance ABMT may also affect other aspects of attention such as attentional control (Heeren et al., 2015a). Following these controversies, it has been suggested to instead adapt ABMT on the basis of theoretical considerations and investigate its benefits for emotional outcomes (Mogg and Bradley, 2018). When such novel ABMT approaches reliably elicit emotional benefits, attentional mechanisms potentially underlying these benefits should be investigated with multiple measures (e.g., for initial attention orienting, attention maintenance, attention bias variability, attentional control; see Mogg and Bradley, 2016; Mogg et al., 2017; Waters et al., 2016). Notably, from a theoretical perspective, both controlled top-down and automatic bottom-up attention processes potentially targeted by the ABMT are relevant for the mutually enforcing optimism-attention interactions that we aimed to investigate (Kress and Aue, 2017). To draw final conclusions about exactly which attentional mechanisms cause benefits of positive-search ABMT on optimism bias, future research needs to investigate (a) how training affects multiple attentional processes and (b) how this relates to changes in optimism bias. Such investigation can then further refine positive-search ABMT to make it more effective.

Subsequent studies should further include the collection of performance data to (i) control for potential differences in training difficulty/performance between the ABMT and control training and (ii) investigate the influence of different combinations of individual performance and training types on optimism in a dose-response manner. Furthermore, comparative optimism bias could be measured indirectly (i.e., by asking participants to rate the probability of a positive future event happening to them and happening to another person separately) to reveal additional information on whether the ABMT training increased ratings for themselves and/or decreased ratings for the average other. The specific assessment of comparative optimism in the current study did not permit such conclusions because participants rated their personal likelihood of encountering positive future events related to the likelihood of the average person of the same gender and age.

In general, the present findings contribute to a more nuanced view on the cognitive processes underlying optimism bias. A cognitive habit to pay attention to positive information is likely involved in the development and maintenance of optimism bias and, therefore, reveals how it can be triggered and maintained (Kress and Aue, 2017).

We have previously shown that optimistic expectancies strongly guide attention toward reward (Kress et al., 2018) and hypothesized that subsequent attention to positive information stabilizes optimism bias. Such supportive attention processes could explain why future expectancies are selectively updated into an optimistic (not a pessimistic) direction following feedback (Sharot, 2011). The current results independently reveal the crucial missing piece of information corroborating our idea that attention processes maintain optimism bias over time: Directing attention to positive information does indeed enhance optimism bias and can thereby provoke positive feedback effects on initial optimistic expectancies. Together, these findings argue for dynamic bidirectional optimism-attention interactions that maintain positivity and contribute to well-being and mental health.

Identifying the concrete attentional mechanisms underlying optimism bias will contribute in an important way to our understanding of its maintenance over time. Along these lines, future research should uncover the neural basis underlying this optimism-attention interplay, thereby supplementing and informing behavioral investigations. Specifically, the neurocognitive model proposed to underlie the dynamic optimism-attention interplay (Kress and Aue, 2017) needs to be backed up with further empirical neural data. For instance, it is possible that optimistic expectancies drive ongoing visual attention toward supporting positive information *via* top-down mechanisms initiated in frontal and prefrontal brain regions (e.g., anterior cingulate cortex, ventromedial prefrontal cortex/orbitofrontal cortex). At the same time, it is possible that bottom-up attentional shifts toward positive environmental information represented in more posterior and parietal brain regions (e.g., posterior parietal cortex, posterior cingulate cortex) strengthen optimism about the future (as future expectations are usually based on information currently at hand).

Examining the neural correlates of positive-search ABMT influencing optimism bias can thus provide essential information on which brain regions are activated when shifts in attention influence optimism and additionally extend the existing literature on neural mechanisms of ABMT which has, so far, focused on threat avoidance (Browning et al., 2010; Månsson et al., 2013; Taylor et al., 2014). Moreover, neuroimaging studies can identify brain areas involved in dynamic cognitive-bias interactions and point to the neurotransmitter systems that are involved. In case an individual manifests malfunctioning or maladaptive interactions (i.e., in psychological disorders), these might then be targeted by specific cognitive and pharmacological interventions. Studies examining neural correlates of cognitive-bias interactions may, therefore, reveal valuable insights for applications in the clinical domain and in everyday life.

In fact, a central finding in the current study is that (comparative) optimism bias is malleable and can be easily modified by adequate attention modification procedures. Thus, being optimistic can be learned or trained and one is not deemed to be either high or low on optimism bias. Moreover, the present findings imply that, in everyday life, focusing on positive aspects of the environment can boost optimism, and thereby most certainly motivation, concerning a difficult task. In the clinical domain, the findings imply that changing one aspect of biased cognition can alter other aspects, thereby revealing multiple starting points for possible modification. The current evidence is hence suggestive and might improve overall conditions for the prevention and treatment of psychological disorders. Notably, ABMT has especially great potential because it can be a low-cost, standardized, and easy-to-access support for psychotherapy. Online training that does not require therapist contact constitutes a first intervention for people with contact anxiety (e.g., social phobia) and for patients who have to wait months before seeing a psychotherapist because of an overstrained health system.

In conclusion, our data show that directing attention toward positive and away from negative social information enhances comparative optimism bias. Uncovering such cognitive processes underlying optimism bias is essential for employing its benefits for mental health. Positive-search ABMT could trigger a self-sustaining upward spiral of positivity (through dynamic optimism-attention interactions), making our findings central for individual well-being as well as for the prevention and treatment of psychological disorders (Garland et al., 2010; Kress and Aue, 2017). In particular, the present findings reveal that paying attention to positive information around us makes us more optimistic about our future and they lead to some practical advice: If we want to look toward a great future, we should start looking at the good things around us right now.

ETHICS STATEMENT

Participants gave written informed consent according to the guidelines of the ethical standards of the Declaration of Helsinki and were told that they could end the experiment at any time. All procedures were approved by the local ethical review board.

AUTHOR CONTRIBUTIONS

LK and TA designed and planned the experiment and reviewed and edited the manuscript. LK performed the experiment, and analyzed the data, and wrote the initial draft of the manuscript. TA provided funding and supervised the project.

FUNDING

This research was supported by the Swiss National Science Foundation (Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung; Grant Number PP00P1_150492, PI: TA). The funding source was not involved in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

ACKNOWLEDGMENTS

We thank Mark Baldwin and Stéphane Dandeneau for providing the attention training used in this study on their website. Moreover, we thank Valérie Cattilaz, Marina Dauwalder, Marion Inhelder, and Katrin Negele for assistance with data collection. A previous version of this manuscript first appeared in LK's dissertation thesis (Kress, 2019).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2019.00222/full#supplementary-material

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

PERSPECTIVE
published: 10 July 2019
doi: 10.3389/fnhum.2019.00237

Promoting Psychological Well-Being Through an Evidence-Based Mindfulness Training Program

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Psychological well-being is a core feature of mental health, and may be defined as including hedonic (enjoyment, pleasure) and eudaimonic (meaning, fulfillment) happiness, as well as resilience (coping, emotion regulation, healthy problem solving). To promote psychological well-being, it is helpful to understand the underlying mechanisms associated with this construct and then develop targeted and effective training programs. In this perspective article, we discuss key components and potential brain-body mechanisms related to psychological well-being and propose mindfulness training as a promising way to improve it. Based on a series of randomized controlled trial (RCT) studies of one form of mindfulness training in adolescents and adults, the integrative body-mind training (IBMT), we use IBMT as an exemplar to provide research evidence of the positive effects of mindfulness training on psychological well-being. We focus on one of the mechanisms by which IBMT enhances psychological well-being—the interaction between mind (mindfulness) and body (bodifulness)—which involves both the central nervous system (CNS) and the autonomic nervous system (ANS). We also highlight the role of brain self-control networks, including the anterior cingulate cortex/prefrontal cortex (ACC/PFC), in improving psychological well-being. We suggest that mindfulness training may be a promising program that promotes the synergistic engagement of mind and body to achieve the goals of enhancing psychological well-being.

Keywords: emotions, psychological well-being, IBMT, mindfulness, bodifulness, quality of life, anterior cingulate cortex, striatum

Edited by:
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Medical University of Vienna, Austria
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Received: *03 April 2019*
Accepted: *26 June 2019*
Published: *10 July 2019*

Citation:
Tang Y-Y, Tang R and Gross JJ (2019) Promoting Psychological Well-Being Through an Evidence-Based Mindfulness Training Program. Front. Hum. Neurosci. 13:237. doi: 10.3389/fnhum.2019.00237

PSYCHOLOGICAL WELL-BEING AND HEALTH

The importance of mental health has been increasingly emphasized in recent decades as public awareness and understanding grow. Mental health is now understood to involve both the absence of mental illness and the presence of psychological well-being. Psychological well-being is a complex construct that concerns optimal psychological functioning and experience. It may be defined as including hedonic (enjoyment, pleasure) and eudaimonic (meaning, fulfilment) happiness as well as resilience [coping, emotion regulation, healthy problem solving; Gross and Munoz, 1995; Ryff, 1995; Ryan and Deci, 2001; Community Translational Science Team (CTST), 2016; NIH Report, 2018]. Elements of psychological well-being include a sense of balance in emotion, thoughts, social relationships, and pursuits [Brown and Ryan, 2003; Community Translational Science Team (CTST), 2016; Feller et al., 2018; NIH Report, 2018], which necessitates active engagement of self-control processes such as emotion regulation. Emotion regulation is defined as the processes by which we influence which emotions we have, when we have them, and how we experience and express them (Gross, 1998).

Accumulating evidence has supported a causal relationship between greater psychological well-being and better overall health and improved disease-specific outcomes (Ong, 2010; Diener and Chan, 2011; DeSteno et al., 2013; Kok et al., 2013; Cohen et al., 2016). For example, changing states of well-being by increasing positive emotion and decreasing negative emotion result in salutary physiological/biological changes (e.g., inflammation, immune functioning), and contributes to diverse positive health outcomes (e.g., cardiovascular health; Kiecolt-Glaser et al., 2002; Howell et al., 2007; Diener and Chan, 2011; Feller et al., 2018).

MINDFULNESS AND PSYCHOLOGICAL WELL-BEING

Several systematic reviews and meta-analyses have suggested that psychological well-being can be enhanced by interventions such as mindfulness training (Brown and Ryan, 2003; Hutcherson et al., 2008; Weinstein et al., 2009; Hofmann et al., 2011; Goyal et al., 2014; Kong et al., 2016; Garland et al., 2017; McConville et al., 2017; Feller et al., 2018). One particular focus has been Integrative body-mind training (IBMT), which shares key components with other forms of mindfulness training, such as a systematic training of attention and self-control with an attitude of acceptance and openness to present experiences (Tang et al., 2007, 2015; Tang, 2017).

In a series of randomized controlled trials (RCTs), IBMT has shown multiple positive effects on psychological well-being and health, including increased self-control and positive emotions, and decreased negative emotions and stress hormones (Tang et al., 2007, 2015; Ding et al., 2014). In one RCT, young adults were assigned randomly to an IBMT or a relaxation training (RT) group for five sessions of brief training (20 min per session). Compared to those in RT, IBMT participants showed greater improvement (from baseline to post-training) of performance in executive control (an index of self-control). IBMT participants also had lower levels of negative affect and higher levels of positive affect (Tang et al., 2007; Ding et al., 2014). In addition, IBMT participants also showed decreased stress hormone cortisol and increased immune reactivity (secretory Immunoglobulin A; Tang et al., 2007). Longer training (e.g., 20 sessions) in IBMT reduced basal stress level of cortisol and increased basal immune function, suggesting better health outcomes (Tang, 2017). To test the generalizability of these IBMT findings, we used the same RCT design in older adults and adolescents and detected similar effects on psychological well-being and health (Tang, 2009, 2017; Tang et al., 2014). In particular, following long-term IBMT practice, older adults showed significantly higher ratings in overall score of quality of life, including physical, psychological, independence and social relationships using WHOQOL-100 (Tang, 2017). Taken together, findings suggest IBMT has positive effects on psychological well-being and health.

Despite these promising findings (Chambers et al., 2009; Hölzel et al., 2011b), neurobiological studies of mindfulness training directly relating behavioral changes to brain functional activity changes remain sparse (Tang et al., 2015; Fox et al., 2016). With regard to psychological well-being, functional neuroimaging studies have yet to demonstrate a straightforward relationship between brain and behavioral improvement following mindfulness training. Nonetheless, there has been some indirect evidence showing that mindfulness capacity, a trait that is often increased after mindfulness training, can modulate neural responses to emotion-related stimuli and influence affective processing (Frewen et al., 2010; Brown et al., 2013). While correlating behavioral outcomes and alterations in brain activity and functional connectivity is somewhat challenging, given the modest sample size of typical neuroimaging studies of mindfulness training, some encouraging findings have illustrated that brain structural changes are related to improved behavioral outcomes. For instance, our RCT study on IBMT has demonstrated that improvements in white matter connectivity in anterior cingulate cortex (ACC) and PCC are correlated with enhanced positive emotion, suggesting a putative neural mechanism that underlies improvement in psychological well-being (Tang et al., 2012). Likewise, one study showed that compared to waitlist control, 2 months of mindfulness-based stress reduction induced gray matter reduction in the amygdala, which was correlated with decreased stress, suggesting an improvement in psychological well-being (Hölzel et al., 2011a; Davidson and McEwen, 2012). Together, these findings provide some evidence that mindfulness training may enhance psychological well-being through influencing brain structural plasticity. However, future investigation should focus on establishing a direct relationship between brain functional changes and behavioral improvement following mindfulness training in RCT design with a large sample size.

HOW INTEGRATIVE BODY-MIND TRAINING (IBMT) WORKS

To design effective interventions for promoting psychological well-being, we need to understand how mindfulness training such as IBMT works. Our previous work has shown increases in functional and structural plasticity of self-control networks—ACC/prefrontal cortex (PFC) and striatum support IBMT effects (Tang et al., 2009, 2010, 2012, 2015; Tang, 2017). For instance, in an RCT study with 40 college students randomly assigned to either an IBMT or RT group (20/group), the IBMT group (not RT group) had a significant cerebral blood flow increase in the (ACC; BA25, BA32), adjacent medial PFC (mPFC; BA10) and insula after a five-session training. The group × session interaction was significant for BA25 and BA10, respectively (Tang, 2017). Another RCT (IBMT vs. RT) with a large sample size also showed the stronger subgenual and adjacent ventral ACC activity and striatum activity following a five-session training in IBMT (Tang et al., 2009). These findings suggest that brief IBMT changes brain activity and functional connectivity in the ACC (Tang, 2017).

Does longer IBMT practice induce brain structural plasticity? To test this hypothesis, we randomly assigned 45 college students into IBMT or RT groups (23:22) and delivered a 20-session training within a 4-week period (30 min per session, ∼10 h in total). Using diffusion tensor imaging (DTI), we found significant increases in fractional anisotropy (an index of the white matter integrity and efficiency) in the ventral and dorsal corona radiata, an important white matter tract connecting the ACC to other structures (Tang et al., 2010). These changes were found in a band of white matter tracts connecting the ACC to striatal and cortical areas (Tang et al., 2010, 2012, 2015). To examine the time-course of white matter plasticity following IBMT, in another RCT, IBMT or RT groups received 10–20 sessions of training within 2–4 weeks. After 2-weeks of IBMT, the structural changes were mainly in axial diffusivity (an index of axonal density), while after 4-weeks both axial diffusivity and radial diffusivity (related to myelination) were improved (Tang et al., 2012; Tang, 2017). These findings indicated that IBMT induced functional and structural plasticity of self-control networks and fit well with meta-analyses of mindfulness effects on functional and structural changes (Hölzel et al., 2011b; Tang et al., 2015).

THE ROLE OF BODY AND MIND

In IBMT practice, cooperation between body and mind is emphasized in facilitating and achieving a meditation state. We thus hypothesized that one key mechanism of IBMT involves the interaction of central nervous system (CNS, brain) and autonomic nervous system (ANS, body; Tang et al., 2007, 2009, 2015). To test the hypothesis that body (physiology) and mind (brain) interaction and balance are crucial to the observed effects of IBMT, in one RCT, one group of college students was randomly assigned to experimental (IBMT) and control (RT) conditions, and received brain imaging (cerebral blood flow) and physiological measures, whereas another group of college students was randomized into IBMT and RT conditions, but underwent EEG with physiological measures. To monitor ANS activity at rest before, during, and after five 30-min sessions of IBMT or RT, in both conditions, the physiological measures included respiratory rate and amplitude, heart rate, and skin conductance response (SCR; Tang et al., 2009).

During and after the 5-session training, the IBMT group showed lower chest respiratory rate, heart rate, and SCR, but greater belly respiratory amplitude than the RT control (Tang et al., 2009), suggesting greater parasympathetic regulation of ANS. High-frequency heart rate variability (HF-HRV) is related to parasympathetic activity of the ANS and ventral ACC activation often correlates with HF-HRV, suggesting ACC regulation of parasympathetic autonomic activity (Kubota et al., 2001; Matthews et al., 2004). Compared to the same amount of RT, we also detected increased HF-HRV and frontal midline ACC theta power, suggesting greater involvement of the ANS (especially parasympathetic activity) during and after IBMT. Brain imaging showed stronger subgenual and vACC activity following IBMT and frontal midline ACC theta also correlated with HF-HRV, suggesting control by the ACC over parasympathetic activity. These findings indicate that after brief training, the IBMT shows improved ANS regulation through the self-control system such as ACC compared to the RT. This enhancement probably reflects training in the coordination and balance of body and mind by IBMT.

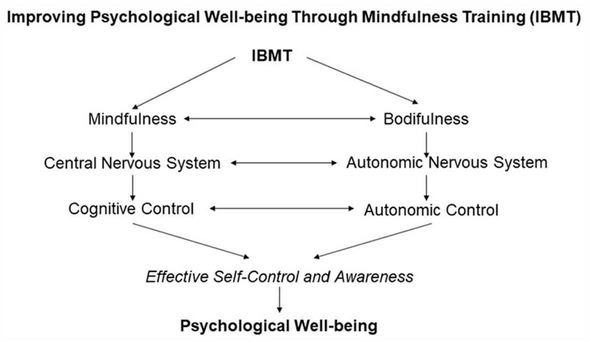

FIGURE 1 | Integrative body-mind training (IBMT) and psychological well-being.

As shown in **Figure 1**, IBMT improves psychological well-being through mindfulness and bodifulness that mainly strengthen self-control ability and related CNS (i.e., ACC/mPFC and striatum) and ANS systems (i.e., parasympathetic activity; Tang et al., 2009, 2010, 2012, 2015; Kong et al., 2015). In the mindfulness field, mind or thought control is often emphasized, but the role of the body is often ignored (Kerr et al., 2013; Tang, 2017). Bodifulness refers to the gentle adjustment and exercise of body posture with a full awareness, in order to achieve a presence, balance, and integration in our bodies. For instance, bodifulness mainly involves implicit processes such as visceral or interoceptive awareness regulated by ANS. Autonomic control requires less effort and is mainly supported by the ACC/mPFC and striatum (Critchley et al., 2003; Naccache et al., 2005; Jones et al., 2015; Tang et al., 2015; Tang, 2017).

In IBMT practice, mind–body coordination and interaction are emphasized and thus significantly facilitate the training outcomes (Tang et al., 2007, 2015; Tang, 2009, 2017). Full awareness and presence of the body (bodifulness) could facilitate the mindfulness process, consistent with the literature that body posture and state affect mental processes such as emotional processing, the retrieval of autobiographical memories, and cortisol concentrations (Hennig et al., 2000; Dijkstra et al., 2007; Niedenthal, 2007; Huang et al., 2011). In early stage, mindfulness requires conscious cognitive control with effort and is supported by the dorsal lateral PFC and parietal cortex but over time, it may well involve less effort when the practice becomes more skillful, which is supported by the ACC and striatum (Tang, 2017). Cognitive control (termed as doing state) and autonomic control (termed as being state) are both key components of self-control supported by the practice and interaction of mindfulness and bodifulness, which may drive behavior and habit formation effectively (Tang et al., 2015; Tang, 2017). Taken together, if interventions such as IBMT target increases in psychological well-being through the engagement of both body and mind, effectiveness may be enhanced.

CONCLUSIONS

A growing literature supports the idea that there is an important relationship between psychological well-being and mental and physical health in both adolescents and adults (Ong et al., 2011; DeSteno et al., 2013). IBMT has been shown to improve psychological well-being, and appears to do so *via* changes in self-control that are reflected in changes in both the central (brain/mind) and the autonomic (body/physiology) nervous systems. In particular, IBMT changes the state of body and mind to lead to positive outcomes in emotion, cognition, and behavior. IBMT is a paradigmatic case of how it is possible to use an evidence-based intervention that targets brain, physiology, and behavior to achieve the goals of psychological well-being and human flourishing.

In this perspective piece, we have focused on the self-control networks supporting psychological well-being following IBMT, but it should be noted that the reward system supporting motivation and positive emotion also closely links to psychological well-being (Tang et al., 2009, 2015; Tang, 2017). Future work should explore the interaction between self-control and reward systems that improve and optimize psychological well-being and mental and physical health. Moreover, different interventions may target different brain networks, and it's important to understand how different types of training programs differentially impact different brain systems and how different people might preferentially benefit from one type of intervention vs. another (Tang et al., 2015, 2016).

DATA AVAILABILITY

No datasets were generated or analyzed for this study.

AUTHOR CONTRIBUTIONS

Y-YT, RT and JG contributed to manuscript writing.

FUNDING

This work was supported by National Institutes of Health (NIH) R61AT010138.

