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Intentionality of Self-Generated Thought: Contributions of Mind Wandering to Creativity

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ABSTRACT

Studies suggest that internally oriented cognitive processes are central to creativity. Here, we distinguish between intentional and unintentional forms of mind wandering and explore their behavioral and neural correlates. We used a sample of 155 healthy adults from the mind-brain-body dataset, all of whom completed resting-state fMRI scans and trait-level measures of mind wandering. We analyzed intentional and unintentional mind wandering tendencies using self-report measures. Next, we explored the relationship between mind wandering tendencies and creativity, as measured by a divergent thinking task. Finally, we describe patterns of resting-state network connectivity associated with mind wandering, using graph theory analysis. At the behavioral level, results showed a significant positive association between creativity and both intentional and unintentional mind wandering. Neuroimaging analysis revealed higher weighted degree connectivity associated with both forms of mind wandering, implicating core regions of the default network and the left temporal pole. We observed topological connectivity differences within the default network: intentional mind wandering was associated with degree connectivity in posterior regions, whereas unintentional mind wandering showed greater involvement of prefrontal areas. Overall, the findings highlight patterns of resting-state network connectivity associated with intentional and unintentional mind wandering, and provide novel evidence of a link between mind wandering and creativity.

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Introduction

Human minds tend to wander. In the absence of external stimuli, thoughts often drift away from the present -here and now- environment, to focus on images, plans, and memories pertaining to the past or future. Mind wandering has emerged as a topic of great interest in cognitive neuroscience, and a growing number of investigations have explored its cognitive and neural basis (for review and discussion, see Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016). The term is borrowed from the popular lexicon, encompassing a wide range of phenomena, and therefore, a lack of consensus over its precise definition persists (Christoff et al., 2018; Seli et al., 2018). Despite the definitional haze, mind wandering may be generally understood as cognition unrelated to the present task or environment (Mills, Raffaelli, Irving, Stan, & Christoff, 2018). In addition, a series of studies suggests that mind wandering can occur both with and without intention (Seli, Risko, Smilek, & Schacter, 2016). Based on this evidence, Seli and colleagues (2016) argue that intentional and unintentional forms of mind wandering are dissociable cognitive experiences and should be studied as such. According to this view, intentional and unintentional mind wandering may be understood as a correspondence to volitional and reflexive attention. Intentional mind wandering involves deliberate control of attention toward self-generated thought, whereas unintentional mind wandering occurs without conscious effort or top-down control. Here, we rely on trait-level self-report measures to study the behavioral and connectomic basis of mind wandering, both with and without intention.

Efforts have been made to rigorously study the neuroscience of mind wandering. The canonical Default Mode Network (DMN), first described as the "default

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mode" of brain function (Raichle et al., 2001), has been extensively linked to self-generated thought and mind wandering (Mason et al., 2007). The DMN has been defined as a set of core regions, including the medial prefrontal cortex and posterior cingulate cortex, that are engaged when individuals remember past experiences, imagine future experiences, or engage in related forms of mental simulation (Buckner, Andrews-Hanna, & Schacter, 2008; Schacter, Addis, & Buckner, 2007). Despite showing reduced activity during attention-demanding tasks, DMN regions exhibit increased activation across a multitude of complex cognitive processes (Smallwood et al., 2021). Recent neuroimaging studies have illustrated the role of the DMN in mind wandering (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Christoff et al., 2016; Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015), self-generated thought (Andrews-Hanna, Smallwood, & Spreng, 2014; Benedek et al., 2016) and creativity (Beaty et al., 2014). Current theories of creativity suggest the DMN works in conjunction with executive control and attention networks, supporting constructive episodic processes (Schacter & Addis, 2007) that enable the generation of novel ideas (Beaty, Thakral, Madore, Benedek, & Schacter, 2018; Benedek et al., 2016; Madore, Thakral, Beaty, Addis, & Schacter, 2019). Additionally, neuroimaging studies exploring the cortical organization associated with intentional and unintentional mind wandering suggest that mind wandering depends on integration between the control and default mode networks (Golchert et al., 2017). The interaction between DMN and executive attention networks may reflect a mode of goal-directed self-generated cognition similar to intentional mind wandering. Given the proposed dissociation between intentional and unintentional mind wandering, analysis of resting-state fMRI data in relation to trait-level mind wandering may provide new insights into the distinct neural mechanisms that underlie the experiential qualities of self-generated thought.