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

ORIGINAL RESEARCH
published: 16 July 2019
doi: 10.3389/fnhum.2019.00242

Emotion Regulation of Hippocampus Using Real-Time fMRI Neurofeedback in Healthy Human

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Real-time functional magnetic resonance imaging neurofeedback (rtfMRI-NF) is a prospective tool to enhance the emotion regulation capability of participants and to alleviate their emotional disorders. The hippocampus is a key brain region in the emotional brain network and plays a significant role in social cognition and emotion processing in the brain. However, few studies have focused on the emotion NF of the hippocampus. This study investigated the feasibility of NF training of healthy participants to self-regulate the activation of the hippocampus and assessed the effect of rtfMRI-NF on the hippocampus before and after training. Twenty-six right-handed healthy volunteers were randomly assigned to the experimental group receiving hippocampal rtfMRI-NF (n = 13) and the control group (CG) receiving rtfMRI-NF from the intraparietal sulcus rtfMRI-NF (n = 13) and completed a total of four NF runs. The hippocampus and the intraparietal sulcus were defined based on the Montreal Neurological Institute (MNI) standard template, and NF signal was measured as a percent signal change relative to the baseline obtained by averaging the fMRI signal for the preceding 20 s long rest block. NF signal (percent signal change) was updated every 2 s and was displayed on the screen. The amplitude of low-frequency fluctuation and regional homogeneity values was calculated to evaluate the effects of NF on spontaneous neural activity in resting-state fMRI. A standard general linear model (GLM) analysis was separately conducted for each fMRI NF run. Results showed that the activation of hippocampus increased after four NF training runs. The hippocampal activity of the experiment group participants was higher than that of the CG. They also showed elevated hippocampal activity and the greater amygdala–hippocampus connectivity. The anterior temporal lobe, parahippocampal gyrus, hippocampus, and amygdala of brain regions associated with emotional processing were activated during training. We presented a proof-of-concept study using rtfMRI-NF for hippocampus up-regulation in the recall of positive autobiographical memories. The current study may provide a new method to regulate our emotions and can potentially be applied to the clinical treatment of emotional disorders.

Keywords: hippocampus, real-time fMRI neurofeedback, emotion, regulation, autobiographical memories

Edited by:
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Received: *21 December 2018*
Accepted: *28 June 2019*
Published: *16 July 2019*

Citation:
Zhu Y, Gao H, Tong L, Li Z, Wang L, Zhang C, Yang Q and Yan B (2019) Emotion Regulation of Hippocampus Using Real-Time fMRI Neurofeedback in Healthy Human. Front. Hum. Neurosci. 13:242. doi: 10.3389/fnhum.2019.00242

INTRODUCTION

Emotion plays a significant role in our daily lives. Our life is colorful through emotion (Dixon et al., 2017). However, the negative emotion has a bad effect on our life. The more we let our negative thoughts occupy our mind without interruption, the more interconnected they will become. Emotional disorders have become a huge threat to human mental health. It includes major depressive disorder (MMD), anxiety disorder (hypochondriasis), and other affective disorders, and patients' symptoms usually occur during emotional fluctuation or in calm state (English et al., 2012). MDD is a common disorder which can be disabling. About two-thirds of MMD patients do not receive adequate treatment in drug therapy and psychological interventions, and only a few of them get symptom relief (Young et al., 2018). These emotional disorders may affect people's work efficiency, causing them to live with the pain and induce disharmony with society. How we regulate our emotions matters: Our well-being is inextricably linked to our emotions. Emotion regulation is a crucial skill associated with well-being and mental health in general.

Real-time functional magnetic resonance imaging neurofeedback (rtfMRI-NF) as a potential method to improve the capability of emotion regulation and alleviate neuropsychiatric disorder symptoms has rapidly developed in recent years (Ruiz et al., 2014). Various brain regions can be used for rtfMRI-NF-augmented emotion regulation training because of their differing involvement in emotion processing and emotion regulation (Morawetz et al., 2017). The activity of some regions is associated with the intensity of emotional experiencing; the activity of other regions is associated with the implementation of emotion regulation strategies (Raffael and Reviews, 2009; Paret et al., 2011). For example, the amygdala and anterior insula (AI) have been repeatedly found to be involved in experiencing both positive and negative emotions (Sergerie et al., 2008; Kurth et al., 2010). Thus, the amygdala or AI activity levels can be taken as correlates of emotional experiencing intensity, regardless of the emotional valence, i.e., regardless of whether the person experiences positive or negative emotions. On the other hand, lateral prefrontal cortex (LPFC) regions have been repeatedly found to be involved in cognitive emotion regulation (Kohn et al., 2014). Thus, LPFC activity levels can be taken as correlates of cognitive emotion regulation efforts. NF-aided emotion regulation can be studied in healthy people, but the clinical goal of rtfMRI-NF is to promote emotion regulation in patients whose ability to regulate emotions is impaired. Emotion regulation impairment is a frequently occurring challenge for patients with different mental disorders, including mood, anxiety, stress, and personality disorders (Kring and Moran, 2008). Thus, a focus on enhancing emotion regulation is a key feature in therapy for many psychiatric patients. At the same time, the type of emotion regulation impairment can differ among patient groups (i.e., different brain regions can be affected or the same regions can be affected in a different way). For example, patients with depression show an exaggerated amygdala response to negative stimuli and an attenuated amygdala response to positive stimuli (Groenewold et al., 2013). Accordingly, the goal of rtfMRI-NF in patients with depression could be to decrease amygdala activity during the experience of negative emotions or to promote amygdala activity while experiencing positive emotions. It has been used in clinical application. For example, some research reduced the symptoms of depression by up-regulating of amygdala. Studies using this technique have demonstrated that it may be possible to successfully manipulate brain areas including the anterior cingulate cortex (Weiskopf et al., 2003; Hamilton et al., 2011), the posterior cingulate cortex (Brewer and Garrison, 2014), the anterior insular cortex (Caria et al., 2007; Andrea et al., 2010; Berman et al., 2013), posterior insular cortex (Mariela et al., 2015), amygdala (Posse et al., 2003; Vadim et al., 2011; Brewer and Garrison, 2014), primary motor and somatosensory cortex cortices (Yoo and Jolesz, 2002; Berman et al., 2012), premotor area, visual cortex (Kazuhisa et al., 2011), auditory cortex (Seung-Schik et al., 2006; Haller et al., 2013), substantia nigra/ventral tegmental area (Sulzer et al., 2013), nucleus accumbens (Greer et al., 2014), and inferior frontal gyrus (Rota et al., 2010).

The hippocampus plays an important role in the system of central nervous, especially in episodic memory and spatial navigation (Squire, 1991; Buzsaki and Moser, 2013). Considerable studies have concentrated on the application of hippocampus in emotion regulation and response to positive emotional pictures or stimuli. Meanwhile, hippocampus engagement appears to be critical for emotion processing and response to positive stimuli, including autobiographical memories (AMs) (Santangelo et al., 2018). Valerio found that low-frequency activities in the hippocampus can enhance the connectivity of interhemispheric resting-state fMRI in various cortices and hippocampus (Russell Wade et al., 2017). The hippocampus, located in the medial temporal lobe and connected with the amygdala that controls emotional memory recalling and regulation (Schumacher et al., 2018); it has increased the functional connectivity with anterior cingulate or amygdala during emotional regulation and recalling of positive memory (Guzmán-Vélez et al., 2016). Brühl et al. (2014) confirmed that the hippocampus is involved in emotion regulation (Ruiz et al., 2014). His finding also suggested that the hippocampus regulation has the potential to be applied in the clinical treatment of mental disorders, such as addiction, anxiety, and depression.

The imaging basis of fMRI is based on the blood oxygenation level dependent (BOLD) effect. In recent years, this technology has been widely used in the study of diseases such as Parkinson's disease and depression. BOLD effect depends on the magnetic properties of deoxyhemoglobin sensitivity. Both regional homogeneity (ReHo) and amplitude of low frequency fluctuation (ALFF) are based on the BOLD signal. ReHo technology can measure the local consistency of the spontaneous low-frequency oscillation signal of the brain. It means that when a functional brain area is activated, the voxel of this brain area has more time-series change consistency. ReHo increase indicates that the local brain area consistency increases. ReHo Decrease the local brain region consistency, which indicates that the abnormality of ReHo value may indicate the consistency of neuronal activity and the abnormality of synchronization, further indicating the disorder of neuronal metabolic activity.

This method can better reflect the active status of whole brain. ALFF reflects the spontaneous activity of neurons. When the spontaneous activity of neurons increases, ALFF increases. When the spontaneous activity of neurons decreases, ALFF decreases. ReHo and ALFF are two different methods of fMRI post-processing. Through these two techniques, more changes in brain function can be found.

In this research, we systematically checked the influence of NF on the activity of hippocampus based on the psychological images of positive AMs. Moreover, we also assessed the influence of NF on regulation by comparing NF and the use of pure mental strategies with pseudo-NF delivery. We used the hippocampus as a region of interest (ROI) which several studies that demonstrate that the hippocampus is an important part of limbic system. We measured the primary experimental outcome using the beta weights of NF condition (regulate) and compared to the view condition (view). We supposed that there was an upward trend of the beta weights in the regulation condition from the run 1 to the run 4 compared with the view condition and this result was better in the NF group (FG) than in the control group (CG). Moreover, the result of a control region indicated that it is not affected by NF. In addition, we investigated the changes of resting-state fMRI data using ReHo (Zang et al., 2004) maps after the rtfMRI-NF, and calculated the amplitude of low frequency (ALF) fluctuations (Zou et al., 2008).

MATERIALS AND METHODS

Participants

Thirty-one right-handed healthy volunteers [mean ± standard deviation (SD) age, 23.2 ± 1.4 years] were recruited from China National Digital Switching System Engineering and Technological Research Center. All participants were healthy and were naive to rtfMRI-NF. We randomly assigned the volunteers to two groups, namely, the experimental group (mean age = 23.7 years, *SD* = 1.3, range 22–26, 10 male, 7 female, feedback from hippocampus: EXP) and the CG (mean age = 22.6 years, *SD* = 1.4, range 21–24, 7 male, 7 female, feedback from the intraparietal sulcus: CON) (Annette Beatrix et al., 2014). Five volunteers were excluded based on the following criteria: due to two subjects unfinished the NF runs, two subjects check realignment >1.5 mm, and one subject technical problem. The Ethics Committee of Henan Provincial People's Hospital approved the research protocol. Volunteers written informed consent to participate in the study and we gave the financial reward to them.

Procedure

Participants were randomly assigned to the FG receiving the NF of the hippocampus ($n = 13$) and the CG provided the NF of intraparietal sulcus ($n = 13$) and completed two sessions (Young et al., 2017). To characterize emotion regulation from the baseline and impulsive traits, the participants completed questionnaires consisting of emotion regulation questionnaire (ERQ), self-rating depression scale (SDS) (Fukuda and Kobayashi, 1973), self-rating anxiety scale (SAS) (Olatunji et al., 2006), positive and negative affect scale (PANAS) (David et al., 1988), and Hamilton depression scale (HAMD). They completed one resting run and two feedback runs. The participants completed their second rtfMRI-NF session after 7 days (**Figure 1**). During Sessions 1 and 2, participants finished two 6 min 20 s resting-state scans in which they were asked to fixate on a cross, stay relaxed. Then, the participants completed rtfMRI-NF training after the resting-state scan (Zhonglin et al., 2016). The NF training run lasted 6 min 20 s. Participants were asked to recall positive AMs when increasing the activity of the assigned region and were instructed to keep this strategy even though they found it has no effect when increasing the ROI activity. They were suggested to concentrate on the positive AMs, the happiness in this memory, and its relation to their self-concept.

The rtfMRI system: it obtains information from signals of BOLD in real-time and closed-loop. Thus, these NF signals of participants can be provided to control the activity of the brain. On the whole, the rt-fMRI system consists of: (1) the subjects, (2) fMRI data scans, (3) preprocessing of fMRI data, (4) analysis, and (5) NF (**Figure 2**).

Experimental Paradigm

A practice run was applied to the participants for approximately 20 min at 1 day before scanning to familiarize them with the experimental procedure. The instructions were given to them, including the purpose of this research and the paradigm of NF. Before scanning, every participant noted down for happy AMs. In this experiment, several examples were provided to them, such as traveling, getting a good grade, and falling in love with a girl or boy. The subjects were instructed to induce positive emotions using positive memories during scanning.

Participants completed four feedback runs. Every run started with a pre-scanning of 20 s to obtain magnetization equilibrium. Then, participants performed five blocks, which included view, count, and feedback conditions. For the view condition, images of positive sets were centrally presented at 4 s each, and participants tried their best to imagine experiencing the depicted situation. For the feedback condition, participants attempted to recall positive AMs that could help them up-regulate their activity of the brain region. For the count condition, participants were asked to fixate at a displayed cross and think of nothing in particular (**Figure 3**).

Each NF run consisted of alternating blocks of pictures, regulation, and count. Each session included two NF runs (6 min 20 s), and a rest run without NF information was provided after two training runs. The stimuli consisted of positive pictures obtained from the International Affective Picture Set. Three pictures were showed in each block lasted for 4 s (total block time is 12 s). Eighty images (mean and *SD* for normative valence 6.67 ± 0.24) were used for two positive runs. All images were displayed in Psychopy[1].

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[1] http://www.psychopy.org/

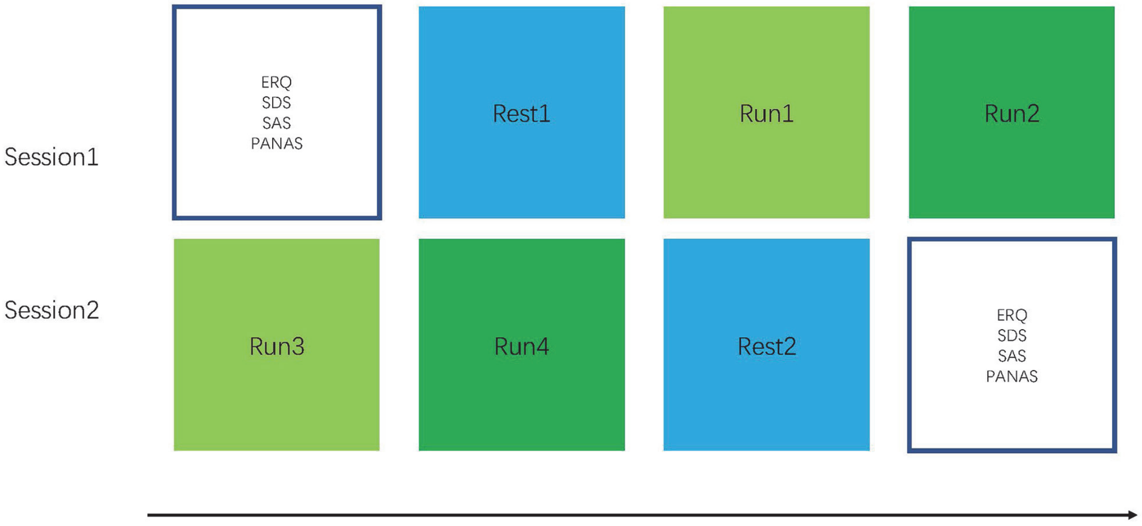

FIGURE 1 | Experimental procedure: The experiment consisted of six runs with a length of 6 min 20 s each. In the beginning of the experiment, a localizer is used for hippocampus mask positioning (participants are instructed to relax). During the four training runs, the participants performed NF-based neurofeedback (NF)-based regulation of hippocampus. For the rest run, the participants are instructed to open their eyes, fixate on a cross, relax, and not think about anything in particular.

Online Data Analysis

Online fMRI data were performed in Analysis of Functional NeuroImages (AFNI[2]). Before the NF procedure, a short EPI (20 s) scan and a T1image were acquired for each participant. The T1 image was transformed in Talairach space. We defined the bilateral ROI in the Talairach space. They were first turned into the original T1 space, and the short EPI scan was used to define the EPI space. Thus, the ROI mask in the EPI space was constructed (**Figure 4**). All volumes of EPI were volume-registered to the same single EPI volume during the rtfMRI-NF. In this way, the masks of ROI were used to all fMRI data in real time (Young et al., 2014). The volume location of all acquired volumes exported to the mean values of BOLD activity for the ROI performed by an AFNI real-time module during the rtfMRI-NF. Real-time data analysis comprised incremental 3D motion detection and correction and drift removal and resulted in incrementally computed statistical maps based on the general linear model (GLM) and event-related averages. Then, the mean signals were used to calculate the NF score and it was updated every 2 s. The NF signal of each feedback condition was computed as follows:

$$\text{Score}_i = \frac{(\text{BOLD}_i - \text{BOLD}_{\text{baseline}})}{\text{BOLD}_{\text{baseline}}} \times 100,$$

where $\text{BOLD}_{\text{baseline}}$ represents the BOLD signal of the hippocampus in the last count condition before the i repetition time (TR), and BOLD_i represents the BOLD signal of the hippocampus in the i TR (i = 1, 2, ...), which are computed every 2 s and expressed in a number (Vadim et al., 2011; Young et al., 2016).

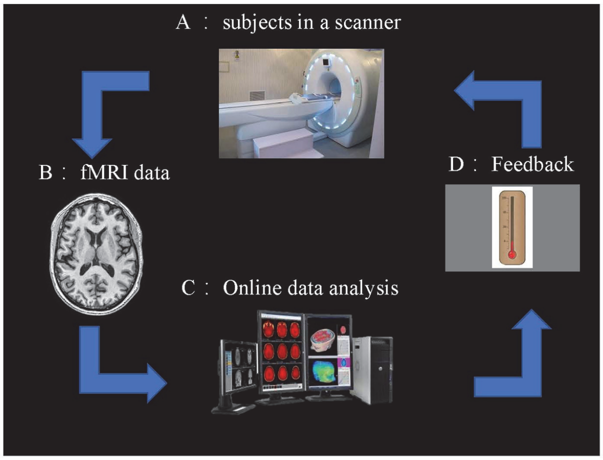

FIGURE 2 | Overview of an rt-fMRI NF system. **(A)** Subjects in the fMRI scanner. **(B)** fMRI data acquisition using an echo planar imaging (EPI) pulse sequence. **(C)** Online data analysis and computation of the NF based on the BOLD responses. **(D)** NF via a scanner projection system.

Data Acquisition

The fMRI data were acquired at the Imaging Center of Henan Provincial People's Hospital. Brain imaging was performed by using a 3.0T GE Discovery MR750 scanner (General Electric, Fairfield, CT, United States) with a standard eight-channel head coil was adopted. We used sponge mats to restrict the motion of the head and diminish the noise of the scanner. fMRI data were acquired by using a standard GRE-T2* EPI sequence and the following parameters were used: field of view = 220 × 220 mm, TR = 2000 ms, TE = 30 ms, matrix size = 64 × 64, slices/slice

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[2] http://afni.nimh.nih.gov/afni/

FIGURE 3 | Experimental procedure in the run. The experiment consists of four runs each lasting for 6 min 20 s each, and each run contains five blocks. During the feedback run, participants experience rt-fMRI NF training consisting of alternating blocks of view, feedback, and count (instructed to count backward from 300 by a given integer). During the "feedback" blocks, they are asked to apply a recall strategy with positive AMs to regulate the ROI activity. The feedback value is computed based on ROI activation.

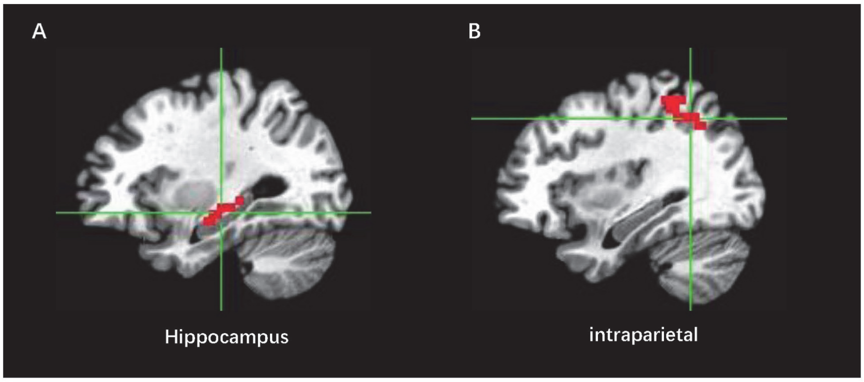

FIGURE 4 | Locations for the feedback and control localizer brain regions in Talairach space: **(A)** ROI_{EXP} indicates the NF region in the right hippocampus, and **(B)** ROI_{con} represents the control NF region in the intraparietal area.

thickness = 33/3.5 mm, and flip angle = 80°. We used a 3D fast spoiled gradient sequence for acquiring the T1-weighted image and the parameters were used: TR/TE = 8.268 ms/3.22 ms, FOV = 256 × 256 mm, matrix size = 256 × 256, slices = 156 mm, and flip angle = 12°.

Preprocessing of fMRI Data

The preprocessing of fMRI data was performed in DPARSF[3], which is based on SPM12 and REST[3]. Analysis of NF training fMRI data was performed through statistical parametric mapping (SPM12[4]). The first 10 initial scans of every fMRI runs were discarded because the unstable magnetic field can cause distortion of data. The following procedure was included in the preprocessing of data. The acquired fMRI data were corrected by slice-timing and realignment. fMRI data were transformed into the standard Montreal Neurological Institute (MNI) space by linearly registering to the anatomical data and a kernel of 6 mm FWHM was used to smooth. Finally, white matter mask, cerebrospinal fluid mask, six head motion parameters, and global mean signal were regressed out of the time series (Brown et al., 2014; Shao et al., 2014; Yao et al., 2016).

Data Analysis

Separate models were established in SPM for the four feedback runs, and two regressors consisted of the GLMs. Three experimental regressors were "view," "NF," and "baseline," and the movement vectors of the realignment were involved in the GLM model. We modeled the conditions as the blocks of brain activation by convolving with function of

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[3] http://www.restfmri.net/

[4] www.fil.ion.ucl.ac.uk/spm

hemodynamic response. Then, the fMRI data were filtered by high pass (128 s).

Region of interest analysis of fMRI data was performed in SPM12. A one-sample *t*-test of the contrasts View > Baseline, Regulation > Baseline, and View > Regulation was conducted on the single level to check the effect of NF. Then, we extracted the mean contrast value from all voxels of the hippocampus and the region of control. Beta weights were extracted from all voxels of ROI. We used a paired two-sample *t*-test for the contrast Regulation > Baseline to verify our directed hypothesis that the activity of hippocampus was increased in the regulate condition when compared to the view condition. We performed the ROI analysis in the hippocampus between the FG and CG.