For decades, there has been anecdotal evidence linking mind wandering and creativity (Roberts, 1989), but not until recently has cognitive neuroscientific inquiry begun to explore these overlapping phenomena (Fox & Beaty, 2019). Creativity is proposed to follow a dual-process model (Finke, Ward, & Smith, 1992), whereby novel ideas are generated and selectively refined over time. The generation and subsequent evaluation or elaboration of ideas over time requires sustained internal attention, drawing on episodic retrieval and reconstructive processes. Therefore, creative cognition is thought to involve self-generated thought processes, shielding internal mentation from external interference (Benedek, 2018). Studies of creative incubation intervals have examined how an individual's temporary shift away from unsolved problems may facilitate creative insights. In a seminal study by Baird and colleagues (2012), experimenters found that mind wandering during a non-demanding incubation period led to improved performance on a subsequent divergent thinking task. In a conceptual replication of these findings, Smeekens & Kane (2016) failed to observe the expected association between mind wandering and divergent thinking. While some studies have noted improved creative performance following an incubation interval (Leszczyzynski et al., 2017; Tan, Zou, Chen, & Luo, 2015), others failed to observe a reliable association between mind wandering and post-incubation creativity (Murray, Liang, Brosowsky, & Seli, 2021; Steindorf, Hammerton, & Rummel, 2021). Further studies have indicated that while the frequency of mind wandering during an incubation period was associated with improvement on some aspects of divergent thinking, it was also linked to a decline in mood and poor mental health (Yamaoka & Yukawa, 2020). Given these mixed results, there remains some doubt about the nature of the association between mind wandering and creativity. Additionally, recent behavioral studies have implemented trait-level mind wandering scales to explore whether intentional and unintentional forms of mind wandering may be differentially related with divergent thinking. Agnoli, Vanucci, Pelagatti, and Corazza (2018) found that intentional mind wandering was positively associated with creative performance, whereas unintentional mind wandering was negatively associated with the same measure. These findings provide suggestive evidence that these dissociable forms of self-generated cognition may be differentially related to creative thinking, though more work is needed to characterize the nature of this relationship.

Openness to experience is characterized as being curious, imaginative, and having a broad range of interests. Decades of behavioral research have examined the relationship between openness to experience and divergent creative thinking (McCrae, 1987; Tan, Lau, Kung, & Kailsan, 2019). Research on brain network dynamics suggests that openness to experience is associated with higher DMN global efficiency and increased connectivity between default and cognitive control networks, which may account for the enhanced creative ability in people high in openness to experience (Beaty et al., 2018, 2016). It may be the case that individuals who are more open to new experiences are also more likely to be exposed to a greater variety of stimuli, which serves as a basis for creativity. Further investigation of the link between openness to experience and divergent thinking will help to more precisely describe the role of personality in creative thinking.

In this study, we extend behavioral research on the dissociation between intentional and unintentional mind wandering in relation to creativity and openness to experience. Furthermore, we describe resting-state connectivity profiles associated with these trait-level measures of mind wandering. To address these issues, we analyze behavioral measures of mind wandering, personality and creativity assessments, along with resting-state fMRI data. Given that resting-state fMRI captures neural activity in the absence of explicit tasks, we believe it is a suitable technique to measure individual differences in mind wandering. Thus, we applied Weighted Degree (WD) analysis -a graph theory centrality metric of functional connectivity- to describe individual differences in resting-state brain activity related to mind wandering. Outside the scanner, a sample of healthy adults (n = 155) completed questionnaires that probe trait-level intentional and unintentional mind wandering (Carriere, Seli, & Smilek, 2013). Additionally, a subset of participants completed the Alternative Uses Task (AUT; Silvia et al., 2008) and NEO personality inventory (Costa & McCrae, 1992; Costa Jr & McCrae, 2008) to further explore the relationships between mind wandering, creativity and personality. We predict that mind wandering will be positively associated with creativity. Bearing in mind the role of the DMN in internally directed cognitive processes, we hypothesize that, in general, mind wandering will be associated with increased connectivity of voxels in the medial prefrontal and posterior cingulate cortices, key nodes in the DMN. We further hypothesize that intentional and unintentional mind wandering will be associated with distinct patterns of degree connectivity across DMN core regions. This study is for the most part exploratory in nature, seeking to further describe the contributions of intentional and unintentional forms of mind wandering to creative ideation.