Resting-State Data Analysis

Low Frequency Fluctuation Analysis

The DPABI was used to calculate ALFFs. To calculate ALFFs of the resting-state data, the fMRI data were smoothed using a Gaussian kernel of 8 mm (FWHM). Next, the time series was transformed into the frequency domain by a fast Fourier transform. Then we calculated the square root at each frequency in the power spectrum. ALFF values of the resting-state data were calculated in every voxel after at the frequency of the power spectrum across 0.01–0.08 Hz. We divided the ALFF of each voxel by the mean ALFF value for standardization. The *T*-test was performed in REST software (Zou et al., 2008).

Calculation of ReHo

Zang et al. (2004) described the specific calculation method, and the analysis of ReHo maps was performed by DPABI (Chao-Gan and Yu-Feng, 2010). ReHo computation is represented using Kendall coefficient of concordance (KCC). It may be used to explore the neuro mechanism in the resting-state. The KCC was used to calculate the ReHo maps of the time-series of a fixed voxel with the nearest 26 adjacent voxels. We divided the ReHo maps by global average value of ReHo. Then, we smoothed the values of ReHo using a kernel of 4-mm FWHM.

The ReHo maps of FG and CG were calculated with a two-sample *t*-test. We computed the maps of ReHo from the resting-state which was scanned before and after the NF training. A paired *t*-test was performed on the ReHo maps of the FG and CG, and the ReHo maps were computed from the resting-state data that collected before and after the rtfMRI-NF training.

RESULTS

Behavioral Data

We compared the questionnaires before and after the training through a paired *t*-tests to analyze the effects of NF training on behavior. And the results of *t*-tests did not show remarkable change during NF training. However, the scale score of the experimental group showed a downward trend in the SAS before the training ($M = 29.2 \pm 49$) compared with after the training ($M = 2.56 \pm 1.8$) of the feedback group (FG). Moreover, subjects were asked to write down the methods they used for the success of regulation. These results are shown in **Table 1**

TABLE 1 | Questionnaire score characteristics (mean ± SD).

Measures	**Mean/*SD***				**Group comparison**	
	FG		**CG**		**Statistics**	
	Before	**After**	**Before**	**After**	**Feedback**	**Control**
N	13		13			
Age	23.7/1.3		22.5/1.4		$t = -1.4$ $p = 0.18$	
Gender	8 m/6 f		6 m/8 f			
SAS	29.2/4.9	25.6/1.8	26/6.02	22.8/2.65	Ns $p = 0.06$	Ns $p = 0.24$
SDS	27.8/4.4	26.3/1.4	23.8/3.1	22.1/1.5	Ns $p = 0.17$	Ns $p = 0.07$
ERQ_rea	32.4/3.4	34/4.5	28.3/4.2	28.9/3.7	Ns $p = 0.26$	Ns $p = 0.16$
ERQ_sup	16.3/2.5	17/4.1	15.3/3.9	16.2/4.1	Ns $p = 0.44$	Ns $p = 0.89$
PANAS(P)	27/6.1	33.1/7.9	26.1/8.6	27.4/9.6	Ns $p = 0.34$	Ns $p = 0.14$
PANAS(N)	13.7/2.8	12.3/2.7	12.4/2.1	13.2/2.6	Ns $p = 0.22$	Ns $p = 0.16$
HAMD	12.7/3.7	8.6/3.1	5.7/4.5	5.1/3.4	Ns $p = 0.47$	Ns $p = 0.29$

Given are the mean/SD of the assessed demographic data. N, number of subjects; m, male; f, female; SAS, self-rating anxiety scale; SDS, self-rating depression scale; ERQ, emotion regulation questionnaire; rea, reappraisal sub-score; sup, suppression sub-score; PANAS, positive and negative affect scale; P, positive; N, negative; HAMD, Hamilton depression scale; Ns, not significant; t-test, two-tailed. The p-values were tested for the before- vs. after-NF testing.

ROI Analysis

Region of interest analysis was used to verify that the change of hippocampus activity is different from the experimental group to the CG. Two ROIs were defined as spheres of 8 mm radius in the MNI, respectively, in the left hippocampus (-25, -7, -22, r = 8mm) and left intraparietal sulcus (-44, -46, 47, r = 8mm), which were used to assess changes in BOLD activity. The beta weights of conditions ("viewing" and "regulation") from the ROIs of FG and CG were computed by a random-effect GLM. For each condition, we used the beta weights to characterize the magnitude of ROI activation during training.

The preliminary research solved the influence of repeated NF runs on hippocampus regulating in the FG (**Figure 5**): Left hippocampus and right hippocampus responses were remarkably higher in the FG of contrast regulate > baseline ($M = 0.25 \pm 0.21$) compared with contrast view > baseline [$M = 0.09 \pm 0.14$, $t(13) = 2.65$, $p < 0.033$]. In the FG, hippocampus activation had a rising trend level across the four NF runs. A *post hoc* analysis was used to directly compared the activation of hippocampus between runs 4 and 1 in the regulate conditions. The activation of the hippocampus during regulation (against baseline condition) was remarkably higher in run 4 compared with run 1: $t(13) = 4.2$, $p = 0.013$. No difference was observed between runs 1 and 4 during view > baseline ($p = 0.814$).

No significant difference was found between the FG and CG in the run 1 (regulation condition, $p = 0.895$), but we found a different trend level in the run 4 ($p = 0.055$). In conclusion, these results showed a remarkably improved hippocampus up-regulation in the FG but not in the CG (**Figure 6**).

In the CG, there was no remarkable differences in the contrast regulate > view, the contrast view > baseline or regulate > baseline between runs (regulate > view

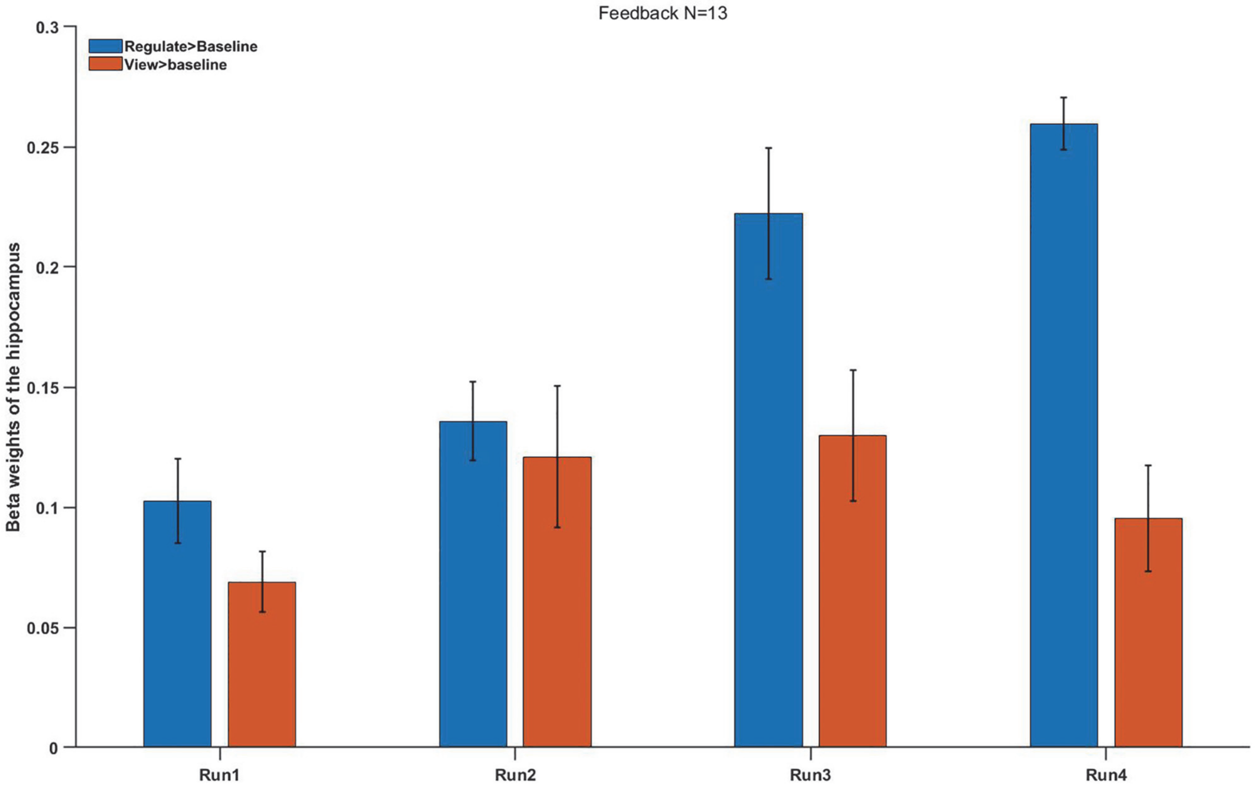

FIGURE 5 | Mean beta weights of the subjects' individual localizer hippocampus ROIs. Conditions regulate > baseline (blue) and view > baseline (red) are presented during the four runs. Error bars represent the standard errors.

condition: $p = 0.741$, view condition: $p = 0.693$, regulate condition: $p = 0.562$).

The BOLD activation levels for the left intraparietal sulcus ROI are close to zero (after group averaging) and exhibit no obvious trend across runs. In the FG, there was no remarkable differences in the contrast view > baseline or regulate > baseline between runs.

Results of ReHo

We used a two-sample *t*-test to investigate the effects in FG and CG. Statistical analysis maps were shown in **Figure 6** and **Table 2**. The score of ReHo maps increased after the training were found in the left anterior cingulum gyrus, left superior parietal gyrus, left inferior parietal gyrus, right frontal gyrus, right angular gyrus, right precuneus, and superior frontal gyrus. The score of ReHo maps decreased after the training were found in the left parahippocampal gyrus, left hippocampus, middle temporal gyrus, right caudate nucleus, right fusiform gyrus, insula, and right postcentral gyrus.

A paired *t*-test was used in the FG. Statistical analysis maps were presented in **Table 3** and **Figure 7**. The ReHo score of increased in the FG was observed in the right hippocampus, right parahippocampal gyrus, left insula, right superior frontal gyrus, left anterior cingulate gyrus, left inferior occipital gyrus, left inferior frontal, and right middle frontal gyrus. The regions of decreased ReHo score were found in the right cingulum, left cingulum, and left middle occipital gyrus.

Results of ALFF

A two-sample *t*-test was used to investigate the effects in FG and CG. The differences of the group were presented in **Table 4** and **Figure 8**. The FG remarkably exhibited reduced ALFF in the left middle occipital gyrus, left parahippocampal gyrus, and right middle frontal gyrus compared with CG. The regions of remarkably increased ALFF was observed in the left anterior cingulate and left superior frontal gyrus.

DISCUSSION

The capability to improve emotional regulation is very important to people. rtfMRI-NF training, in which BOLD fMRI data processing is concomitantly performed with data acquiring, has enabled rtfMRI-NF training in which individuals recognize and regulate the BOLD signals from their brain. Increasing evidence suggests that rtfMRI-NF has clinical utility in reducing symptoms associated with chronic pain (Zhang et al., 2009), smoking cessation (Hartwell et al., 2016), anxiety (Zilverstand et al., 2015), post-traumatic stress disorder (PTSD) (Nicholson et al., 2016), and MDD (Linden et al., 2012). The amygdala and the hippocampus are, respectively, associated

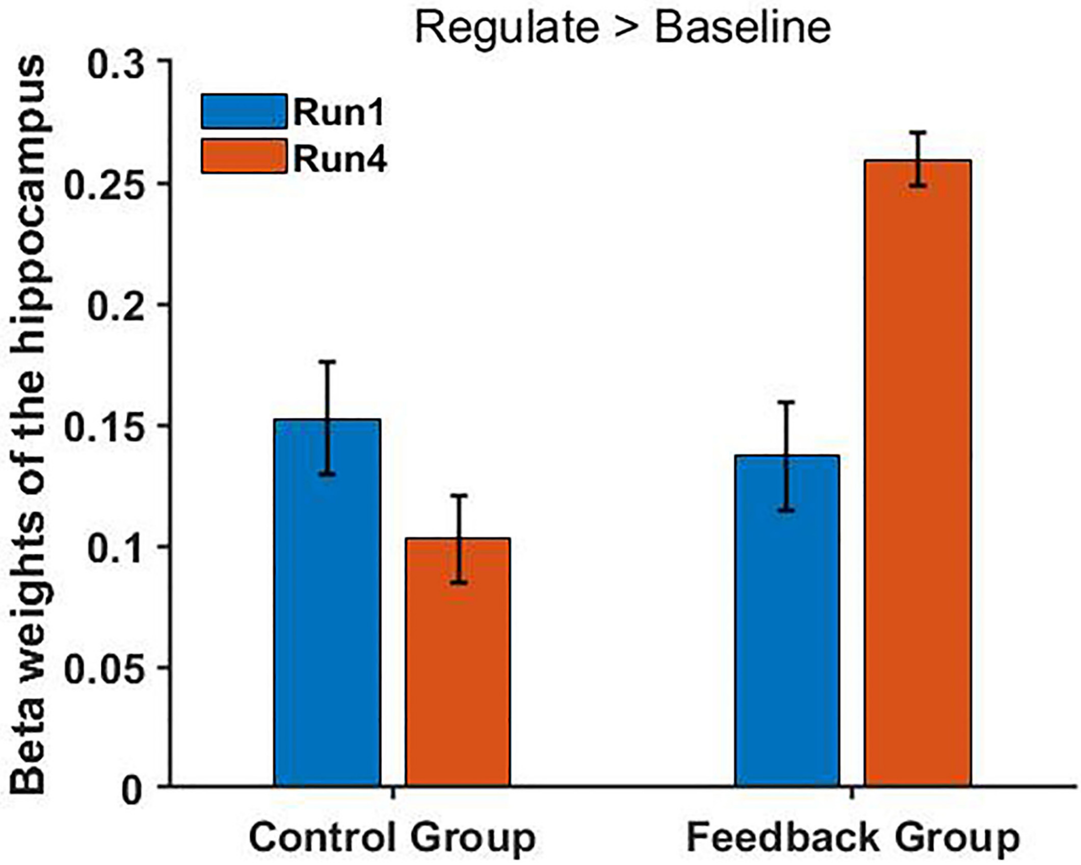

FIGURE 6 | FG shows a significantly increased hippocampus activity in the main contrast (regulate > baseline) [$t(13) = 2.756$, $p = 0.034$] in the fourth run but not in the first run (regulate > view: $p = 0.648$) compared with the CG. Bars indicate the standard errors.

with emotional processing and declarative memory (Guzmán-Vélez et al., 2016). A mature neurobiological model of emotion regulation is associated with cognitive control of emotions to prefrontal cortex areas including the amygdala and hippocampus. Many rtfMRI studies have targeted the brain region critically involved in both emotional processing and the pathophysiology of MDD, i.e., the amygdala (Young et al., 2014). The amygdala is an important part of emotion generation (Phelps and Ledoux, 2005) and regulation, and hippocampus constitutes a core structure of emotion processing and working memory through the functional coupling with the amygdala. The hippocampus is also related to NF of emotion regulation (Schumacher et al., 2018).

The goals of this study are assessing the effect of NF of hippocampal activity during four NF runs by recalling of AMs. Recall of AMs is an effective method of emotion regulation. In our study, we systematically analyzed the change of self-regulation efficacy induced by NF of ROI activity in the hippocampus based on positive AMs and sense. We also verified the feasibility of training healthy participants to improve their hippocampus BOLD activity using contemplating positive AMs during four NF runs. The FG showed remarkably higher activation of the hippocampus in the run 4 compared with the run 1 during the up-regulation of their NF. This effect of FG was better than in the CG, which is also trained with NF from the hippocampus. We also extracted the BOLD signal of the control region (intraparietal sulcus). There was no significant difference of the control region

TABLE 2 | Brain regions where the ReHo map differed between the feedback group (FG) and control group (CG).

Brain region	Voxels	MNI coordinates			*t*-value
		X	*Y*	*Z*	
R Superior frontal gyrus	31	−15	57	27	5.55
L Middle temporal gyrus	20	−54	−21	−24	−4.39
L Anterior cingulate gyrus	24	0	−48	42	3.60
B Lingual gyrus	16	−9	−99	−21	−5.22
L Inferior occipital gyrus	34	−39	−84	3	−6.97
L Frontal lobe	35	6	54	18	4.52
R Superior temporal gyrus	56	60	−54	21	6.06
L Middle occipital gyrus	69	45	−84	−12	−4.92
R Precentral gyrus	46	54	9	33	5.82
R Middle frontal gyrus	106	45	9	57	5.55

L, left; R, right; B, bilateral; AlphaSim corrected $p < 0.01$.

TABLE 3 | Brain regions of the FG where the ReHo map differed between the Rest1 and Rest2.

Brain region	Voxels	MNI coordinates			*t*-value
		X	*Y*	*Z*	
R Superior frontal gyrus	12	18	−15	75	−4.358
L Middle temporal gyrus	15	−51	72	24	−5.5967
B Cingulate gyrus	24	0	−48	42	−3.5991
B Frontal lobe	34	−15	57	27	5.5533
L Inferior frontal	15	−30	21	−15	4.7447
L Para hippocampal gyrus	17	27	−18	−18	4.4082
L Lingual gyrus	19	−9	−99	−21	−5.2165
R Fusiform gyrus	21	39	−48	−18	−4.5105
R Inferior occipital gyrus	34	−39	−84	−3	−6.917

L, left; R, right; B, bilateral; AlphaSim corrected $p < 0.01$.

TABLE 4 | Brain regions where the ALFF differed between the FG and CG.

Brain region	Voxels	MNI coordinates			*t*-value
		X	*Y*	*Z*	
B Inferior frontal gyrus	57	28	21	−15	5.2198
R Hippocampus	56	20	−5	−12	4.8907
B Inferior frontal	102	26	21	−19	4.7205
R Insula	83	27	25	−11	4.6870
L Anterior cingulate	71	0	36	29	4.214
L Paracentral	759	0	−27	60	−4.5413
R Amygdala	82	21	−5	−12	4.8632
R Para hippocampal gyrus	89	27	−20	−22	3.2294

L, left; R, right; B, bilateral; AlphaSim corrected $p < 0.01$.

during the four NF training sessions. In the intraparietal sulcus, we did not observe NF alter the activity of the brain, which supports the hypothesis NF specificity on the hippocampus. This also demonstrated the specificity of the effect of hippocampus-based NF training. Our results indicated that individuals could voluntarily control BOLD responses in the hippocampus during emotional memory recall by using short rtfMRI-NF training.

To characterize emotion regulation from the baseline and impulsive traits, the participants completed questionnaires consisting of ERQ, SDS, SAS, PANAS, and HAMD. We compared the questionnaires before and after the training through a paired *t*-tests to analyze the effects of NF training on behavior. And the results of *t*-tests did not show remarkable change during NF training. Those results may indicate that we reduced the negative emotions of the subjects and increased the positive emotions of the subjects after NF training. No behavioral change observed. It may be due to the reason that our experiment is aimed at healthy people, and the insufficient number of NF training.

We employed a control condition in which subjects received rtfMRI-NF from the intraparietal sulcus, a region primarily implicated in number processing. The BOLD activation levels for the left intraparietal sulcus ROI are close to zero (after group averaging) and exhibit no obvious trend across runs (**Figure 9**). This result suggests that the experimental and CGs differed in their NF training effects based on the specific target brain region (left hippocampus and left intraparietal sulcus). The enhanced control over left hippocampus BOLD activity appeared to specifically result from rtfMRI-induced learning. The CG underwent the same rtfMRI NF procedure as the experimental group, but received sham NF information corresponding to BOLD activity in the left intraparietal sulcus, a region that has been consistently implicated in numeric processing. Although the CG initially showed a similar level of BOLD activity in

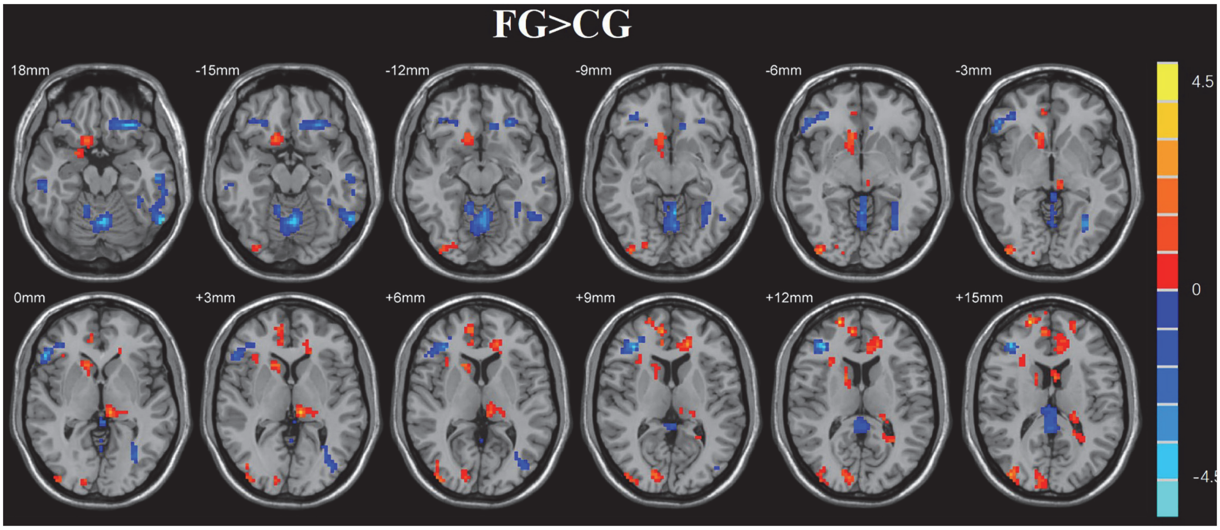

FIGURE 7 | Regions with altered ReHo score in the experimental group after rtfMRI-NF training. The score of ReHo maps increased after the training were found in the left anterior cingulum gyrus, left superior parietal gyrus, left inferior parietal gyrus, right frontal gyrus, right angular gyrus, right precuneus, and superior frontal gyrus. The score of ReHo maps decreased after the training were found in the left parahippocampal gyrus, left hippocampus, middle temporal gyrus, right caudate nucleus, right fusiform gyrus, insula, and right postcentral gyrus (AlphaSim corrected $p < 0.01$).

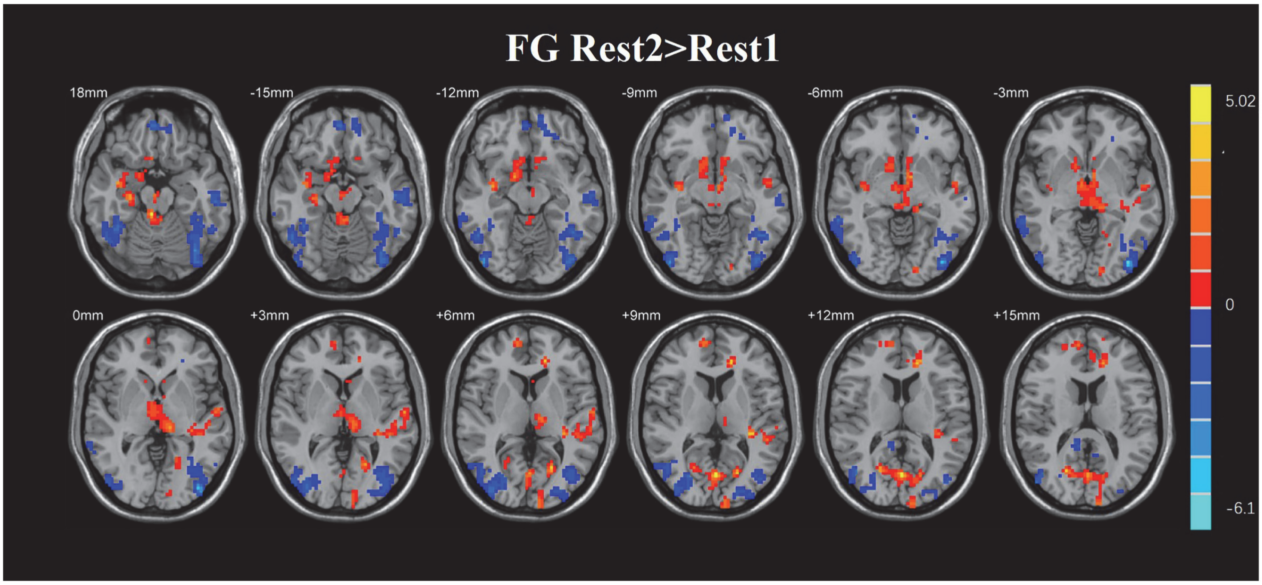

FIGURE 8 | Regions with altered ReHo score in the experimental group after rtfMRI-NF training. The ReHo score of increased in the FG was observed in the right hippocampus, right parahippocampal gyrus, left insula, right superior frontal gyrus, left anterior cingulate gyrus, left inferior occipital gyrus, left inferior frontal, and right middle frontal gyrus. The regions of decreased ReHo score were found in the right cingulum, left cingulum, and left middle occipital gyrus (AlphaSim corrected $p < 0.01$).

the target ROIs as the experimental group, the CG did not differentially modulate activity in either the intraparietal sulcus or the hippocampus across runs. Therefore, the observed learning effect appeared attributable to ROI-specific NF training rather than to nonspecific aspects of task performance such as repetition or practice effects.

The imaging basis of fMRI is based on the BOLD effect. In recent years, this technology has been widely used in the study of diseases such as Parkinson's disease and depression. BOLD effect depends on the magnetic properties of deoxyhemoglobin sensitivity. Both ReHo and ALFF are based on the BOLD signal. ReHo can measure the local consistency of the spontaneous low-frequency oscillation signal of the brain. It means that when a functional brain area is activated, the voxel of this area has more time-series change consistency. The increasing of ReHo indicates that the consistency of brain area increases. The decreasing of ReHo shows the opposite result, which means that the abnormality of ReHo value may represent the consistency of neuronal activity and the abnormality of synchronization, further indicating the disorder of neuronal metabolic activity. This method can better reflect the whole brain active status. ALFF also reflects the spontaneous activity of neurons. When the spontaneous activity of neurons increases, ALFF increases. When the spontaneous activity of neurons decreases, ALFF decreases. ReHo and ALFF are two different methods of fMRI post-processing. Through these two techniques, more changes in brain function can be found. In this study, the brain region of the ReHo value changes coincides with the brain region where the ALFF value changes. Some scholars believe that the increase in ReHo value may promote local neuronal activity. The enhancement of ReHo and ALFF values in some brain regions is also increased, which may indicate the local consistency of neuronal electrical activity in these brain regions.

ReHo

In clinical research, the ReHo is mainly used as a brain imaging sign to explore the neural mechanism of mental illness by comparing the difference in ReHo values between mental patients and normal people, and as a means to predict and diagnose mental illness. At present, many scholars have applied the ReHo method to the study of brain diseases such as depression, schizophrenia, epilepsy, traumatic stress disorder, and anxiety. The ReHo analysis has been widely used in the study of mental disorders such as depression, traumatic stress disorder, and anxiety disorders. Wei et al. (2015) found abnormalities in the neuro activity of the hippocampus, anterior cingulate gyrus, and central posterior gyrus in depression patients. Li et al. (2017) conducted a meta-analysis of the literature on depression ReHo from 2003 to 2016. It was found that there were abnormalities of ReHo maps in the precuneus, cingulate gyrus, fusiform gyrus, postcentral gyrus, frontal lobe, and other brain regions of patients with depression.

We assessed the effect of emotion regulation using NF. Moreover, we considered the changes in ReHo maps of healthy subjects when they keep the resting-state after the NF training. The results of the ReHo indicated that there are many regions which have a statistically remarkable difference in the FG and CG. We found that the left precuneus, middle cingulum gyrus, middle frontal gyrus, insula, left inferior parietal, and superior parietal gyrus have a remarkable difference between the FG and CG. Prefrontal lobe, temporal lobe, and parahippocampal gyrus are related to emotion regulation. Compared with CG, we also

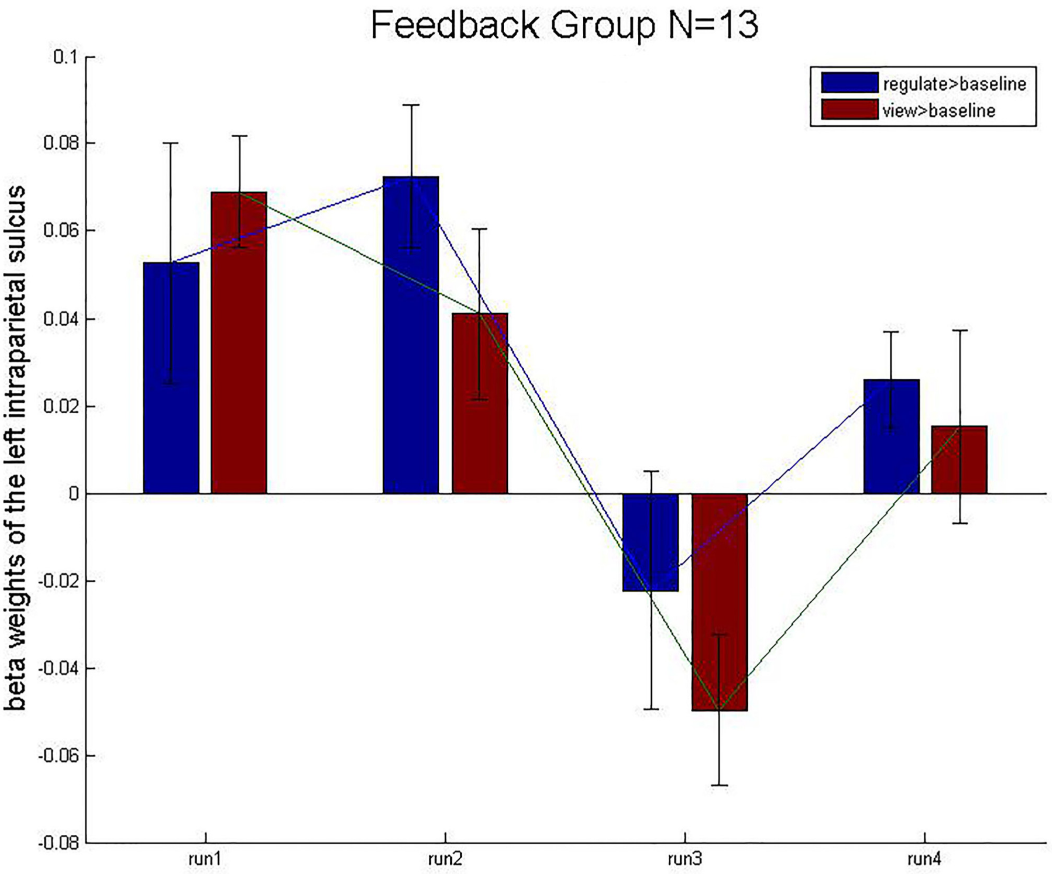

FIGURE 9 | Mean beta weights of the subject's localizer the intraparietal sulcus ROIs. Conditions regulate > baseline (blue) and view > baseline (red) are presented during the four runs. Error bars represent the standard errors.

detected that there was a statistically remarkable difference in the regions of ReHo map in the FG. The results indicated that the brain regions related to emotion may be regulated by the presented rtfMRI-NF.

Regional homogeneity analysis was used to investigate the effects of neuropsychiatric disorders in previous, such as MMD, BPD, and PTSD. In the research about MMD, there was a remarkable difference between healthy and depressed subjects in the fusiform gyrus, temporal lobe, amygdala, parahippocampal gyrus, and hippocampus. The regions of the brain, which were influenced by NF, were the same as the regions with unusual ReHo maps in the disorders. Our study demonstrates that rtfMRI-NF may be helpful in human beings to regulate the activity of their brain, and the analysis of ReHo provides a new method which is helpful to study the mechanism of emotion regulation.

ALFF

We applied the resting-state data to investigate the influence of NF. On the basis of a previous research, Zou et al. (2008) defined a standard measure of ALFF. Subsequently, ALFF is used to represent different physiological states of the brain and is a helpful method to investigate the brain activities of healthy subjects. In the present study, we found that many regions of FG have a statistically remarkable difference in ALFF compared with CG. The left inferior parietal, left cingulum gyrus, middle frontal gyrus, and superior parietal gyrus showed a remarkable difference in the FG and CG.

By analyzing the experimental results, we found that most of the brain regions where the ALFF value changes are the right brain regions. In recent years, the default network has received a lot of attention. The activity of default network is enhanced in the resting state, and it is weakened in the task state. It is a brain network system with high activity in the resting state of the brain. It contains bilateral hippocampus, medial prefrontal lobe, posterior cingulate gyrus/the precuneus, and the bilateral angulation. The default network is closely related to advanced functions such as self-introspection, memory, and emotional/maintenance awareness. In this study, the brain regions with some functional changes are part of the default network. It may be due to NF training. In addition, the medial frontal cortex participates in the cognitive execution network. In this experiment, the ALFF value of the left frontal gyrus was higher than that of the CG, which the cognitive performance of the subject may be improved due to NF training (**Figure 10**).

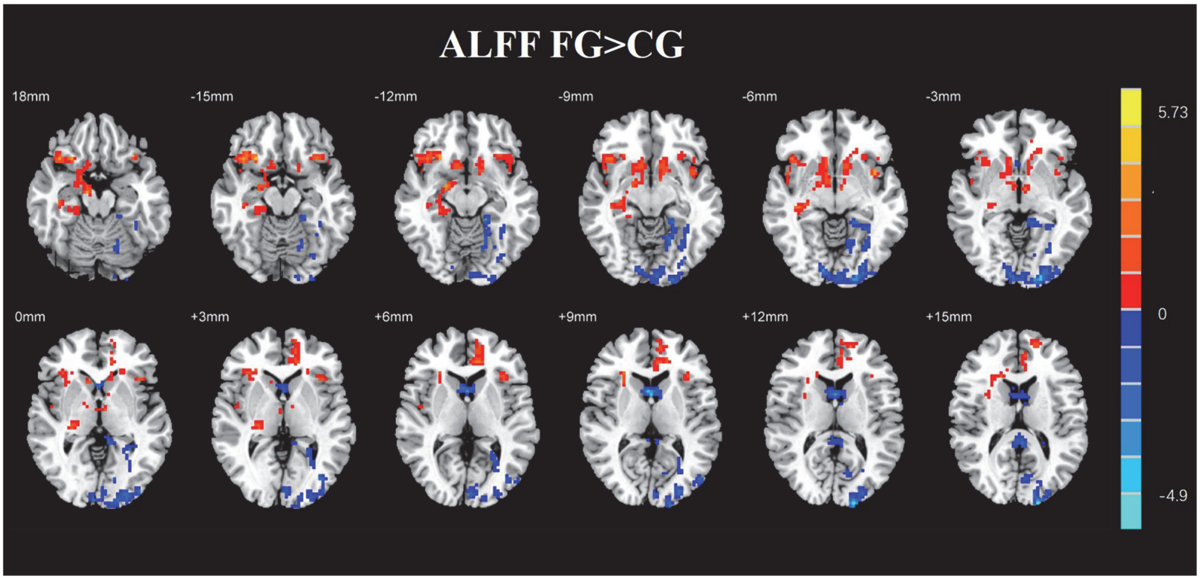

FIGURE 10 | Regions with altered ALFF score comparison of the experimental and CGs. The FG remarkably exhibited reduced ALFF in the left middle occipital gyrus, left parahippocampal gyrus, and right middle frontal gyrus compared with CG. The regions of remarkably increased ALFF were observed in the left anterior cingulate and left superior frontal gyrus (AlphaSim corrected $p < 0.01$).

The precuneus is associated with high-level cognitive functions such as contextual memory and consciousness. In the resting state, the precuneus is highly active. A study of Cabeza et al. (2003) showed that the precuneus was involved in the conscious short-term memory recall of the subjects. In our study, the ALFF value of the precuneus increased, indicating that the NF training through the hippocampus may affect the function of the emotional memory.

The cingulum gyrus brings back the output from the hippocampus, the amygdala, the orbit frontal cortex, and the medial frontal gyrus, and the nerve impulse is transmitted to the anterior cingulate and striatum, which has always been an important part of the emotional circuit. It also participates in emotional and self-evaluation processes, which are closely related to depressive symptoms. The cause of this phenomenon may be due to NF from the hippocampus, and the participants used positive AM recalls. The middle frontal gyrus participates in the cognitive execution network. In this experiment, the ALFF value of the left frontal gyrus was higher than that of the CG, which may improve the cognitive performance of the subject due to NF training. The parietal cortex plays an important role in the process of concentration. It consists mainly of the cortex that senses and monitors the response of various parts of the body to external stimuli. NF training requires the subjects to maintain a high degree of attention, monitoring the feedback information and using strategies to regulate.

The thalamus, amygdala, and hippocampus are considered to be the key brain regions of the limbic system and are closely related to the emotional memory function. The results showed that the ALFF values of the amygdala and hippocampus were increased in the experimental group compared with the CG. This may be due to that the NF training changed the emotional network of the subjects, and the local consistency was enhanced, indicating the emotional memory functions of the subjects had been improved.

To our knowledge, our findings may provide guidance for the application of NF in emotional disorders. It may help people understand the underlying working mechanism of the hippocampus.

CONCLUSION

Our study demonstrated that NF training could up-regulate the activity of the hippocampus. The activation of hippocampus increases after four NF runs and alters the ReHo and ALFF of the resting-state hippocampus. The hippocampal activity of the experimental participants was higher in the FG than in the CG. Emotion regulation training by using the recall of positive AMs, which supports the hippocampus NF, is more efficient than training with the NF of intraparietal sulcus. This research is a beginning for further investigating the application of NF of the hippocampus as a promising tool in emotion regulation of healthy human. In addition, up-regulation of the hippocampus could be useful for diseases which has the problems in emotion regulation and elevated hippocampus activity. NF could be used to train the capability of emotion regulation. It can provide a potential tool to increase efficacy under these circumstances.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of "The Ethics Committee of Henan

Provincial People's Hospital" with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the "The Ethics Committee of Henan Provincial People's Hospital."

AUTHOR CONTRIBUTIONS

YZ, HG, and LT conceived and designed the experiments. YZ, QY, and ZL performed the experiments. YZ and CZ analyzed the data. LW and BY contributed to reagents, materials, and analysis tools.

FUNDING

This work was funded by the National Key Research and Development Plan of China under grant 2017YFB1002502, the National Natural Science Foundation of China (No. 61701089), and the Natural Science Foundation of Henan Province of China (No. 162300410333).

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Conflict of Interest Statement: 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.

frontiers
in Human Neuroscience

ORIGINAL RESEARCH
published: 23 July 2019
doi: 10.3389/fnhum.2019.00253

Neural Basis of Professional Pride in the Reaction to Uniform Wear

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Professional pride is a positive emotion that includes self-reflection or evaluation and attitude toward one's own occupational group. Uniforms can encourage the wearer to have professional pride. The current study aimed to elucidate the neural basis of professional pride using an experimental task related to the self in uniform and functional magnetic resonance imaging (fMRI). The person-adjective matching task, in which a participant or other in uniform or casual wear was presented with positive and negative words, was used for scanning fMRI. Imaging data from 21 adults who had an occupation requiring a uniform were analyzed to identify the main and interaction effects of individual (self vs. other), clothes (uniform vs. casual wear), and valence (positive vs. negative). Identified brain activities were correlated with psychological scales including the Rosenberg Self-esteem Scale and Group Environment Questionnaire. Whole brain analyses found that the interaction between individual and clothes was present in multiple regions such as the right ventrolateral prefrontal cortex (VLPFC), left dorsolateral prefrontal cortex, left middle and inferior temporal gyri, left posterior superior temporal sulcus, right temporoparietal junction, left lingual gyrus, left calcarine cortex, right insula, left caudate, and right putamen. In particular, activities in the right VLPFC, left calcarine cortex, and right putamen in the self/uniform condition were positively correlated with several psychological scales. These results suggest that professional pride may be represented through multiple brain networks related to empathy, reward, and emotion regulation as well as the theory-of-mind network. The neural basis of professional pride is closely related to positive self-evaluation and group cohesion.

Keywords: professional pride, uniforms, reward network, emotion regulation, group cohesion

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Received: *31 January 2019*
Accepted: *08 July 2019*
Published: *23 July 2019*

Citation:
Hong Y-J, Park S, Kyeong S and Kim J-J (2019) Neural Basis of Professional Pride in the Reaction to Uniform Wear.
Front. Hum. Neurosci. 13:253.
doi: 10.3389/fnhum.2019.00253

INTRODUCTION

Apparel has instrumental functions such as ensuring self-concept through clothing and enhancing self-esteem through other people's positive responses to the meaning of the clothing (Solomon, 1983). The clothing represents the wearers themselves and is usually used as an "identity kit" to convey a desired impression to others (Scheff, 2005). By receiving or imagining a response from others, people perceive their appearance and achieve the idea of self that they are trying to define (Hormuth, 1990). In particular, the uniform, one of social apparel, is designed to act as a visual symbol to group members and can yield easier identification of roles as well as increased positivity (Adomaitis and Johnson, 2005). Wearing a uniform is also an effective means of identifying members and non-members and contributes to obtain social recognition from others or a sense of belonging (Lapitsky, 1961). Uniforms can give legitimate authority to certain roles in specific situations, promoting a sense of competence among the wearer and others. For example, wearing police uniforms gives the belief and authority that members will perform much more competently and responsibly than when they wear casual wear (Daniel, 1996). To sum up, uniforms can help foster a sense of pride and belonging and promote professionalism. In other words, uniforms can encourage the wearer to have a positive emotion of professional pride.

Pride is a self-focused emotion experienced when an individual or a group rises in social status (Tracy and Robins, 2007) and is a subjective, status-related, self-conscious emotion (Bolló et al., 2018). Expressing high status, which is beneficial for both the displayers and observers, is a social function of pride (Martens et al., 2012). Pride facilitates navigation in the social hierarchy and drives an individual to behave in socially appropriate ways (Tracy and Robins, 2004; Steckler and Tracy, 2014). Previous neuroimaging studies have reported that pride engages theory-of-mind (ToM)-related regions such as the medial prefrontal cortex (MPFC) and posterior superior temporal sulcus (pSTS) or temporo-parietal junction (TPJ) because it involves appraisals of social meaning (Takahashi et al., 2008) and self-referential processing (SRP)-related regions such as the MPFC and precuneus, as it is a self-oriented state (Zahn et al., 2009; Simon-Thomas et al., 2012; Roth et al., 2014).

Professional pride includes self-reflection or evaluation and attitude toward one's own occupational group. With respect to the neural correlates of professional pride, it would engage ToM-related and SRP-related regions because of having pride as an element, while brain regions related to professionalism are also expected to be involved. Professionalism includes empathy, teamwork, and lifelong learning as key elements (San-Martín et al., 2017). It has been considered that professionalism may also include various other attributes such as the acceptance of a commitment to service, social responsibility and accountability, reliability, specialized knowledge, and self-regulation (LaSalal and Nelson, 2005). Although these elements cannot all be assumed to be related to professional pride, much is expected to be involved and possibly linked with the functions of different brain regions. For example, personal responsibility in decision-making produces a characteristic neurophysiological change (Li et al., 2011), and the empathy network including the anterior cingulate cortex (ACC) and insula (Engen and Singer, 2013) and teamwork-related brain reward responses (Morawetz et al., 2014) have been consistently reported. Therefore, in addition to the ToM-related and SRP-related regions, more brain regions would be involved in professional pride, but little is known about the neural correlates of this positive emotion.