Methods

Participants

We analyzed data from 155 healthy, native German-speaking adults (71 females; age range: 20–35), collected as part of a larger cross-sectional data-collection study carried out at the Max Planck Institute (MPI) of Human Cognitive and Brain Sciences in Leipzig, Germany (Babayan et al., 2019; Mendes et al., 2019). Given that analysis of aging effects is beyond the scope of this project, we restricted analysis to adults aged 20–35 years. All statistical analyses included participant sex as a covariate. All participants included in the study were screened for past and present psychiatric and neurological conditions and fulfilled the MRI safety requirements for the MPI and provided written informed consent prior to testing. Participants received monetary compensation for their involvement. Since the sample consisted of native German-speaking participants, questionnaires were translated into German by a professional translator. The study was approved by the Faculty of Medicine IRB of the University of Leipzig. This is a secondary analysis; the authors of this paper did not have any involvement with the data collection process. These data were obtained from the Open fMRI database (accession number: ds000221).

Mind wandering scales

To assess trait-level tendencies of mind wandering, we analyzed data from scales targeted at deliberate and spontaneous mind wandering (Carriere et al., 2013). Deliberate mind wandering includes items that are related to intentional forms of mind wandering, for example: “I allow my thoughts to wander on purpose” or “I enjoy mind wandering.” Spontaneous mind wandering includes items that are related to unintentional forms of mind wandering, such as: “When I mind wander my thoughts tend to be pulled from topic to topic” or “It feels like I don’t have control when my mind wanders.” Each scale consisted of four items, to which participants rate their agreement on a 5-point Likert scale ranging from 1 (almost never) to 5 (very often). Scores for each participant are computed independently as the mean response for intentional and unintentional mind wandering. Both scales provide good internal consistency and are moderately correlated (Mendes et al., 2019).

Creativity assessment

A subset of our total sample (n = 68, 28 females) also completed the Alternative Uses Task (AUT), a reliable measure of divergent thinking commonly used to assess creativity (Silvia et al., 2008). In this task, participants were asked to generate creative uses for three items: an umbrella, a car tire, and a water hose. For each item, participants were given two minutes to write down their ideas. AUT performance was measured across four dimensions: fluency, creativity, elaboration, and uniqueness. Fluency refers to the total number of ideas generated for each item. To assess creative quality and elaboration, three trained judges rated the answers on a scale from 0 to 4. The interrater reliability was moderate to high (intra-class correlation of 0.74–0.82) for the rated scores (Mendes et al., 2019). Uniqueness refers to the statistical rareness of ideas, generated by assessing the relative frequency of each response. We take the mean scores for fluency, creativity, elaboration, and uniqueness across all three AUT items as measures for each participant.

NEO personality inventory – revised

A subset of our total sample (n = 135, 59 females) also completed the NEO Personality Inventory – Revised (Costa & McCrae, 1992; Costa Jr & McCrae, 2008; Ostendorf & Angleitner, 2004). The NEO assesses the big five personality traits: neuroticism, extroversion, agreeableness, conscientiousness, and openness to experience. The questionnaire consists of 241 items, for each item participants rate their agreement on a Likert scale ranging from 1 (completely disagree) to 5 (completely agree). Scores are based on a sum for each of the five personality traits.

Image acquisition

Functional Magnetic Resonance Imaging (fMRI) data were recorded for all participants on a 3 T Siemens Magnetom Verio Scanner. During the resting-state scans, participants were instructed to remain awake and lie still with their eyes open while looking at a fixation cross. Image acquisition parameters have been previously published and explained in detail (Marques et al., 2010). High-resolution structural images were acquired using an MP2RAGE sequence (TR = 5000 ms, TE = 2.92 ms, TI1 = 700 ms, TI2 = 2500 ms, flip angle 1 = 4°, flip angle 2 = 5°, voxel size = 1.0 mm isotropic, duration = 8.22 min). Additionally, resting-state (rs fMRI) scans was acquired for each participant. The rs fMRI data were recorded using a blood-oxygen-level dependent (BOLD) multiband echo-planar imaging (EPI) sequence with the following parameters: TR = 1400 ms, TE = 39.4 ms, flip angle = 69°, multiband acceleration factor = 4, voxel size = 2.3 mm isotropic, 64 slices, 657 volumes, duration = 15.30 min.