In the current study, we drew inferences that uniforms can be effective visual means to examine the positive facet of professional pride, and thus developed a person-adjective matching task in which uniforms were used with casual wears as control stimuli and positive and negative words were used for assessing pride. The purpose of the study was to elucidate the neural basis of professional pride through functional magnetic resonance imaging (fMRI) using this task. We hypothesized that the positive emotion provoked by matching the self in uniform and pride-related words would recruit the empathy network or reward pathway as well as the ToM-related and SRP-related regions.

MATERIALS AND METHODS

Participants

We recruited participants from the age of 25–40 years old who had a uniform-dressing job through Internet advertising. Among the volunteers, those with left-handedness as screened using the Edinburgh Handedness Inventory (Oldfield, 1971) and any neurological history or psychiatric illness were excluded. Finally, 22 volunteers participated in the experiment so as to include as many occupational groups as possible (six nurses, three soldiers, two medical doctors, two dentists, two radiological technologists, two bankers, one pilot, one stewardess, one athlete, one researcher, and one lawyer). However, because the data from one participant (one banker) who provided incomplete behavioral responses owing to drowsiness were discarded, the analysis only included data from the remaining 21 participants (10 females/11 males, mean age: 29.86 ± 4.14 years, age range: 25–39 years). This study was approved by the Institutional Review Board of Gangnam Severance Hospital, Yonsei University and carried out in accordance with the Declaration of Helsinki. All participants provided written informed consent before the start of the experiment.

Self-Report Assessments

To investigate the psychological factors that could affect the positive self-evaluation, the Rosenberg Self-esteem Scale (RSES; Rosenberg, 1965) was assessed. To measure group cohesion, the Group Environment Questionnaire (GEQ; Carron et al., 1985) was administered and four subscale scores including Group Integration-Task, Group Integration-Social, Individual Attractions to Group-Task, and Individual Attractions to Group-Social were counted. Additionally, to measure the pride of wearing uniforms, we used our own questionnaire (the Uniform Questionnaire; UQ) to ask about the feel of uniforms. This contained three items, as follows: "When I wear the uniforms of our group, I feel responsible and think I should do better," "When I meet someone else, I am proud and confident that I am wearing a uniform," and "When I wear my uniform, I become more engaged and focused on my work." Each question was scored according to a five-point Likert scale (from 1 = not at all to 5 = extremely), and thus total scores ranged from three to 15 points.

Behavioral Task

Before the fMRI experiment, participants were photographed to make their own pictures which were shown on the screen during the experiment. They were asked to bring in their own uniforms and casual wear to take pictures. The photographs were taken while looking at the front with a neutral facial expression and sitting in uniform or casual wear with both hands on the table, and were edited to show only the upper body.

As shown in **Figure 1**, the picture conditions were prepared in four different ways: one's own face and uniform, one's own face and casual wear, the other's face and one's own uniform, and the other's face and one's own casual wear. The other's face was that of a same-sex person unfamiliar to the participant and one of the neutral faces of three males or three females selected from the Korean Facial Expressions of Emotion (KOFEE; Park et al., 2011), which was edited to take only the face part to replace the participant's face. As word stimuli, we used 10 positive trait adjectives (e.g., "generous") and 10 matching negative trait adjectives (e.g., "unfriendly"), which were selected from a normalized pool (Anderson, 1968). The picture was edited to place the word under the person of the upper body. The backgrounds of the pictures were masked in gray color. Adobe Photoshop CS6 software (Adobe Systems Incorporated, San Jose, CA, United States) was used for editing the images.

Since there were 20 words in each of the four condition types, a total of 80 visual stimuli were produced in one set, in which positive and negative words were configured to match the same number in each of the self, other, uniform, and casual wear. Next, the other set of 80 visual stimuli was produced in a way such that the matching words were interchanged between the opposite conditions. During the fMRI experiment, the task sequence was separated into two sessions, in which the duration of each trial was 3 s and the inter-trial intervals varied from 0 to 8 s. Each session was configured to randomly present 80 events consisting of a set of pre-generated stimuli, and took a total duration of 8 min and 10 s. During the experiment, participants were asked to answer to a question of "Is the word appropriate to the person?" by pressing one of the four corresponding buttons for "strongly disagree," "disagree," "agree," and "strongly agree."

Imaging Data Acquisition and Preprocessing

MRI data were acquired on a 3-Tesla scanner (Magnetom Verio; Siemens Medical Solutions, Erlangen, Germany). Functional images were collected using an echo planar sequence (echo time = 30 ms; repetition time = 2,000 ms; flip angle = 90°; slice thickness = 3 mm; field of view = 240 mm; and matrix = 64 × 64). T1-weighted images were also collected using a 3D spoiled-gradient-recall sequence (echo time = 2.46 ms; repetition time = 1,900 ms; flip angle = 9°; slice thickness = 1 mm; number of slices = 176; and matrix size = 256 × 256).

Using the Statistical Parametric Mapping (SPM)12 (Wellcome Department of Cognitive Neurology, Institute of Neurology, London, United Kingdom[1]) and MATLAB 2018a (Mathworks, Natick, MA, United States), the following image-preprocessing steps were conducted in order: realignment on the first image, slice-timing correction, co-registration and spatial normalization using a standard Montreal Neurological Institute (MNI) template, and smoothing using a Gaussian kernel with a full-width at half maximum of 8 mm.

Behavioral Response Analysis

The agreement ratings were defined by assigning from −2 for "strongly disagree" to 2 for "strongly agree" in the positive word condition (the degree of agreement) and were defined as the inverse of the number assigned in the same way in the negative word condition (the degree of disagreement), so that higher scores indicated a positive view for both conditions. To determine the influence of individual (self vs. other), clothes (uniform vs. casual wear), and valence (positive vs. negative), repeated-measures analysis of variance (ANOVA) and a *post hoc* paired *t*-test were conducted on the positive ratings and response time (RT) using the Statistical Package for the Social Sciences (SPSS) version 17.0.0 software program.

Imaging Data Analysis

Analysis was performed using a general linear model at the single-subject level. Images of the parameter estimates for different conditions were created during first-level analysis, during which individual realignment parameters were entered as regressors to control for the movement-related variance. There were eight conditions possible, from the combination of the two types of

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[1] http://www.fil.ion.ucl.ac.uk/spm

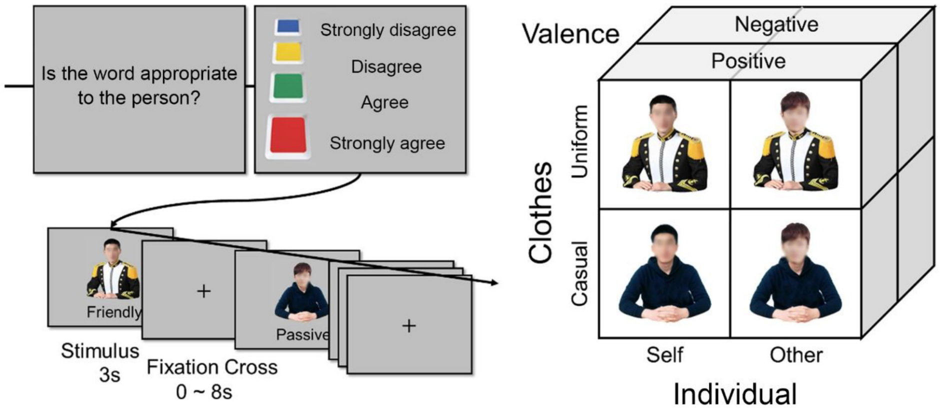

FIGURE 1 | The person-adjective matching task, in which the images of self or other in uniform or casual wear are serially presented with positive or negative adjectives.

individual (self and other), two types of clothes (uniform and casual wear), and two types of valence (positive and negative), i.e., from self/uniform/positive to other/casual wear/negative. Second-level analysis was executed in a 2 (individual) × 2 (clothes) × 2 (valence) flexible repeated-measures ANOVA to identify brain regions showing the main and interaction effects. Statistical threshold was set at voxel-level $p < 0.001$ (uncorrected) at first, and then all clusters that met false discovery rate (FDR) corrected $p < 0.05$ at the cluster level were considered significant. Next, based on our hypothesis that the self/uniform condition would be associated with positive self-evaluation and pride in collective belonging, we extracted beta values in the self/uniform condition from the clusters showing significant interaction effects of individual × clothes using the Marsbar toolbox for SPM 12[2]. Their regional activity values were used to calculate the correlations with psychological assessment scores, such as the RSES score and four subscales scores of the GEQ. The significance level was $p = 0.01$ (0.05/5), considering that there were the correlations with the five scores.

RESULTS

Behavioral Results

Participants reported the positive response to their uniform wearing; the mean total score of the UQ (range 3–15; median 9) were 10.71 ± 2.55. The UQ showed a good internal consistency, which was proven by Cronbach's alpha of 0.88 based on participants' responses. **Supplementary Table 1** shows the results from the other self-report assessments. Behavioral responses in each condition during the experimental task are presented in **Supplementary Table 2**.

The agreement rating revealed significant main effects of individual, clothes, and valence. It was significantly higher in the self condition than in the other condition (0.74 ± 0.42 and 0.35 ± 0.50, respectively; $F_{(1,20)} = 21.78$, $p < 0.001$), in the uniform condition than in the casual condition (0.65 ± 0.44 and 0.43 ± 0.44, respectively; $F_{(1,20)} = 14.19$, $p = 0.001$), and for the negative words than for the positive words (0.69 ± 0.40 and 0.39 ± 0.52, respectively; $F_{(1,20)} = 12.18$, $p = 0.002$). A significant interaction was found only between clothes and valence ($F_{(1,20)} = 7.65$, $p = 0.012$); the agreement rating was significantly higher in the uniform condition than in the casual condition for both the positive words (0.56 ± 0.57 and 0.22 ± 0.55, respectively; $t_{20} = 3.76$, $p = 0.001$) and the negative words (0.75 ± 0.40 and 0.64 ± 0.44, respectively; $t_{20} = 2.21$, $p = 0.045$). However, conversely, it was significantly higher for the negative words than for the positive words in the casual condition ($t_{20} = 4.13$, $p = 0.001$), but not so in the uniform condition ($t_{20} = 2.05$, $p = 0.053$) (**Figure 2A**).

Response time showed significant main effects of individual and clothes, but no main effect of valence; it was significantly shorter in the self condition than in the other condition (1,490.77 ± 210.57 and 1,631.02 ± 215.08 ms, respectively; $F_{(1,20)} = 12.53$, $p = 0.002$) and in the uniform condition than in the casual condition (1,493.86 ± 219.48 and 1,627.93 ± 210.33 ms, respectively; $F_{(1,20)} = 10.30$, $p = 0.004$). A significant interaction was found only between individual and valence ($F_{(1,20)} = 4.87$, $p = 0.039$) and between clothes and valence ($F_{(1,20)} = 5.65$, $p = 0.028$). In *post hoc* analysis, participants responded significantly faster in the self condition than in the other condition for both the positive words (1,561.75 ± 220.15 and 1,621.38 ± 207.10 ms, respectively; $t_{20} = -2.43$, $p = 0.025$) and the negative words (1,419.78 ± 310.93 and 1,640.65 ± 229.08 ms, respectively; $t_{20} = 3.06$, $p = 0.006$). However, the difference between the self and other conditions was significantly greater for the negative words than for the positive words (220.87 ± 330.77 and 59.63 ± 112.36 ms, respectively; $t_{20} = 2.21$, $p = 0.039$) (**Figure 2B**). Furthermore, participants' responses were significantly faster in the uniform condition than in the casual condition for the negative words (1,411.07 ± 340.31 and 1,649.36 ± 226.79 ms, respectively; $t_{20} = 2.86$, $p = 0.010$), but there was no difference between the two conditions for the positive words (**Figure 2C**).

Imaging Results

Brain Regions Related to the Factors

As shown in **Table 1**, whole-brain analysis yielded significant main effects of individual, clothes, and valence. The main effect of individual was found in the bilateral frontopolar

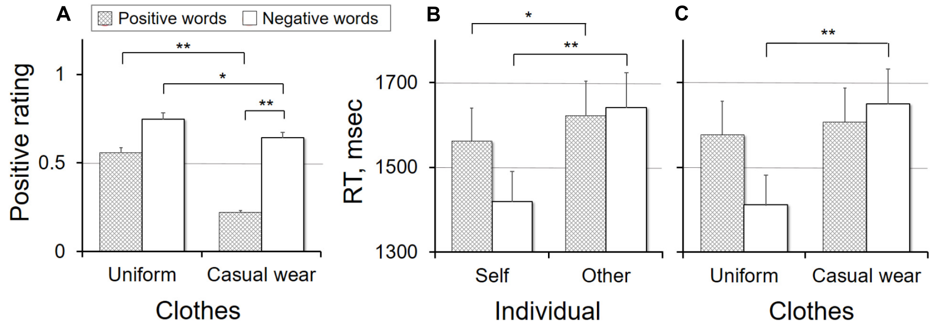

FIGURE 2 | Behavioral findings showing the interaction effect. Significant results were identified in the positive rating between clothes and valence **(A)**, reaction time (RT) between individual and valence **(B)**, and RT between clothes and valence **(C)**. $^{*}p < 0.05$, $^{**}p < 0.01$.

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[2] http://marsbar.sourceforge.net

TABLE 1 | The clusters showing the significant main and interaction effects.

	MNI coordinate				MNI coordinate		
Main effect Brain region (BA)	***x/y/z***	**Number voxels**	$Z_{\max}$	**Interaction effect Brain region (BA)**	***x/y/z***	**Number voxels**	$Z_{\max}$
Individual				**Individual × Clothes**			
L. FPC (10)	−48/47/−4	49	4.09	R. VLPFC (47)	24/29/5	58	4.80
R. FPC (10)	45/44/−7	34	3.86	L. DLPFC (8)	−30/14/47	35	4.30
R. VLPFC (45)	54/20/5	109	4.67	L. MTG (21)	−42/−49/2	51	3.73
R. SMG (40)	39/−55/56	29	3.52	L. ITG (21)	−57/−7/−22	57	4.62
				L. pSTS (39)	−39/−55/26	127	4.43
Clothes				R. TPJ (39)	39/−67/29	312	5.54
R. VLPFC (44)	45/11/20	85	4.09	L. Lingual gyrus (19)	−18/−52/8	30	4.23
R. Putamen	21/−10/2	40	5.06	L. Calcarine cortex (17)	−12/−91/5	36	3.63
				R. Insula (13)	30/11/23	147	4.70
Valence				L. Caudate	−2/−13/23	280	5.05
R. ACC (32)	3/26/38	79	4.34	R. Putamen	21/−7/−4	51	3.88
R. VLPFC (44)	57/17/8	153	4.58		27/−28/14	138	4.06
R. SMG (40)	42/−34/41	103	4.35	**Clothes × Valence**			
L. SMG (40)	−48/−37/38	132	4.72	R. TPJ (39)	39/−73/32	55	4.89
L. Insula (13)	−33/17/−1	70	3.98	L. Caudate	−21/−13/20	23	4.22
R. Insula (13)	42/2/8	50	4.52	**Individual × Valence**			
				L. Insula (13)	−33/−16/26	103	4.97

Significant clusters were obtained at voxel-level $p_{unc} < 0.001$ and cluster-level $p_{FDR} < 0.05$. BA, Brodmann area; MNI, Montreal Neurological Institute; L., left; R., right; FPC, frontopolar cortex; VLPFC, ventrolateral prefrontal cortex; SMG, supramarginal gyrus; ACC, anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; ITG, inferior temporal gyrus; MTG, middle temporal gyrus; pSTS, posterior superior temporal gyrus; TPJ, temporoparietal junction.

cortex, right ventrolateral prefrontal cortex (VLPFC), and right supramarginal gyrus. In *post hoc* tests, all of these regions showed increased activity in the self condition compared to the other condition. Brain regions showing the main effect of clothes were the right VLPFC and right putamen, where activity was increased in the uniform condition compared to the casual condition. The main effect of valences was identified in the right ACC, right VLPFC, bilateral supramarginal gyrus, and bilateral insula, all of which showed increased activity in the positive condition compared to the negative condition. Whole-brain analysis also yielded significant interaction effects of individual × clothes, clothes × valence, and individual × valence, but there was no interaction of individual × clothes × valence. The interaction between individual and clothes was found in multiple regions such as the right VLPFC, left DLPFC, left middle and inferior temporal gyri, left pSTS, right TPJ, left lingual gyrus, left calcarine cortex, right insula, left caudate, and right putamen. The interaction between clothes and valence was observed in the right TPJ and left caudate, and the interaction between individual and valence was identified only in the left insula. Differences among the conditions in the regions showing the interaction effects are presented in **Figure 3**.

Correlations Between Brain Activity and Behavioral Variables

Among the brain regions showing the interaction effect between individual and clothes, significant correlations between regional activity in the self/uniform condition and behavioral variables were found in three regions such as the right VLPFC, left calcarine cortex, and right putamen (**Figure 4**), as follows: right VLPFC activity with the level of Group Integration-Social in the GEQ ($r = 0.63$, $p = 0.002$); left calcarine cortex activity with the RSES scores ($r = 0.62$, $p = 0.003$) and the level of Individual Attractions to Group-Social in the GEQ ($r = 0.56$, $p = 0.008$); and right putamen activity with the level of Individual Attractions to Group-Social in the GEQ ($r = 0.58$, $p = 0.006$).

DISCUSSION

This study was performed to elucidate the neural basis of professional pride in the reaction to uniform wear using the person-adjective matching task. In the behavioral results, participants reported a positive response in the self-report regarding their uniform wear and their agreement ratings in the uniform condition were higher in comparison with the casual condition, suggesting that uniform wear induces positive emotions. Particularly, because the agreement ratings were higher in the self condition than in the other condition, these positive emotions are likely to be related to professional pride. The certainty of this view is supported by the other behavioral findings reflecting the confidence of participants, in that the degree of disagreement with the negative words was greater than that of agreement with the positive words, and this disagreement with the negative words was faster in the self condition than in the other condition and in the uniform condition than in the casual condition.

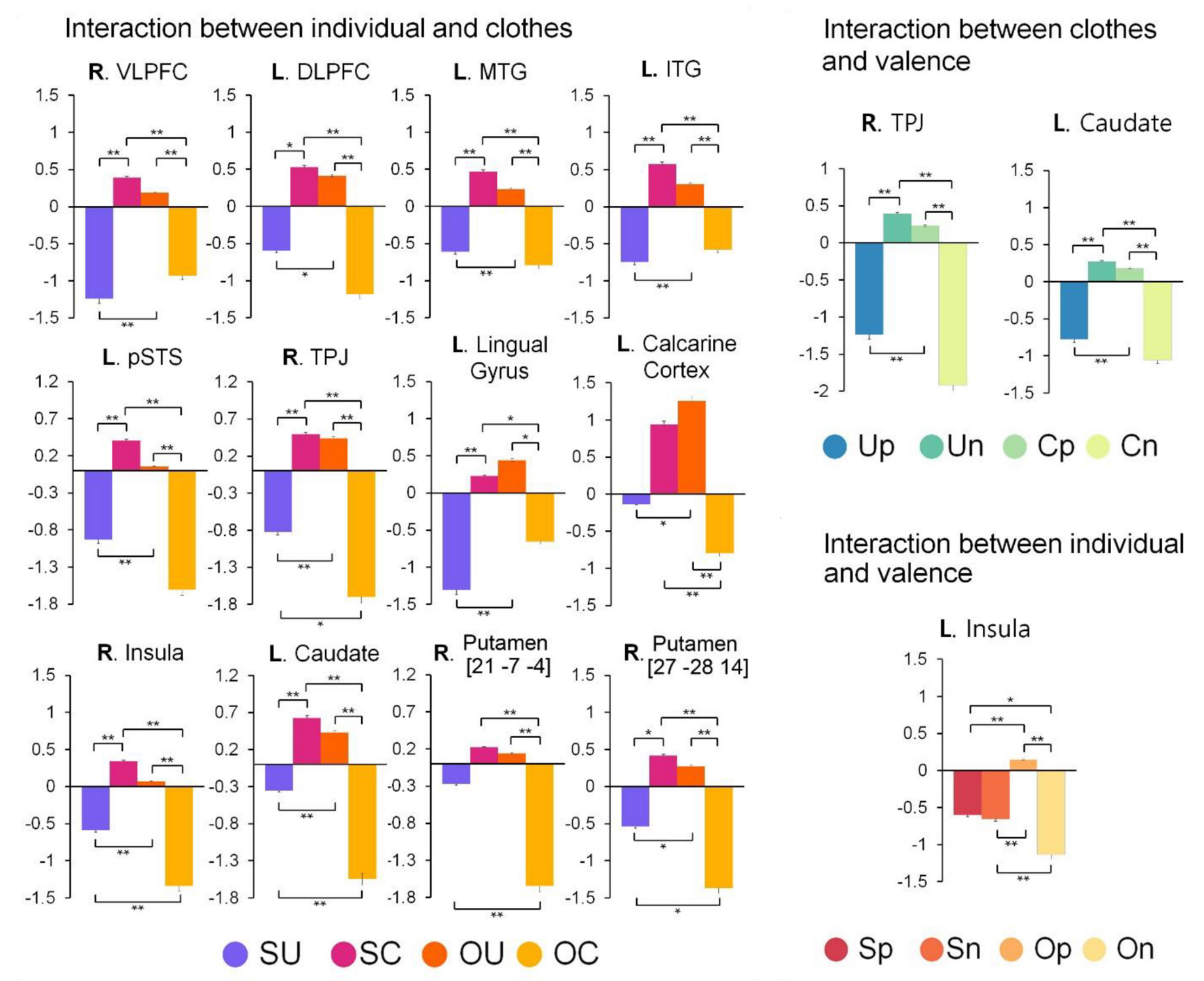

FIGURE 3 | Comparison of regional activity among the conditions in the regions showing the interaction effects. The numbers under the subtitles for the right putamen mean the Montreal Neurological Institute (MNI) coordinates. SU, the self/uniform condition; SC, the self/casual condition; OU, the other/uniform condition; OC, the other/casual condition; Up, the uniform/positive condition; Un, the uniform/negative condition; Cp, the casual/positive condition; Cn, the casual/negative condition; Sp, the self/positive condition; Sn, the self/negative condition; Op, the other/positive condition; and On, the other/negative condition; R., right; L., left; VLPFC, ventrolateral prefrontal cortex; DLPFC, dorsolateral prefrontal cortex; MTG, middle temporal gyrus; ITG, inferior temporal gyrus; pSTS, posterior superior temporal sulcus; TPJ, temporoparietal junction. *$p < 0.05$, **$p < 0.01$.