Preprocessing

Structural

MRI data were preprocessed using FMRIB Software Library v5.0.7 (FSL) and MATLAB 2017a. The anatomical T1 preprocessing pipeline included: reorientation to right-posterior-inferior (RPI); alignment to anterior and posterior commissures; skull stripping; gray matter, white matter and cerebrospinal fluid segmentation; and computation of non-linear transformation between individual skull-stripped T1 and 2 mm resolution MNI152 template images.

Functional

Following procedures consistent with previous work (Orwig, Diez, Vannini, Beaty, & Sepulcre, 2021), the functional MRI preprocessing pipeline included: slice time correction; reorientation to RPI; realigning functional volumes within runs with a rigid body transformations (6 parameters linear transformation); intensity normalization; transformation to 3 mm MNI standard space, concatenating the transformation from functional to structural and from structural to MNI; spatial smoothing with an isotropic Gaussian kernel of 8-mm FWHM; removal of confounding factors from the data using linear regression – including 6 motion-related covariates, linear and quadratic terms, and five components each from the lateral ventricles and white matter. Additionally, band-pass filtering (0.01–0.08 Hz) was applied to reduce low-frequency drift and high-frequency noise. Global signal regression was not applied due to the spurious correlations this can introduce (Murphy, Birn, Handwerker, Jones, & Bandettini, 2009). Head motion was quantified using realignment parameters obtained during image preprocessing, which included 3 translation and 3 rotation estimates. Scrubbing of time points with excess head motion eliminated all time points with a frame displacement > 0.5 mm. Subjects with more than 25 time points exceeding the scrubbing head motion correction threshold were removed. Note: of the original 157 subjects, two subjects were excluded from the analysis due to excessive head motion.

Statistical analysis

Behavioral

We conducted linear regression models to examine the relationships between measures of mind wandering, creativity, and personality. We computed a multivariate linear regression model with both intentional and unintentional mind wandering as predictors of creativity. Additionally, we performed regression models using fluency and uniqueness as our response variable. In relation to personality measures, we explored intentional and unintentional mind wandering as predictors of openness to experience and conscientiousness. Lastly, we computed a univariate regression analysis to determine the relationship between openness to experience and creativity. We included participant sex as a covariate in all analyses. We report the Pearson correlations (r) for these analyses along with regression parameters (F, t and p statistics), with a significance threshold of $\alpha = .05$. All statistical analysis with behavioral data was conducted in R.

Weighted Degree (WD)

A WD metric was used to analyze the functional connectivity profiles of hub centrality associated with mind wandering. The weighted degree of a given node represents the sum of the strengths of connections it shares with the rest of the brain (Bullmore & Sporns, 2009). To determine the relative importance of each node in the overall functional brain network, voxel-level WD values were computed using in-house MATLAB code. First, Pearson correlation coefficients were used to compute the functional connectivity matrices of each subject using the time series of all pairs of gray matter and subcortical voxels. A Fisher transformation was applied to the resulting correlation matrix and negative values were removed due to their controversial interpretation (Qian et al., 2018). To reduce noise, we considered only the most significant links using a false discovery rate (FDR) multiple comparison correction at q-level = 0.0001 (Benjamini & Hochberg, 1995). After obtaining a high-resolution 41,954 x 41,954 connectivity matrix for each subject, we summed all the connections of each voxel to generate a WD map showing the extent to which each voxel is functionally connected to the rest of the brain. General linear models were used to compute the associations between WD and intentional and unintentional mind wandering. We also computed the association between WD and AUT creativity. Cortical surfaces were visualized using the population-average landmark and surface-based projections of CARET software (Van Essen, 2005). Surface images were displayed using a color scale based on T-scores, black lines denote FDR corrected areas (Allen, Erhardt, & Calhoun, 2012). Additionally, conjunction analysis was performed to identify clusters of voxels associated with both intentional and unintentional mind wandering.

Results

Behavioral correlates of mind wandering

At the behavioral level, we examine the relationships between mind wandering, creativity and personality measures (Figure 1). Consistent with previous studies, we detect a moderate correlation (r = .41) between intentional and unintentional mind wandering. Multiple linear regression was used to test whether intentional and unintentional mind wandering together were significantly predictive of creativity. The overall regression was statistically significant ($F(3, 65) = 5.52$, $p < .005$). It was found that intentional mind wandering significantly predicted creativity ($t = 2.09$, $p = .04$), whereas unintentional mind wandering was just above the significance threshold ($t = 2.00$, $p = .0503$) (Figure 2).