Our main hypothesis included the involvement of the ToM-related and SRP-related regions in professional pride. Previous neuroimaging studies have shown that several distinct regions form an integrated functional network for ToM reasoning, and the MPFC in the anterior brain and the pSTS and TPJ in the posterior brain form the core in the network (Carrington and Bailey, 2009). The MPFC is a critical region for mentalizing, whereas the pSTS and TPJ play an important role in perspective-taking (Frith, 2007). In our experiment, these ToM-related regions were found in the posterior brain, but not in the anterior brain. A previous study suggested a functional dissociation within the ToM network for different mental contents, with a common recruitment for cognitive and affective states in the pSTS and TPJ, but not in the MPFC (Corradi-Dell'Acqua et al., 2014). The only involvement of these posterior regions was also reported in a previous study of pride, which did not find the engagement of the MPFC, a region responsible for self-reflection, probably because pride might require less self-reflection compared to negative self-conscious emotions such as guilt or embarrassment (Takahashi et al., 2008). Likewise, the reason for why the SRP-related regions such as the MPFC and precuneus (Northoff et al., 2006; Uddin et al., 2007) did not appear in the results may be that professional pride is relatively less self-reflective. Meanwhile, a neural effect of linear combination of the self and uniform factors would be expected in our experiment. However, the ToM-related regions in the self/uniform condition showed greater activation relative to

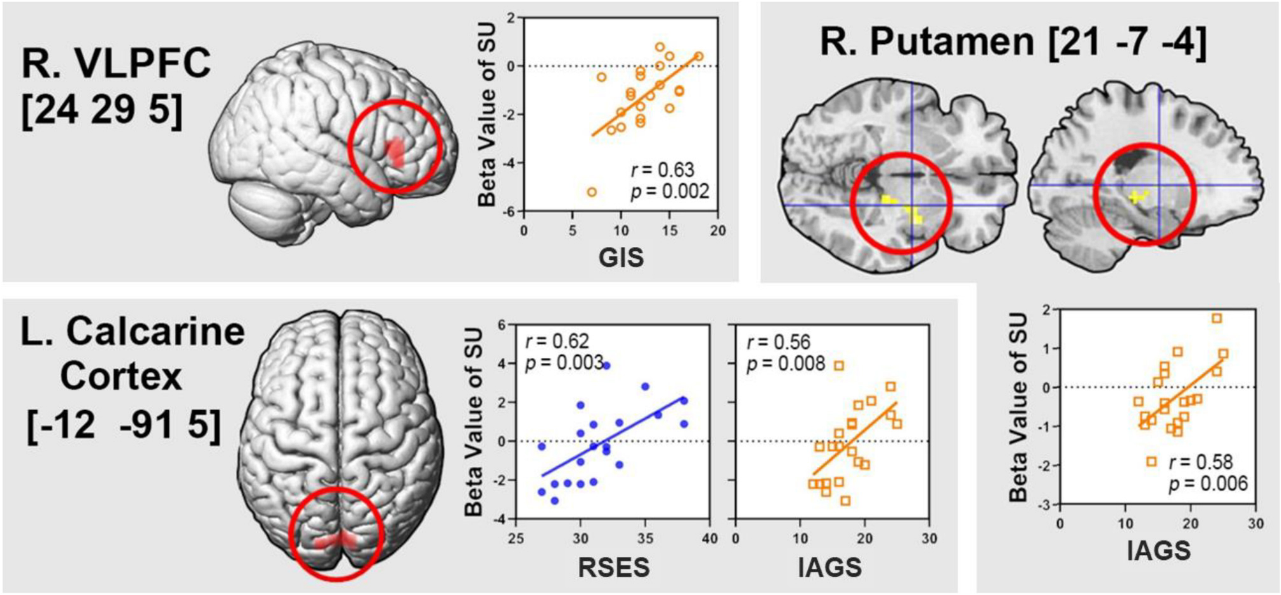

FIGURE 4 | Brain regions showing the interaction effect between individual and clothes, and significant correlations of regional activity in the self/uniform condition (SU) with behavioral variables. The numbers associated with the region name mean the Montreal Neurological Institute (MNI) coordinates. R., right; L., left; VLPFC, ventrolateral prefrontal cortex; RSES, Rosenberg Self-esteem Scale; GIS, Group Integration-Social in the Group Environment Questionnaire (GEQ); IAGS, Individual Attractions to Group-Social in the GEQ.

the other/causal condition, but not relative to the self/causal and other/uniform conditions. This results suggest that ToM-related neural activity in the self/uniform condition may be a product of complicated non-linear rather than linear combination of the self and uniform factors involving the self-evaluation and group cohesion processes.

Our additional hypothesis was that professional pride would recruit the empathy network and reward pathway. The imaging results showing the interaction of individual and clothes included the insula, which is part of the empathy network (Engen and Singer, 2013) and is also involved in emotion regulation and reward processing (Tanaka et al., 2004; Villafuerte et al., 2012). It has been known that the insula uses secondary reward signals and integrates contingencies to compensate for the negative feeling of social pain (Cristofori et al., 2015). However, it is unlikely that insula activity is confined to negative feelings alone. Our task provoked a positive feeling rather than a negative feeling, as shown in the behavioral results. It should be noted that the insula is activated when an individual is faced with choices that have both positive and negative social outcomes (Knutson and Greer, 2008).

Other evidence of the involvement of the reward pathway in professional pride is that the interaction of individual and clothes was found in the striatum such as the caudate and putamen. It is well-known that the striatum plays a critical role in processing both monetary and social rewards (Izuma et al., 2008; Albrecht et al., 2014). This role has been confirmed by some previous findings of enhanced caudate activity in response to recalling positive autobiographical memories (Speer et al., 2014) and reward-augmenting reciprocated cooperation (Rilling et al., 2012). In addition, our results showed that putamen activity in the self/uniform condition was positively correlated with the level of individual attractions to group-social. The function of the putamen supported by this finding is consistent with the role of the striatum that integrates social information into the coding of social action and reward (Báez-Mendoza and Schultz, 2013). The role of the striatum is likely to include cooperating behaviors in that this region is activated while working together to complete a maze (Krill and Platek, 2012). Considering that empathy and teamwork are key elements of professionalism (San-Martín et al., 2017), our findings on the insula and striatum support an important role of the empathy and reward networks in professional pride.

In our study, activity in the lateral prefrontal regions such as the VLPFC and DLPFC also showed the interaction of individual and clothes. Accumulative data have suggested that these two regions are involved in numerous higher cognitive processes including working memory, implementation of top-down goals and plans, episodic retrieval, inhibition, and self-control (Snow, 2016), and have dissociable roles; for example, the VLPFC may implement action control, whereas the DLPFC may represent the task goal (Swann et al., 2013). Furthermore, previous neuroimaging studies have found that both the VLPFC and DLPFC are core regions involved in various kinds of emotion regulation (Buhle et al., 2014; Kohn et al., 2014). While the DLPFC plays a general role in emotion regulation, reflecting a cognitive demand for regulation (Golkar et al., 2012), the VLPFC is engaged in both the generation and regulation of emotion through subcortical pathways including the striatum and amygdala (Wager et al., 2008). These two regions are both implicated in processing of social hierarchy (Zink et al., 2008; Marsh et al., 2009). A previous study reported that both regions are activated while viewing social interaction video clips related to dominance, suggesting their roles in power-related social motivations (Quirin et al., 2013). Looking at the more specialized features, the VLPFC has been demonstrated in the regulation of social exclusion and the reduction of social pain (Eisenberger et al., 2003; He et al., 2018). Based on these previous reports, our finding that VLPFC activity in the self/uniform condition was positively correlated with the level of group integration-social may suggest the role of this region in the generation and regulation of emotion in a social context. This role is certainly important in that uniform wear leads to emotional affirmation as a member of the organization and also to the need for behavioral abstinence. Taken together, the involvement of the VLPFC and DLPFC in self and uniform processing may reflect professionalism-related social responsibility and self-regulation.

There are some limitations in the current study. First, because of the small sample size, sex or career variation was not analyzed. Second, in some cases, there may be occupations where uniform wear is negative rather than positive, and these groups were not included in the current study. Third, the connectivity issue was not determined even though we discussed various networks based on the activated regions. Therefore, future research with effective connectivity analysis is required to address this issue.

CONCLUSION

The current study using the person-adjective matching task and fMRI for elucidating the neural basis of professional pride revealed that brain activity related to the self in uniform was found in various regions including the VLPFC, DLPFC, pSTS, TPJ, insula, and striatum. These results suggest that professional pride may be represented through multiple brain networks related to empathy, reward, and emotion regulation as well as the ToM network. These findings may reflect the characteristics of uniform wear including emotional affirmation as a member of the organization and the need for behavioral abstinence. Therefore, the neural basis of professional pride is closely related to positive self-evaluation and group cohesion.

ETHICS STATEMENT

This study was approved by the Institutional Review Board of Gangnam Severance Hospital, Yonsei University and carried out in accordance with the Declaration of Helsinki. All participants provided the written informed consent before the start of the experiment.

AUTHOR CONTRIBUTIONS

SP and J-JK designed the study. Y-JH and SP acquired the data. Y-JH and SK analyzed the data. Y-JH and J-JK wrote the manuscript. All authors reviewed and approved the final manuscript.

FUNDING

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIP) (No. NRF-2016R1A2A2A10921744).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2019.00253/full#supplementary-material

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Conflict of Interest Statement: 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.

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in Human Neuroscience

SYSTEMATIC REVIEW
published: 16 August 2019
doi: 10.3389/fnhum.2019.00276

Separate Neural Systems Value Prosocial Behaviors and Reward: An ALE Meta-Analysis

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Background: It has been argued that prosocial behaviors and momentary rewards activate similar reward systems. However, a recent theoretical hypothesis encourages a fundamentally different view. Specifically, the social heuristic hypothesis posits that individuals internalize prosocial behaviors that are advantageous in their daily social life. These advantageous behaviors are fundamentally different from tangible and immediate reward.

Objectives: Our objectives are to test a hypothesis that these advantageous prosocial behaviors are so critical to survival that it is necessary to have a neural system in the brain that leads people to maintain repeated social interactions. These neural systems are different from the computations of rewards because prosocial behaviors are not advantageous if only considering the computations of rewards.

Methods: To deepen the understanding of the neural systems of prosocial behaviors and reward, we conducted activation likelihood estimation (ALE) to examine brain activation in prosocial behaviors and reward tasks.

Results: Prosocial behaviors specifically activated distinct brain systems to a greater degree than reward. These systems were implicated in the processing of social behaviors and included the insula, temporal lobe, and superior temporal gyrus. By contrast, reward specifically activated the lentiform nucleus, thalamus, caudate nucleus, parahippocampal gyrus, and anterior cingulate cortex, which are associated with the brain reward system.

Conclusions: These findings suggest that prosocial behaviors are different from reward and involve specific brain mechanisms.

Keywords: reward, ALE, fMRI, social heuristic hypothesis, prosocial behaviors

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Received: *14 March 2019*
Accepted: *24 July 2019*
Published: *16 August 2019*

Citation:
Wang H, Zhang J and Jia H (2019) Separate Neural Systems Value Prosocial Behaviors and Reward: An ALE Meta-Analysis. Front. Hum. Neurosci. 13:276. doi: 10.3389/fnhum.2019.00276

INTRODUCTION

Prosocial behaviors refer to "a broad category of acts that are defined by some significant segment of society and/or one's social group as generally beneficial to other people" (Penner et al., 2005, p. 366). How prosocial behaviors arise is one of the fundamental questions of social life (Darwin, 2009). Prosocial behaviors, such as cooperation and altruism, are beneficial for group survival. However, these group advantageous behaviors come at a cost to the individual's momentary reward (Wilson and Wilson, 2007). It remains unclear whether the intangible advantageous benefits of prosocial behaviors are integrative or segregated to the disadvantageous computations of tangible rewards for prosocial behaviors.

Research has suggested that a positive reward accompanied by prosocial behaviors usually involves two pathways. One boosts the performers' inclusive fitness reward and leaves them with a larger number of genetically related offspring by helping their relatives (known as "kin selection theory") (Hamilton, 1964). Another receives reciprocity reward directly from the beneficiary (Trivers, 1971) or indirectly from other observers through an established reputation (Nowak and Sigmund, 2005). Indeed, theoretical and empirical evidence has argued that prosocial behaviors produce reward and value for the performers *per se* (Harbaugh et al., 2007; Aknin et al., 2013).

Despite this progress, key questions about the nature of prosocial behaviors remain unresolved. Perhaps the most fundamental question is whether prosocial behaviors and reward are segregated or integrated in a common region in the brain. Scholars have proposed an integrative hypothesis (Landreth and Bickle, 2008; Leknes and Tracey, 2008; Levy and Glimcher, 2012), which posits that a common currency in the brain is a way to represent the value of tangible rewards and provides a common scale to value fundamentally incommensurable goods or behaviors. According to this view, the intangible advantageous benefits of prosocial behavior would be integrative to the cost of tangible reward (Saxe and Haushofer, 2008).

Although the integrative hypothesis remains highly influential, new empirical evidence has shown that prosocial behaviors may be fundamentally different from reward. This idea is consistent with new findings that prosocial behaviors may be intuitive. For example, individuals who make their decisions more quickly are more cooperative in the public goods game; moreover, forcing individuals to decide quickly increases their contributions in the game (Rand et al., 2012). Meta-analysis has also shown that intuition promotes cooperation relative to reasoning (Rand, 2016). This evidence suggest that prosocial behaviors is beyond reward-cost computations. In other words, there is a growing recognition that prosocial behaviors may have a fundamentally different nature from pure reward-cost computations. Moreover, at the theoretical level, the social heuristics hypothesis (SHH) posits that prosocial behaviors are intuitive because prosocial behavior heuristics are developed in daily social interactions where prosocial behaviors are advantageous (Rand et al., 2013). This advantage hypothesis of social behaviors implies that these group advantageous behaviors may have separate neural systems that process intangible advantageous representations from the tangible reward.

These competing hypotheses make it difficult to obtain a clear understanding of the neural systems of prosocial behaviors in the brain (Penner et al., 2005; Levy and Glimcher, 2012; Dovidio et al., 2017; Lamm et al., 2019). First, the heterogeneity of the theoretical and empirical results is partly due to the different experimental paradigms that have aimed to answer diverse aspects of prosocial behaviors (Penner et al., 2005). Second, it is unknown whether activation patterns reflect processes that are common to both prosocial behaviors and reward or instead serve incidental functions (Cutler and Campbell-Meiklejohn, 2019). Although a new theory has proposed to differentiating prosocial behaviors from pure benefit–cost computations (Rand et al., 2013), consistent neural evidence is lacking.

Thus, it is important to pool prior studies together to probe whether prosocial behaviors are fundamentally different from reward computations. In this research, we examine this segregationist model. We neither attempt a comprehensive and exhaustive discussion nor provide a detailed overview of prosocial behavior, phenomena that have been the topic of other recent reviews (Reddy and Roy, 2019). Based on the SHH, we challenge the claims of integration that prosocial behaviors are just a form of reward (Sommerville et al., 2018).

As the size and scope of the functional magnetic resonance imaging (fMRI) literature have burgeoned, it has become increasingly difficult to synthesize new data into existing competing frameworks and theories. This problem is particularly serious when trying to probe data from different domains, such as prosocial behaviors and reward. This difficulty can be solved by employing a new approach for performing coordinate-based meta-analyses (CBMAs) (Eickhoff et al., 2009; Laird et al., 2009). CBMA provides an opportunity to evaluate whether imaging studies of prosocial behaviors and reward are integrative at the neural level. The results from CBMAs provide evidence for colocalization or segregation of prosocial behaviors and reward in the brain.

METHOD

Literature Search and Study Selection

Neuroimaging studies published from January 1, 1997 to November 1, 2018, were identified by a literature search of PubMed (http://www.pubmed.org), BrainMap (http://www.brainmap.org/software.html#Sleuth), and Google Scholar (https://scholar.google.com.hk/) for different combinations of the terms "fMRI," "neural," "reward," "money," "value," "prosocial," "altruis*," "charity," "charitable," "public goods," "cooperation," "public goods," "social value orientation," "reputation," "dictator," "ultimatum," "trust game," and "prisoner*." Further papers were obtained by reference tracing of the retrieved papers and previous meta-analyses on prosocial and reward. Papers were considered if they reported novel fMRI data not reported elsewhere, collected while participants conducted tasks regarding prosocial behaviors and reward, and analyzed whole-brain data.

To provide comprehensive, best-practice analyses of consistent activation by prosocial behaviors and reward, we applied the inclusion and exclusion criteria discussed below.

1. To infer consistency across experiments, only fMRI studies were included.
2. To ensure that the likelihood of brain activation under the null hypothesis is equal across the brain (Eickhoff et al., 2009), experiments were only included if they reported whole-brain activation coordinates.
3. Experiments were only included if reported coordinates were represented in standardized space, either Montreal Neurological Institute (MNI) coordinates or Talairach (TAL) coordinates. If coordinates were localized in TAL, they were converted to MNI space employing software embedded in GingerALE (Eickhoff et al., 2009).

4. Coordinates were only included if they were the result of a contrast analysis that directly tested prosocial behaviors or reward.
5. Finally, only experiments that used healthy participants were included to help control for individual differences in brain activation across populations.

After the exclusion and inclusion criteria had been applied, a total of 114 experiments consisting of 2,023 participants and 1,273 foci were used (see **Figure S1**). Prosocial behaviors included 136 foci from 19 experiments with 361 participants. Reward included 1,137 foci from 95 experiments with 1,662 participants.

Separate meta-analyses were only performed if a sufficient number of experiments were available (>17 experiments) (Eickhoff et al., 2016). All analyses (except those with <17 experiments) were repeated to examine (1) patterns of common and specific activation across prosocial behaviors and reward, and (2) corrected results.

Activation Likelihood Estimation

Following previous studies, the activation likelihood estimation (ALE) meta-analyses were conducted according to the standard procedures employing GingerALE 2.3.6 software (Eickhoff et al., 2009). Coordinates reported in TAL were transformed into Montreal Neurological Institute (MNI) space by using TAL-MNI conversion software, embedded within GingerALE. All results in our meta-analyses were thresholded at a cluster-level corrected threshold of $p < 0.05$ (cluster-forming threshold at voxel level $p < 0.001$).

RESULTS

Meta-Analyses Across Prosocial Behavior Experiments

Prosocial behaviors activated emotional prosocial brain, the insula, the temporal lobe, and the superior temporal gyrus (see **Figure 1** and **Table S1**).

Meta-Analyses Across Reward Experiments

Reward activated the reward system, including the lentiform nucleus, thalamus, caudate nucleus, anterior cingulate cortex, parahippocampal gyrus, inferior frontal gyrus, and medial frontal gyrus (see **Figure 2** and **Table S2**).

Contrast Meta-Analyses

Contrasting the activation caused by prosocial behaviors and reward, we found that prosocial behaviors significantly activated the insula to a greater degree (see **Figure S2** and **Table 1**). The lentiform nucleus, thalamus, caudate nucleus, parahippocampal gyrus, and anterior cingulate cortex showed greater activation with reward than with prosocial behaviors (see **Figure S3** and **Table 2**).

We conducted conjunction analyses to identify the common areas between prosocial behaviors and reward. None of the conjunction meta-analyses revealed any significant results.

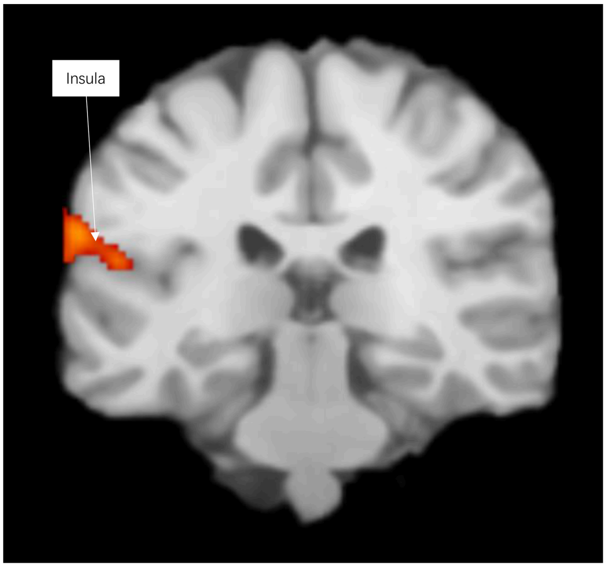

FIGURE 1 | Significant clusters in the ALE meta-analysis across prosocial behavior experiments (cluster-level corrected threshold of $p < 0.05$).

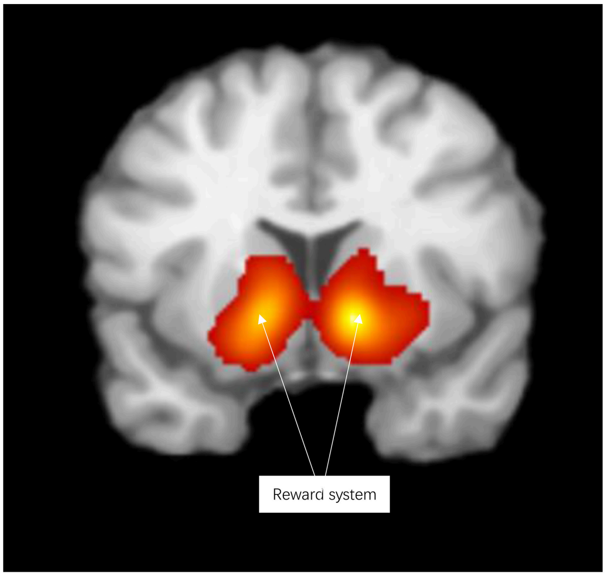

FIGURE 2 | Significant clusters in the ALE meta-analysis across reward experiments (cluster-level corrected threshold of $p < 0.05$).