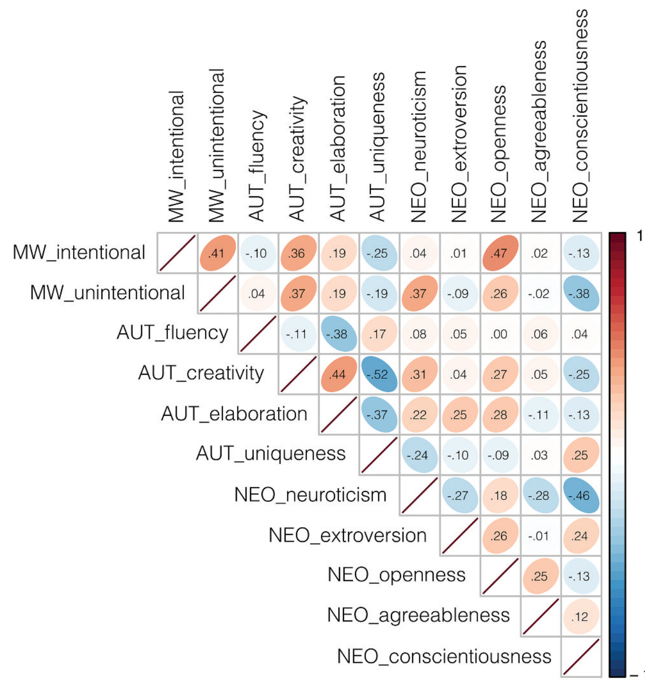

Figure 1. Correlation matrix.

We did not observe any significant associations when using fluency ($F(3, 65) = .83$, $p = .48$) or uniqueness ($F(3, 65) = 2.00$, $p = .12$) as the response variable. In relation to personality traits, we found that openness to experience was positively correlated with intentional mind wandering ($t = 6.26$, $r = .47$, $F(2, 131) = 24.17$, $p < .005$) and unintentional mind wandering ($t = 3.10$, $r = .26$, $F(2, 131) = 8.61$, $p < .005$). The association between openness to experience and creativity was not significant ($t = 1.86$, $r = .27$, $F(2, 62) = 5.61$, $p = .07$). Conscientiousness was negatively associated with unintentional mind wandering ($t = -4.77$, $r = -.38$, $F(2, 131) = 12.70$, $p < .005$); however, we did not observe a significant association between conscientiousness and intentional mind wandering ($t = -1.49$, $r = -.13$, $F(2, 131) = 2.27$, $p = .14$).

Connectivity profiles of mind wandering

Our WD analysis sought to highlight individual differences in resting-state network connectivity associated with intentional and unintentional mind wandering. We performed whole-brain WD analysis to identify the relationship between the WD of each voxel with intentional mind wandering (Figure 3a). Results showed that intentional mind wandering was positively associated with WD across the posterior cingulate cortex, a prominent node within the DMN. Intentional mind wandering scores were also positively correlated with WD of voxels in the left temporal pole. We additionally

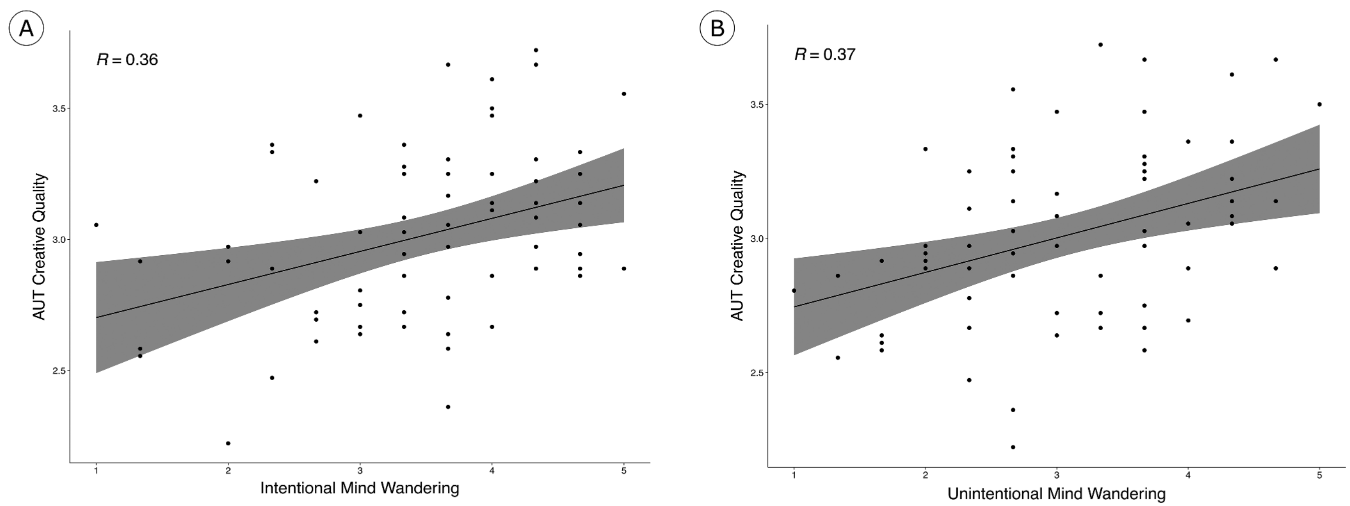

Figure 2. Behavioral results.

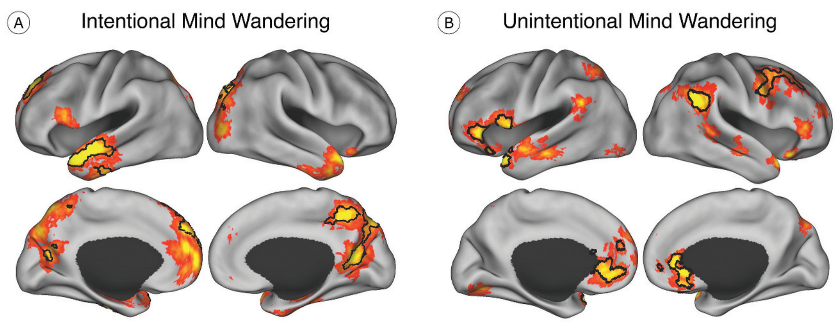

Figure 3. Neuroimaging results.

performed WD analysis to identify connectivity patterns associated with unintentional mind wandering (Figure 3b). Results indicated that unintentional mind wandering scores were positively associated with WD in the anterior medial prefrontal cortex, another core region within the DMN. Unintentional mind wandering was also positively associated with WD in voxels in the right temporoparietal junction and left temporal pole.[1] There were no negative associations between WD and either mind wandering scale. AUT creativity scores were positively correlated with WD of voxels in the hippocampus and prefrontal cortex (*Supplementary Materials*).[2]

A cluster of voxels in the anterior portion of the left temporal pole are common to the connectivity maps for both intentional and unintentional mind wandering. Conjunction analysis revealed no significant results after correcting for multiple comparisons; however, to visualize the trend of functional connectivity associated with both intentional and unintentional mind wandering, we generated cortical projections using uncorrected WD maps. Results indicate small clusters of voxels within the anterior temporal lobe, medial prefrontal, and posterior cingulate cortex (Figure 4). WD maps are defined by color: intentional mind wandering (blue), unintentional mind wandering (red), and conjunction (purple).

Discussion

In this study, we extend research on the distinction between intentional and unintentional forms of mind wandering and their relation to creativity. Results indicate a positive association between both mind wandering measures and the creative quality of ideas generated on a divergent thinking task. We observed that people who reported greater openness to experience also tended to score higher on the creativity task, although this association is not significant. Neuroimaging analysis revealed distinct topological profiles within the DMN associated with mind wandering behavior – intentional mind wandering was associated with higher weighted degree connectivity to the posterior cingulate/retrosplenial cortex,