DISCUSSION

How does the brain compare prosocial behaviors and reward? One intriguing hypothesis is that they can represent the subjective value of all reward types on a common neural scale (Levy and Glimcher, 2012). However, does this common neural currency exist? The results from our meta-analysis refute claims that prosocial behaviors and reward are the same thing and shared common neural currency in the

TABLE 1 | Brain areas specifically activated by prosocial behaviors from ALE analysis.

Region	BA	MNI coordinates		
		X	*Y*	*Z*
L Superior temporal gyrus	22	−63	−38	21
L Temporal lobe	42	−62	−33	24
L Insula	13	−58	−31	20

Clusters in the contrast analyses were thresholded at uncorrected $p < 0.05$ *with 5,000 permutations and a minimum cluster size of 50* mm^3.

TABLE 2 | Brain areas specifically activated by reward from ALE analysis.

Region	BA	MNI coordinates		
		X	*Y*	*Z*
R Parahippocampal gyrus		−8	7	−1
R Lentiform nucleus		24	20	−2
R Extra-nuclear		5	4	3
R Caudate		10	26	−5
R Thalamus		4	−18	16
L Thalamus		0	−20	6
L Cingulate gyrus	32	4	30	36

Clusters in the contrast analyses were thresholded at uncorrected $p < 0.05$ *with 5,000 permutations and a minimum cluster size of 50* mm^3.

brain. Instead, our observations show that prosocial behaviors and reward are fundamentally different from each other. In fact, these results from our meta-analyses do not preclude the possibility that they may integrated at finer levels of analysis. For instance, it is possible that prosocial behaviors and reward may be integrated into individual participants or neurons. Similarly, common neural currency may be present on a finer timescale that is resolved by conventional fMRI studies. Nevertheless, what these results from our meta-analysis do demonstrate is that conventional fMRI studies of prosocial behaviors and reward are segregated into different brain areas.

These findings are consistent with the theory of SHH (Rand et al., 2012, 2013; Rand, 2016). This hypothesis was set out to answer an interesting question: is our first response to be selfish such that we show prosocial behaviors through careful reasoning? Or are we predisposed toward prosocial behaviors, with deliberative self-control leading to self-interest? SHH posits that individuals internalize behaviors that are typically advantageous and successful in their daily repeated social behaviors and interactions (Rand et al., 2013). These advantageous and successful prosocial behaviors are fundamentally different from tangible and immediate rewards, which is supported in our meta-analysis. Thus, our results suggest that interventions that designed to promote prosocial behaviors should be aware of the fundamental differences between prosocial behaviors and reward.

The specific brain areas involved in prosocial behaviors in our meta-analysis were mostly located in the insula. In a review of prosocial behaviors literature (Cutler and Campbell-Meiklejohn, 2019), the insula was related to prosocial behaviors. The insula may encode intangible advantageous benefits of prosocial behaviors beyond reward-cost computations.

Reward processing in our meta-analysis was distinguished by modulating activity in the lentiform nucleus, thalamus, caudate nucleus, parahippocampal gyrus, and anterior cingulate cortex. The results from previous neuroimaging studies (Shackman et al., 2011; Levy and Glimcher, 2012) and the current meta-analysis support the notion that humans independently process prosocial behaviors and reward. Importantly, segregation models and domain-specific neural implementation were threshold-dependent (Jiang and Egner, 2013); thus, probing the potential factors influencing the thresholding between prosocial behaviors and reward would be a valuable future direction.

A possible limitation of the current meta-analysis is that we did not include psychological and motivational experiences associated with prosocial behaviors, such as gratitude, awe, compassion, kindness, and empathy (Bartlett and DeSteno, 2006; Grant and Gino, 2010; Masten et al., 2011; Piff et al., 2015; Flournoy et al., 2016; Van der Graaff et al., 2018). Based on SHH, prosocial behaviors are advantageous in repeated daily life. This theory is silent on the motivational experiences associated with prosocial behaviors. Thus, it is unclear whether prosocial motivation such as compassion are also advantageous in daily life. It has been argued that empathy, compassion, and prosocial behaviors are distinct phenomena and they differ with respect to their neural mechanisms (Lamm et al., 2019). Thus, to directly test the prediction from SHH, we only included prosocial behaviors. Still, future studies may focus on whether psychological and motivational experiences that induce prosocial behaviors, such as empathy and compassion, share common neural systems with reward.

Two methodological caveats must be noted. First, as stated above, we did not collect experiments about prosocial motivation such as empathy, compassion, and kindness. We only included prosocial behaviors to obtain behavioral level experiments. Although prosocial behaviors are more directly related to our theoretical hypothesis that prosocial behaviors instead of prosocial motivation are advantageous in repeated daily social interactions, the limited experiments of these prosocial motivations may produce less specific regions of prosocial psychological experiences. Second, we used the CBMA method. It has been argued that more information may be obtained employing a map-based meta-analysis (Maumet and Nichols, 2015). However, this undertaking was not possible because the contrast and standard error maps are not widely shared in our study.

CONCLUSION

We investigated the integrative hypothesis and segregationist model regarding prosocial behaviors and reward by using a meta-analytical method. Prosocial behaviors specifically activated distinct brain systems to a greater degree. These systems were implicated in the processing of social behaviors. By contrast, reward specifically activated the brain reward system. We documented that prosocial behaviors are different from reward-cost computations and involve specific brain mechanisms. These results suggest that interventions that designed to promote prosocial behaviors should be aware of the fundamental differences between prosocial behaviors and reward.

AUTHOR CONTRIBUTIONS

Each author made contributions to the conception, design of the work, the acquisition, analysis, and interpretation of data. HW drafted the manuscript. HJ and JZ revised it.

FUNDING

This work was supported by the Program of National Natural Science Foundation of China (grant number 71801109); Beijing Natural Science Foundationand (grant number 9194025); National Science Foundation for Post-doctoral Scientists of China (grant number 2018M640879); Foundation Major Cultivation Project of Guangdong Province, China (grant number 2017A030308013); and National Natural Science Foundation of China (grant number 71571087).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2019.00276/full#supplementary-material

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Conflict of Interest Statement: 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.

frontiers in Human Neuroscience

ORIGINAL RESEARCH
published: 06 November 2019
doi: 10.3389/fnhum.2019.00389

Effects of Expressive Writing on Neural Processing During Learning

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Expressive writing about past negative events has been shown to lead to a slew of positive outcomes. However, little is known about why writing about something negative would have positive effects. While some have posited that telling a narrative of a past negative event or current anxiety "frees up" cognitive resources, allowing individuals to focus more on the task at hand, there is little neural evidence suggesting that expressive writing has an effect on cognitive load. Moreover, little is known about how individual differences in the content of expressive writing could affect neural processing and the cognitive benefits writing confers. In our experiment, we compared brain activity in a group that had engaged in expressive writing vs. a control group, during performance on a feedback-based paired-associate word-learning task. We found that across groups, differential activation in the dorsal striatum in response to positive vs. negative feedback significantly predicted better later memory. Moreover, writing about a past failure resulted in more activation relative to the control group during the learning task in the mid-cingulate cortex (MCC), an area of the brain crucial to processing negative emotion. While our results do not provide support for the assertion that expressive writing alters attentional processing, our findings suggest that choosing to write about particularly intense past negative experiences like a difficult past failure may have resulted in changes in neural activation during task processing.

Keywords: expressive writing, fMRI, learning, feedback, striatum, MCC, medial cingulate cortex

OPEN ACCESS

Edited by:
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Reviewed by:
Crystal Reeck,
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Specialty section:
This article was submitted to Cognitive Neuroscience, a section of the journal Frontiers in Human Neuroscience

Received: *20 December 2018*
Accepted: *17 October 2019*
Published: *06 November 2019*

Citation:
DiMenichi BC, Ceceli AO, Bhanji JP and Tricomi E (2019) Effects of Expressive Writing on Neural Processing During Learning. Front. Hum. Neurosci. 13:389. doi: 10.3389/fnhum.2019.00389

INTRODUCTION

Expressive writing about a past negative experience has been shown to lead to a slew of positive outcomes. For example, writing about a past trauma has led to reductions in anxiety and depression (Lepore and Smyth, 2002; Smyth et al., 2008), as well as improvements in physical health (Pennebaker et al., 1988; Harber and Pennebaker, 1992). Writing about anxieties has also resulted in improved cognitive performance, both in the laboratory (Klein and Boals, 2001; DiMenichi and Richmond, 2015; DiMenichi et al., 2018) as well as in the classroom on high stakes exams (Ramirez and Beilock, 2011).

What is it about writing about negative experiences that leads to such benefits? While there is some evidence that writing about a past negative event leads to reductions in the physiological stress response (DiMenichi et al., 2018), some have posited that writing down negative feelings "frees up" cognitive load to better focus on the task at hand (Klein and Boals, 2001; Ramirez and Beilock, 2011), thus leading to observed performance benefits. However, there is little empirical evidence regarding how expressive writing relates to cognitive processing in the brain, as well as other brain networks vital to cognition.

If writing about negative experiences like past traumas or current anxieties "frees up" cognitive resources, one would subsequently expect to see less activation in areas of the brain typically correlated with cognitive load, such as the dorsolateral prefrontal cortex (dlPFC; Rypma et al., 2002). Yet, no expressive writing intervention initiatives have examined how expressive writing affects neural processing, so it remains difficult to draw firm conclusions that changes in cognitive load are the mechanism behind the success brought about by expressive writing.

Alternatively, writing about a negative event like a past failure might lead to performance improvements *via* changes to affective or emotional processes. It is important to note that simply inducing a sad mood through writing has not been shown to improve cognitive performance, whereas writing about a negative event specific to the self, such as a failure, has been shown to confer cognitive benefits (DiMenichi et al., 2018). It is possible that being reminded of a past negative experience may cause an individual to be more sensitive to a new negative experience, such as negative feedback about performance. Therefore, we might expect to see changes in activation in the striatum, an area of the brain primarily associated with processing affective information, such as monetary rewards and punishments (Delgado et al., 2000, 2003), and positive and negative feedback about performance during learning (Tricomi and Fiez, 2012; DePasque and Tricomi, 2015; Lempert and Tricomi, 2016).

Furthermore, expressive writing about negative events or current worries may evoke strong emotions, which may alter neural activation in areas of the brain that typically process strong negative emotion. Thus, we hypothesized that changes in affective or emotional processing may be responsible for the benefits of expressive writing. However, without empirical evidence from the brain, it is difficult to draw conclusions about this proposed mechanism behind the success of expressive writing.

Individual Differences in Brain Processing

While differences in brain processing between writing groups may help us gain insight as to the benefits of expressive writing about past failures, individual differences in the quality, stressfulness, intensity, or other aspects of their expressive writing sample may help us understand what specifically about writing about past failure guides performance improvements. Considering that writing about more intense failures has previously led to greater health benefits (Harber and Pennebaker, 1992; Pennebaker, 1997), one would expect that writing about a more stressful or intense failure may also result in greater immediate benefits to cognitive performance. Furthermore, information about individual differences in brain processing, and how these differences in brain processing relate to performance, may help us gain further information about the mechanism behind the benefits of expressive writings about past failures.

Current Study

In this experiment, we examined how writing about a past failure affected both cognitive performance and neural processing on a feedback-based paired-association word-learning task. In previous studies using this task, distinct neural signatures in the striatum to positive vs. negative performance feedback have been elicited, in addition to engagement of a host of brain regions typically associated with the cognitive processes underlying effortful encoding (Tricomi and Fiez, 2012; DePasque and Tricomi, 2015; Lempert and Tricomi, 2016). We hypothesized that writing about a difficult time in which one did not succeed would result in better memory both during the word-learning task, as well as at a later surprise recall task, with changes in brain activation predicting these group performance differences. In particular, we hypothesized that there might be group differences in the neural responses to positive and negative feedback, or in activation of brain regions underlying effortful cognition. Alternatively, we predicted that individual differences in the quality of writing samples about past failures could predict individual differences in neural processing, which could, in turn, predict subsequent memory differences on our task.

MATERIALS AND METHODS

Participants

Forty right-handed adults (24 female, 16 male) aged 18–35 were recruited from the surrounding area of Rutgers University-Newark. Sample size was determined based on a behavioral pilot study examining the effect of our writing manipulation on test performance in our task (see **Supplementary Material**). The pilot produced an effect size of $d = 0.93$. At 80% power and with an alpha of 0.05, this suggests a sample size of 40 (20 per group), which is the recommendation we used for our experiment. Participants (mean age = 22.23, SD = 3.81) reported to the Rutgers University Brain Imaging Center (RUBIC, Newark, NJ, USA). Participants were paid $50 for their participation. All participants gave written informed consent. The experiment was approved by the institutional review board of Rutgers University.

Writing Task

Before the start of the scan, participants completed a writing manipulation adapted from DiMenichi and Richmond (2015). In the "failure" condition, participants saw a prompt on a computer screen that asked them to spend the next 10 min writing about a difficult time in which they did not succeed. They typed their response in the computer. Participants pseudo-randomly assigned to the "control" condition were prompted to write about the plot of a movie they had recently viewed. The goal of the control condition was to control for the general effects of writing on performance.

Paired-Association Word Learning Task

After completing the writing task, all participants completed a paired-association learning task with and without feedback inside the magnetic resonance imaging (MRI) scanner (Tricomi and Fiez, 2012; Lempert and Tricomi, 2016). In the "learning phase" of the experiment, participants viewed a "target" word with two arbitrary word choices below each target, and participants were told to select the word that matched the target word. Before each set of trials, participants were shown a label

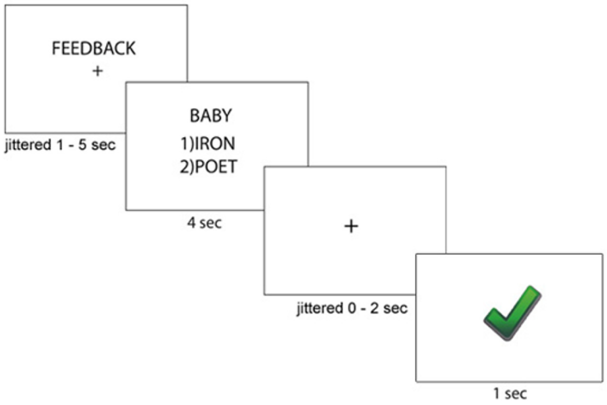

FIGURE 1 | Paired-Association Word Learning Task Description. Participants were told whether they would receive feedback for the current block. Then, participants viewed a target word with two word choices, and pressed the key responding to their word choice. Participants then saw immediate accurate feedback regarding their word choice.

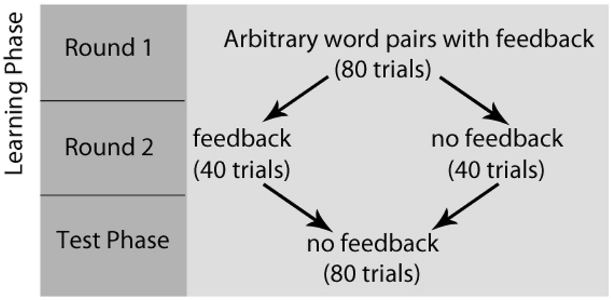

FIGURE 2 | Paired-Association Word Learning Task Experimental Design. Participants completed two rounds of the learning phase, followed by the test phase. In the first round of the learning phase, word matches were arbitrary, but participants received feedback for all trials and were told to use this feedback for future rounds. After completing both rounds of the learning phase, participants completed the "test phase," which asked participants to select the word that matched the target (without receiving any feedback) and rate their confidence in their response.

indicating if the block contained "feedback" or "no feedback." In the feedback block, participants were given accurate feedback about their response—a green check mark if they were correct, or a red "X" if they were incorrect. In the no-feedback condition, participants saw a pound sign after their response; see **Figure 1** for task description. Participants completed two rounds during the learning phase of the experiment. In the first round of the learning phase, word matches were new (and therefore arbitrary), but participants received feedback for all trials and were told to use this feedback for future rounds. Trials for which participants did not respond within the 4 s window were repeated at the end of each round. After completing both rounds of the learning phase with the same set of words, participants completed the "test phase" on the words from the task outside the scanner, which asked participants to select the word that matched the target(without receiving any feedback) and rate their confidence in their response on a Likert scale (1 = complete guess, 7 = completely sure); see **Figure 2** for experimental design.

Survey Battery

After the conclusion of the surprise recall task, participants provided demographic information, as well as several surveys corresponding to traits that could possibly affect our writing manipulation. The battery included the Connor-Davidson Resilience Scale, which measures individual differences in trait resiliency (Connor and Davidson, 2003); the Achievement Goal Questionnaire, which examines preference for wanting to achieve goals in order to master a new skill, perform well, or avoid failure (Elliot and Church, 1997); and the Need For Cognition Scale (NFC), which measures the tendency for an individual to prefer to engage in thinking (Olson et al., 1984). We also included the Cognitive Inference Questionnaire (CIQ), which asks participants to indicate how often they had thoughts that could have interfered with performance—e.g., worries about task performance, thoughts about things other than the task, etc. (Sarason et al., 1986). The Marlow-Crowne Social Desirability Scale was also included to measure any bias in responding to the survey battery (Crowne and Marlowe, 1960). Surveys were completed on a computer *via* the website Qualtrics (Provo, Utah) and presentation order was randomized by the computer to prevent order effects.

Lastly, we probed participants about their subjective experience of different aspects of the task. Specifically, we asked participants to rate how much they enjoyed and cared about doing well on the word-learning task, if they preferred negative to no feedback on the task, and to rate their level of stress upon arrival, during the writing task, while completing the writing task, and while completing the survey. We also asked participants how stressed they felt when the original event they wrote about occurred (either their past failure or movie). Specifically, participants were asked, "Please rate how stressful the event was WHEN IT ORIGINALLY OCCURRED."

fMRI Data Collection and Analyses

We utilized a 3 Tesla Siemens TRIO scanner and 12 channel head coil at the RUBIC. Stimulus presentation was implemented with E-Prime Experimental Software (Psychology Software Tools, Pittsburgh, PA, USA), and functional magnetic resonance imaging (fMRI) data were preprocessed and analyzed using BrainVoyager QX 2.3.1 Software (Brain Innovation, Maastricht, The Netherlands). Anatomical slices were collected using a T1-weighted protocol of 176 isotropic 1-mm voxel sagittal slices, while functional slices were collected using a single-shot EPI pulse sequence with a TR of 2,500 ms and TE of 25 ms. Forty-one contiguous oblique-axial 3 mm × 3 mm × 3 mm voxel slices were acquired in an oblique orientation of 30° to the anterior commissure-posterior commissure (AC-PC) axis. This orientation has been found to reduce signal dropout in the ventral prefrontal cortex (vPFC; Deichmann et al., 2003).

During analysis, fMRI data were normalized to the Talairach stereotaxic space (Talaraich and Tournoux, 1988) before preprocessing. Preprocessing included slice-time correction, motion correction, 4 mm spatial smoothing, and high-pass temporal filtering (high pass GLM-Fourier, 3 sines/cosines, 3 s). Preprocessed data was then analyzed using a random-effects general linear model (GLM).

For each participant, we modeled the 4-s word presentation screen (Slide 2 in **Figure 1**) and the 1-s feedback presentation screen (Slide 4) as regressors in our model. The regressors were convolved with a canonical hemodynamic response function. A predictor for missed trials (i.e., when subjects failed to respond on Slide 2 within the 4-s response window) was included in the model as a predictor of no interest. Additionally, the six motion parameters were also included in the model as predictors of no interest. For all analyses, we utilized the continuity-based cluster-level threshold estimator in BrainVoyager, with an initial significance threshold of $p < 0.005$. We then selected to run 1,000 Monte Carlo simulations, and corrected each contrast to a contiguity threshold cluster-level false-positive alpha rate of 0.05. Due to concern that this two-step cluster thresholding procedure is susceptible to inflated type 1 error (Eklund et al., 2016), we supplemented this analysis with permutation-based non-parametric tests, submitting images for each participant (contrast of beta weights from subject-level GLM estimation: positive feedback minus negative feedback; non-feedback trial word presentation beta weights) using the FSL randomize procedure with threshold-free cluster enhancement, using 10,000 iterations (Smith and Nichols, 2009). The non-parametric contrasting procedure provides further information on results that survive the more rigorous threshold. In regions of interest that survive this rigorous threshold (striatum and mid-cingulate cortex, MCC), peaks from the parametric analysis are identified for visualization (**Figure 3**) and further analysis (individual differences correlations and psychophysiological interaction (PPI) analysis).

Analysis of Feedback Across All Participants

We conducted a whole-brain analysis that examined activation at the time of feedback presentation during round 2 of the learning phase (i.e., when word matches are no longer arbitrary, therefore making feedback meaningful to choice). A contrast of interest included Positive Feedback > Negative Feedback to replicate previous results showing that this task elicits positive vs. negative feedback differences in brain areas typically associated with feedback processing (e.g., DePasque Swanson and Tricomi, 2014; Lempert and Tricomi, 2016).

Analysis Across Writing Groups

We also conducted a whole-brain analysis that examined group differences in activation between both writing groups (failure writing topic vs. control writing topic). Contrasts of interests included a contrast that examined activation differences in the failure writing vs. control writing groups at time of word presentation during the learning phase of the task, as well as contrasts that examined group differences (failure vs. control) in feedback processing (i.e., positive feedback overall, negative feedback overall, and positive vs. negative feedback).

Functional Connectivity Analysis

Additionally, we conducted a PPI analysis. Based on the results from our GLM analysis, we examined task-based functional connectivity between the MCC (signal time series from peak of the failure writing vs. control word presentation contrast) and other brain regions, for the failure writing group and the control group. We used the time period of the word presentation in the learning phase as the psychological context, because this is the time period in which we observed an effect in the MCC in our GLM analysis.