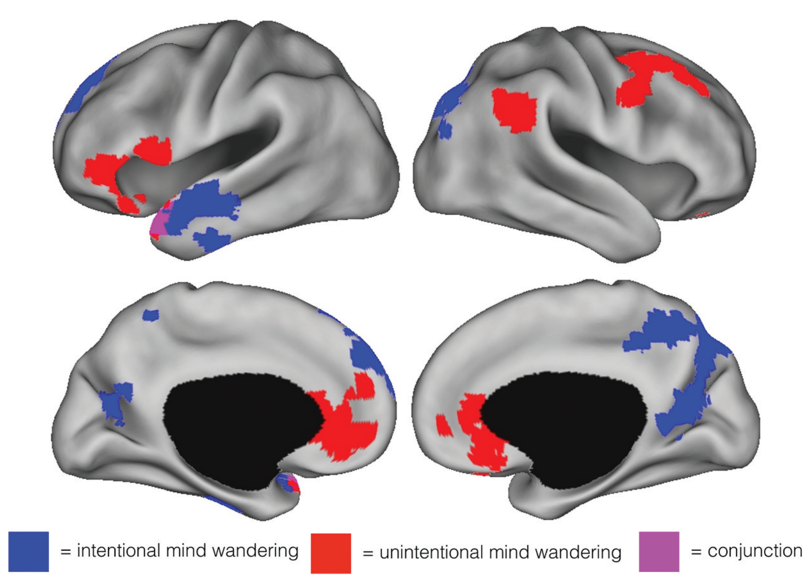

Figure 4. Conjunction analysis

whereas unintentional mind wandering implicated more anterior medial prefrontal regions. Surprisingly, a cluster of voxels within the anterior left temporal pole was associated with both intentional and unintentional mind wandering.

The posterior cingulate and anterior medial prefrontal cortex comprise a set of "hubs" within the DMN, sharing the high levels of betweenness-centrality (Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010). The retrosplenial cortex sits within the posterior cingulate cortex and is thought to be involved in episodic memory, navigation and scene construction (Vann, Aggleton, & Maguire, 2009). Studies of structural brain data have suggested that intentionality of mind wandering may be associated with cortical thickness in the retrosplenial cortex (Golchert et al., 2017; Seli et al., 2018). Our results highlight the positive association between voxels in the retrosplenial cortex and intentional mind wandering, and also revealed a positive association between unintentional mind wandering and WD of medial prefrontal cortex, which has long been associated with self-referential processing (Gusnard, Akbudak, Shulman, & Raichle, 2001). Further research will be needed to assess the reliability of the observed dissociation between intentional and unintentional mind wandering and its theoretical significance.

Application of graph theory techniques in neuroimaging have characterized the left temporal pole as a prominent region within the dorsomedial prefrontal subsystem of the DMN (Andrews-Hanna et al., 2010, 2014). In a recent study, people deemed to be "creative experts" were found to show greater functional connectivity within this DMN subsystem at rest, suggesting they may be more readily able to engage in distal episodic simulation (Meyer, Hershfield, Waytz, Mildner, & Tamir, 2019). Our conjunction analysis highlights a cluster of voxels within the anterior left temporal lobe which is common to both intentional and unintentional mind wandering profiles. While the specific neural substrates which support mind wandering are still difficult to pin down precisely, this study provides novel evidence that DMN regions are differentially activated during intentional and unintentional mind wandering.

Psychological research suggests that highly creative people are generally more open to new experience and less conscientious than less creative people (Feist, 1998; McCrae, 1987). Neuroimaging studies have provided further evidence, suggesting a role for the DMN that may account for the enhanced creative capacity in people who are more open to experience (Beaty et al., 2018, 2016). In the present study, we observe a similar trend, whereby more creative individuals tend to report higher levels of openness and lower levels of conscientiousness. Additionally, we observe that individuals who report more trait level mind wandering, intentional or unintentional, also report higher openness to experience and generate more creative solutions on a divergent thinking task. Our findings thus suggest that trait-level mind wandering and openness to experience may be important features in the disposition of creative individuals.

There are several limitations of this research. The analyses presented are strictly correlational and rely on self-report measures, therefore we exercise caution in interpreting these results. More nuanced assessments of intentional and unintentional mind wandering may lead to future discoveries in this domain. Within this limited scope, we believe these findings represent a promising step toward understanding the neurocognitive mechanisms that underlie productive mind wandering and demonstrate its relevance for the study of creativity.

Notes

1. Multivariate analyses including both intentional and unintentional mind wandering measures were also conducted; however, we find no regions associated with intentional or unintentional mind wandering when controlling for the other mind wandering measure. This outcome is likely due to the two mind wandering measures being highly correlated with each other.
2. Given the relatively small number of participants who completed the AUT (n = 68) these results should be interpreted with caution and are not the focus of this paper.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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