Behavioral Analyses

As a manipulation check, an independent rater rated each of the writing samples on a 7-point Likert scale for negativity, emotional content, intensity, persistence, finding a "silver lining," and relation to self. We expected the writing samples to vary greatly in content but expected the samples from the failure condition to be higher on each of these measures than the samples from the control condition.

We conducted *t*-tests that examined group-level differences in performance on the word association learning task. We looked at percent correct during round 2 of the learning phase (i.e., when choice is no longer arbitrary) excluding trials with no response, as well as performance differences within each feedback context (feedback condition vs. no feedback condition). We also repeated these tests for test phase performance. We also examined whether there were any significant correlations between our survey measures, performance, and brain activation in areas associated with writing group differences. Brain activation estimates were extracted from peak voxels in left caudate (positive vs. negative feedback contrast, all participants) and MCC (failure writing vs. control word presentation contrast). All analyses based on survey measures were exploratory.

RESULTS

Behavioral Results

We found that there was a significant difference between groups in event stress ratings, with participants in the failure group rating the event they wrote about as more stressful than participants in the control group (failure writing group mean = 4.55, SD = 1.8; control group mean = 1.10, SD = 137; $t = 6.77$, $p < 0.001$). Additionally, the writing samples from the failure content were rated as more emotional ($p = 0.02$), more intense ($p < 0.001$), more related to the self ($p < 0.001$), and marginally (although not significantly) more negative ($p = 0.071$).

We also examined performance at each phase of the task. All analyses were performed after discarding missed trials (i.e., trials where participants did not respond within the 4 s response window). There was no difference in the number of missed trials between groups (failure writing group mean = 4.85, SD = 10.01; control group mean = 2.30, SD = 6.97; $t = 0.94$, $p = 0.356$). As expected, participants were at chance for round 1, when word matches were arbitrary and there was no way of knowing in advance which word would be the correct match, and there was no difference between groups (failure writing group mean = 52.63%, SD = 7.90%; control writing group mean = 53.81%, SD = 10.19%; $t = 0.37$, $p = 0.7152$). However, contrary to our hypothesis and the results of our behavioral pilot study (see **Supplementary Figure S2**), we did not find

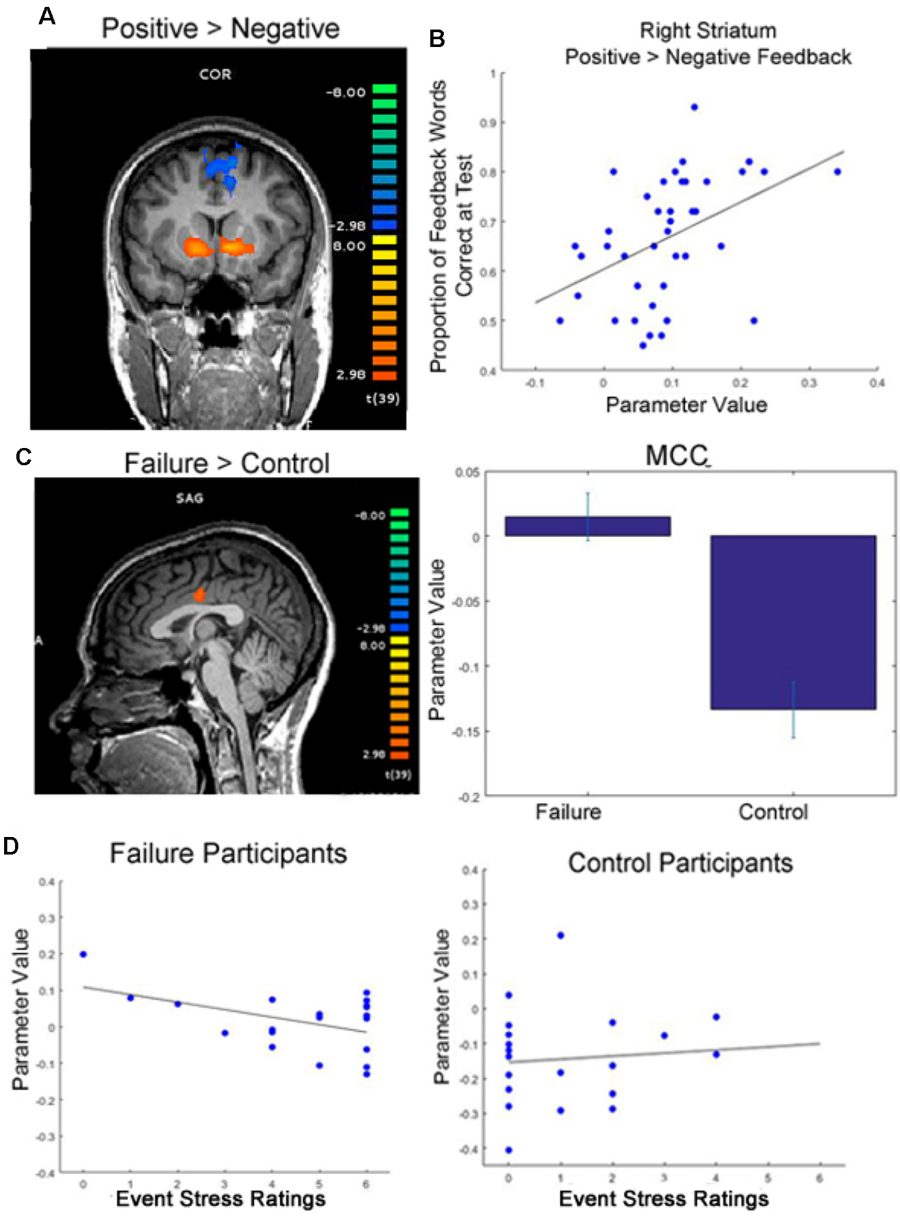

FIGURE 3 | Functional magnetic resonance imaging (fMRI) results. **(A)** Participants showed greater activation in the striatum when viewing positive feedback than negative feedback during round 2 of the learning phase, when feedback was meaningful for performance ($p < 0.05$, cluster corrected; initial cluster forming threshold $p < 0.001$). **(B)** Greater differential activation in the right dorsal striatum when viewing feedback was significantly correlated with later memory for feedback words. **(C)** Participants who were randomly assigned to write about past failures showed greater activation in the mid cingulate cortex (MCC) while viewing target words throughout the learning phase than participants who wrote about a trivial topic ($p < 0.05$, cluster corrected, initial cluster forming threshold $p < 0.005$; peak activation coordinates in Talaraich space: −4, −11, 30). Whereas control subjects showed typical decreases in activation in the MCC during the task, failure subjects' activation was near baseline averaged around 0 (right). **(D)** Individual differences in self-reported event stress ratings significantly predicted MCC deactivation for failure participants (left). We did not see this same relationship for control subjects (right).

a significant difference in performance scores on round 2 of learning phase between writing groups, when performance depended on memory of the correct pairs from round 1 (failure writing = 58.28%, SD = 7.77%, control writing = 57.51%, SD = 9.70%; $t_{(38)} = 0.279$, $p = 0.782$), nor did we see differences when examining only words from the feedback (failure writing = 60.24%, SD = 8.64% control writing = 58.14%, SD = 11.61%; $t_{(38)} = 0.65$, $p = 0.520$) or no feedback rounds (failure writing = 56.32%, SD = 09.22% control writing = 56.87%, 10.11%; $t_{(38)} = -0.18$, $p = 0.856$). Furthermore, we did not see a significant difference between writing groups' scores at test (failure writing = 61.90%, SD = 8.87%, control writing = 64.65%, SD = 9.55%; $t_{(38)} = -0.94$, $p = 0.351$), nor did we see significant differences between groups' later memory for words learned in a feedback (failure writing = 65.90%, SD = 11.93%, control writing = 67.15, SD = 13.08%; $t_{(38)} = -0.32$, $p = 0.754$) or no feedback context (failure writing = 57.90, SD = 8.59%, control writing = 62.50, SD = 9.92%; $t_{(38)} = -1.45$, $p = 0.156$).

Overall, the average confidence ratings were not significantly different across groups (failure writing group mean = 5.41, SD = 0.88; control writing group mean = 4.93, SD = 1.21, $t = 1.44$, $p = 0.157$). However, across both groups, we found that confidence ratings at test significantly correlated with scores during round 2 of the learning phase ($r = 0.43$, $p = 0.006$), as well as greater later memory for words learned in a feedback context ($r = 0.31$, $p = 0.05$), but not the no feedback context ($r = 0.05$, $p = 0.77$).

Moreover, when examining correlations between behavioral results and survey measures, we found that self-reported scores on the Need for Cognition (NFC) scale significantly positively correlated with overall performance scores in round 2 ($r = 0.32$, $p = 0.04$), as well as for later memory of words learned in a no feedback context ($r = 0.34$, $p = 0.035$). We also found that self-reported desire to do well on the task, as well as task enjoyment, significantly correlated with performance during round 2 of the learning phase (care ratings, $r = 0.33$, $p = 0.039$; enjoy ratings, $r = 0.32$, $p = 0.045$). Last, age was significantly positively correlated with overall performance during round 2 of the learning phase ($r = 0.573$, $p < 0.001$), as well as test phase memory ($r = 0.50$, $p = 0.001$), task enjoyment ($r = 0.33$, $p = 0.036$), and scores on the NFC scale ($r = 0.38$, $p = 0.016$).

fMRI Results

Across All Participants

Replicating previous findings (DePasque Swanson and Tricomi, 2014; Lempert and Tricomi, 2016), participants exhibited significantly more activation in the striatum (caudate and nucleus accumbens) for positive vs. negative feedback during feedback blocks in round 2 of the learning phase; see **Figure 2** for whole-brain differences, and **Table 1** for full brain results.

To examine whether individual differences in brain activation correlated with performance measures, we examined whether individual differences in the strength of the positive vs. negative feedback contrast in this striatal region correlated with performance across all participants. We found a significant correlation between differential activation in the right striatum when viewing positive feedback contrasted with negative feedback during the task and later memory for words learned in a feedback setting ($r = 0.35$, $p = 0.027$). Thus, more differentiated activation in the striatum in response to feedback during learning resulted in better later memory for words originally learned in a feedback setting.

Across Writing Groups

While we did not see significant differences in feedback processing across groups, at the time of word presentation failure writing participants exhibited significantly greater activation in the MCC than participants who wrote about a trivial topic (**Table 1** and **Supplementary Table S2**). Specifically, failure writing participants exhibited significantly greater activation in the MCC than participants who wrote about a trivial topic. To determine the direction of this relationship—for example, if failure participants exhibited greater activation vs. less deactivation than control participants, we examined the beta weights of the GLM of this contrast. After examining these parameter values, it became evident that while control participants exhibited decreases in activation in the MCC, the mean activation in the MCC for failure participants increased slightly from baseline; see **Figure 3C** for visualization.

Additionally, we conducted a PPI analysis that examined functional connectivity between the MCC and other brain regions. We found significant functional connectivity between the MCC and both the caudate and the medial prefrontal cortex (mPFC) in failure subjects at the time of word presentation. We further interrogated the role of the caudate and mPFC regions on behavior in our failure subjects but found no significant relationship between connectivity in these regions and performance on round 2 of the learning phase. We also conducted a second PPI analysis that examined MCC functional connectivity in control participants using the same procedures. We did not find that MCC activation significantly correlated with other brain regions in control participants. This finding was expected given that the MCC was more active in failure participants than control participants. These analyses are included in **Supplementary Figure S1**, **Table S1**.

Because the MCC is typically deactivated during task engagement (Harrison et al., 2011), while increases in activation are typically associated with processing of negative emotion (Maddock et al., 2003; Shackman et al., 2011), we also examined how individual differences in MCC activation correlated with aspects of participants' writing. Specifically, we found that within the group of participants assigned to write about a past failure, writing about more severe failures (self-reported by the participant) predicted greater deactivation in the MCC ($r = -0.47$, $p = 0.038$). We did not see this same relationship for control participants ($r = 0.10$, $p = 0.680$); see **Figure 3D** for an illustration of these correlations.

Additionally, we tested whether the ratings of the negativity of the writing samples were correlated with MCC activation for each of the groups. The correlation was not significant for either the control group ($r = 0.32$, $p = 0.191$) or the failure group ($r = -0.074$, $p = 0.756$), suggesting that heterogeneity in valence of the movie content or failure experience was not driving neural activation in the MCC.

DISCUSSION

Writing about a negative experience like a past failure has been shown to lead to a variety of benefits (Harber and Pennebaker, 1992; Pennebaker, 1997; Ramirez and Beilock, 2011; DiMenichi and Richmond, 2015). However, little is known about how writing and thinking deeply about a past failure could affect processing in the brain. Information about how expressive writing affects neural processing could offer valuable insight as to why previous studies have found that expressive writing leads to cognitive and emotional benefits.

TABLE 1 | Brain regions identified by GLM analysis.

Region	BA	Number of voxels (3 × 3 × 3 mm^3)	Peak (Talaraich: x, y, z)	*t*
Feedback Presentation During Round 2 of Learning Phase (all subjects, $p < 0.001$, corrected to $p < 0.05$)				
Positive > Negative				
Right occipital gyrus	19	7,444	11, −102, −6	5.89
*Right putamen		1,732	14, 10, −6	6.02
*Left caudate head		1,720	−7, 10, −3	6.47
*Left occipital lobe	17	988	−16, −92, 12	5.14
Negative > Positive				
Superior frontal gyrus	6	2,058	−10, 1, 57	7.30
Thalamus		895	−13, −17, 6	5.61
Word Presentation During Learning Phase (across subjects, $p < 0.005$, corrected to $p < 0.05$)				
Failure > Control				
*Mid-cingulate cortex	23	531	−4, −11, 30	3.98
Left cerebellum		326	−31, −77, −30	3.64

Indicates that the given peak survives the corresponding non-parametric permutation-based statistical contrast (corrected p < 0.05, full results in* **Supplementary Table S2*).*

When examining brain activation in all participants in our task, we found greater activation in the striatum when participants viewed positive feedback on the task as compared to negative feedback. This finding replicated previous work that suggests the striatum plays an important role in feedback processing (Tricomi and Fiez, 2012; DePasque Swanson and Tricomi, 2014; Lempert and Tricomi, 2016). Moreover, greater differences in activation in the striatum in response to positive vs. negative feedback resulted in better subsequent memory for words originally learned in a feedback setting. Our findings support previous research that has suggested that individuals who exhibit greater striatal sensitivity exhibit better error correction (Klein et al., 2007; Krugel et al., 2009; Ullsperger et al., 2014). When individuals are less affected by feedback (as evidenced by less differential response in the striatum) they may not learn as much from this type of feedback.

Furthermore, when examining differences across our two writing groups, we found that participants who were assigned to write about a difficult time in which they did not succeed exhibited greater activation in the MCC as compared to control subjects, who on average displayed decreases in activation from baseline. Our finding within control subjects may have represented typical deactivation of the MCC that is found when an individual is processing a task and therefore not processing information with an emotional context (Harrison et al., 2011). Asking an individual to reflect on a particularly emotional time in his or her life may have elicited increases in brain processing in the cingulate cortex, which has been implicated in processing negative emotion (Maddock et al., 2003; Shackman et al., 2011). Whereas the amygdala, which did not show differential activation between groups in our study, is heavily involved in processing negative emotions pertaining to vigilance, such as fear (Hamann et al., 2002), the cingulate cortex tends to be more involved in processing negative emotions that relate to the self, such as during one's own experience of negative affect (Shackman et al., 2011). Moreover, the anterior region of the cingulate cortex (ACC) has been implicated in processing error detection, while the MCC is reported to play a vital part in processing information regarding negative emotion (Maddock et al., 2003). This region also tends to be more active while an individual experiences physical pain (Shackman et al., 2011). Therefore, participants who wrote about past failures may have shown greater activation in the MCC because they were recently asked to process highly emotional (and likely negative) information about their past failings. Future research is necessary to confirm that writing about failures truly induces negative emotion (e.g., by asking participants to rate their emotion after writing, rather than their stress level), and examine how these ratings relate to MCC processing. Paradoxically, when examining individual differences in failure writing and activation in the MCC, we found that self-reported event stress ratings actually predicted greater *de*activation of the MCC. Disclosure literature suggests that expressive writing about more intense negatives from one's past may actually result in greater health, physical, and cognitive benefits (Harber and Pennebaker, 1992; Pennebaker, 1997). Furthermore, in longitudinal mindfulness interventions, individuals are trained to draw awareness to one's thoughts and feelings in the present moment, and then slowly let go of negative or nagging feelings to focus on the current moment (Kabat-Zinn, 2009). Neuroimaging studies suggest that mindfulness training can result in reduced activation in the MCC during emotional stimuli (Farb et al., 2010). In the same way that drawing one's awareness to negative emotions may result in greater deactivation of the MCC, writing about a past failure may also utilize similar neural processing in order to result in improved cognitive processes. Moreover, while writing about failures superficially may have resulted in increased emotional processing, reflecting on a particularly intense failure may have resulted in neural processing that more closely resembles not being exposed to emotional stimuli—i.e., the MCC deactivation exhibited by control writing participants. One possibility is that writing about more intense failures may allow an individual to better process negative thoughts before moving on to a new task.

Much of the work on the benefits of expressive writing has focused on how writing about very negative experiences, such as trauma, provides emotional benefits (Pennebaker et al., 1988; Harber and Pennebaker, 1992; Lepore and Smyth, 2002; Smyth et al., 2008). However, there is also evidence that writing about more universally experienced negative events and emotions, such as test anxiety and failure, confers benefits as well (Klein and Boals, 2001; Ramirez and Beilock, 2011; DiMenichi and Richmond, 2015; DiMenichi et al., 2018). Our neural results show that expressive writing about commonplace negative events, such as failure, leads to differences in neural processes during cognitive tasks similar to those encountered in school environments, such as memory tasks. This suggests that expressive writing has downstream effects not only for those who have endured very negative experiences, such as trauma but for almost anyone. This has implications for educational environments, as it shows how experiences that may seem unrelated to the task at hand, such as experiencing and writing about failure, can then influence neural processing during learning. Furthermore, since failure can be experienced within academic environments (e.g., failing a test or a class), strategies for overcoming these failures are particularly important. Indeed, previous work showing that writing about test anxiety helps decrease that anxiety and boosts performance suggests that expressive writing may be an effective tool for educators to use to address negative emotions stemming from classroom experiences.

Nevertheless, our fMRI results suggest that writing about particularly stressful failures may have led to MCC activity more like control participants, which is in line with previous findings that the benefits of expressive writing may be strongest when writing about strongly negative events (Harber and Pennebaker, 1992; Pennebaker, 1997). This may be one possible reason why, contrary to the results of our pilot behavioral study, we did not see significant performance differences across writing groups on our task. It is possible that behavioral differences between groups would be stronger if the writing topic was more strongly negative, such as a trauma. It is interesting to note that previous research has suggested that the beneficial outcomes of expressive writing may be related to positive aspects of writing, such as meaning making and affect labeling (Pennebaker and Chung, 2011; Memarian et al., 2017). In our dataset, externally coded scores based on the writing samples were not associated with behavioral or neural outcomes, whether they were based on the negativity of the writing samples or more positive aspects, such as persistence and finding a “silver lining.” Instead, it was the participants’ own ratings of the stressfulness of the event which correlated with MCC activation, lending support to the idea that the experience that the participant writes about may be at least as important as the content of the writing sample.

Although we did not observe behavioral differences between groups in our sample, differences in neural activation between groups in the absence of behavioral differences can still reveal important differences in cognition underlying behavior (Gilman et al., 2015). Behavioral results were also highly correlated with age in our sample, perhaps suggesting that younger participants had greater difficulty focusing on our learning task. Indeed, a recent study suggested that adults perform slightly better on this task than adolescents (DePasque and Galván, 2019). Furthermore, although we did not find a significant relationship between age and self-reported event stress ratings, perhaps younger participants were less likely to have experienced the *type* of failures that result in learning benefits after writing about them, especially considering that persistence improves as one ages, likely as a result of experience (Duckworth et al., 2007). Future studies might consider implementing our task on a sample with a slightly older mean age.

We conducted a PPI analysis that found that, among participants who wrote about past failures, the MCC may participate in a network of activation in conjunction with the caudate and mPFC. This activation may underlie differences in affective experience of the task. However, individual differences in activation in these regions did not predict any measures of behavior. Future directions may include measuring affect throughout the task in order to better parse the relationship between MCC and subsequent neural activation.

A potential limitation of our experimental design is that the content of the writing in our control condition was free to vary along many dimensions, including valence, based on the movie each participant chose to write about. However, ratings of negativity of the writing samples within the control condition were not significantly correlated with MCC activation, suggesting that heterogeneity in the negativity of the writing content in this condition was not driving activation in this region. Furthermore, the control condition was designed to be rich in episodic content, rather than completely neutral in valence, since writing about something fully neutral could have introduced a potential confound of boredom. Additionally, the study’s goal was not to investigate neural responses to the writing itself, but rather, how neural responses in a well-studied learning task differ based on the previous writing experience. That a 10-min writing exercise resulted in group differences in subsequent neural activation during an unrelated learning task emphasizes the underappreciated role of state-based differences in neural activation to the task at hand, which may be related to recent experiences, such as recalling and writing about a failure.

Broadly speaking, our findings suggest that writing about a past failure, especially a failure that one found to be particularly stressful, may be related to altered neural processing in the MCC. In addition to adding to our understanding of the mechanisms by which expressive writing influences cognition, our results have implications for educators hoping to improve learning, especially after students experience academic failure.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the Rutgers Institutional Review Board with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Rutgers Institutional Review Board.

AUTHOR CONTRIBUTIONS

BD and ET designed the experiment. BD ran subjects through the task and performed statistical analyses. All authors contributed to advising on statistical analyses and writing the manuscript.

FUNDING

This research was supported by NSF Grant BCS 1150708.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2019.00389/full#supplementary-material.

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Conflict of 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.

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