Differential Prediction of Creative Thinking by Different Types of Mind Wandering and Their Neural Mechanisms

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Abstract

The relationship between mind-wandering (MW) and creative thinking is complex. However, previous studies have only explored mind-wandering as a unitary construct, neglecting its heterogeneity, which has led to divergent research conclusions. This study employed functional near-infrared spectroscopy (fNIRS) through two experiments to investigate the predictive role and neural mechanisms of different types of mind-wandering on creative thinking at both trait and state levels.

The results revealed that in the resting state, positive-constructive daydreaming (PCD) mediated the positive prediction of creative idea generation by functional connectivity between the bilateral superior temporal gyrus, the negative prediction of creative idea generation by functional connectivity between the frontopolar cortex and the left middle temporal gyrus, and the positive prediction of creative idea evaluation by functional connectivity between the left dorsolateral prefrontal cortex and the right inferior frontal gyrus (Experiment 1).

In the task state, compared to deliberate MW, task-related MW had a greater predictive weight for creative thinking and could negatively predict static functional connectivity between the left inferior frontal gyrus and the left supramarginal gyrus, as well as between the bilateral inferior frontal gyrus, while positively predicting dynamic functional connectivity between the right dorsolateral prefrontal cortex and the right inferior frontal gyrus during creative tasks (Experiment 2). These results indicate that specific types of mind-wandering can positively predict creative thinking, providing new insights for correctly understanding the adaptive role of mind-wandering and elucidating the potential pathways underlying the formation of creative thinking.

Full Text

Preamble

Differential Prediction of Creative Thinking by Different Types of Mind-Wandering and Their Neural Mechanisms

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Abstract: The relationship between mind-wandering (MW) and creative thinking is complex. Previous studies have often treated MW as a unitary construct, overlooking its heterogeneity and leading to divergent findings. This study employed functional near-infrared spectroscopy (fNIRS) across two experiments to investigate the predictive role of different types of MW on creative thinking and their underlying neural mechanisms at both trait and state levels. In Experiment 1 (resting state), we found that positive-constructive daydreaming (PCD) mediated the positive prediction of creative idea generation by functional connectivity (FC) between the bilateral superior temporal gyrus, the negative prediction of idea generation by FC between the frontopolar cortex and the left middle temporal gyrus, and the positive prediction of creative idea evaluation by FC between the left dorsolateral prefrontal cortex and the right inferior frontal gyrus. In Experiment 2 (task state), task-related MW (MW-r) showed a greater predictive weight for creative thinking compared to deliberate MW (MW-d). Specifically, MW-r negatively predicted static FC between the left inferior frontal gyrus and the left supramarginal gyrus, as well as between the bilateral inferior frontal gyrus, while positively predicting dynamic FC between the right dorsolateral prefrontal cortex and the right inferior frontal gyrus during creative tasks. These results suggest that specific types of MW positively predict creative thinking, providing new insights into the adaptive role of MW and the potential pathways underlying the formation of creative thought.

Keywords: creative thinking, mind-wandering, positive-constructive daydreaming, task-related mind-wandering, functional near-infrared spectroscopy (fNIRS)

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Mind-wandering (MW), also known as daydreaming, refers to thoughts unrelated to the task at hand and is characterized as a form of spontaneous thought that proceeds in a relatively free and unconstrained manner [?, ?]. Research indicates that MW occurs across various life events, occupying approximately 30% to 50% of people’ s daily waking hours [?]. For a long time, MW was considered a product of cognitive control failure, negatively impacting task performance, mental health, and life satisfaction [?, ?, ?]. However, other studies have identified adaptive roles for MW; for instance, MW during an incubation period can enhance subsequent creative thinking performance [?, ?], a phenomenon known as the "incubation effect." Creative thinking is a high-level cognitive activity in which individuals generate novel and appropriate ideas [?], and it is a key competency for innovative talents to produce creative outcomes and contributions. Investigating the predictive role and neural mechanisms of spontaneous thoughts like MW on creative thinking is essential for understanding the nature and developmental laws of creativity. It is also a vital pathway for cultivating innovative talent, empowering new quality productive forces, and achieving high-quality national development.

Dual-process theory posits that creative thinking involves a bottom-up generation stage and a top-down evaluation stage [?, ?]. MW is closely related to both stages of this dual process [?]. During the generation stage, individuals organically combine existing memory experiences to form new ideas [?]. This combination of experiences is somewhat stochastic and can be viewed as "blind variation" [?], involving more bottom-up processing. MW is a dynamic and variable state of mind, often containing past memories or future projections [?, ?], thereby providing the "raw materials" for creative thinking. In contrast, the evaluation stage requires individuals to assess and refine the generated ideas, a process of "selective retention" [?] that involves more top-down processing. Individuals can become aware of their MW and self-report it, using its content to refine future plans [?]; this process is similar to the cognitive monitoring involved in assessing utility during idea evaluation. While the spontaneity of MW reflects its bottom-up nature, the meta-awareness and intentional deployment of MW involve more top-down processing. That is, when MW involves top-down processing, it can effectively utilize freely moving mental "raw materials" to facilitate creative performance following an incubation period. Thus, MW and creative thinking are intrinsically linked through these cognitive processes.

However, existing research remains divided regarding the impact of MW on creative thinking. On one hand, MW may facilitate creativity. [?] introduced an incubation period between a pre-test and post-test of the Alternative Uses Task (AUT), using n-back tasks of varying difficulty (2-back for high demand, 0-back for low demand). They found that the 0-back group had a significantly higher proportion of MW and produced more creative responses in the post-test, with MW frequency positively correlating with creative performance. Subsequent studies further confirmed that MW during incubation directly predicts improvements in later creativity tasks [?, ?]. On the other hand, some studies have found no significant correlation between incubation-period MW and creative thinking [?, ?]. [?] conducted two experiments to replicate the findings of [?]. Experiment 1 included only an incubation period and a post-test AUT, while Experiment 2 more closely mirrored the original study with both pre- and post-tests. Although MW frequency was higher in the 0-back task, the n-back condition had no significant main effect on post-test AUT performance after controlling for pre-test scores, and MW frequency failed to predict post-test performance. Similarly, [?] found that MW frequency was unrelated to post-test AUT scores. A possible reason for these discrepancies is that previous research focused solely on the frequency of MW, ignoring its heterogeneity as a mental construct with diverse contents and origins [?]. Different types of MW may produce different effects; focusing only on frequency may confound these effects, making it difficult to obtain replicable results. Only by exploring "what kind" of MW promotes creative thinking can we clarify the boundary conditions of the incubation effect.

Some researchers have begun to emphasize the relationship between specific types of MW and creative thinking. [?] categorized trait MW by content into positive-constructive daydreaming (PCD) and guilty-dysphoric daydreaming (GDD). PCD involves "planning, pleasant thoughts, vivid and hopeful imagery, and curiosity," while GDD involves "obsessive, guilty, and painful fantasies." [?] found that PCD traits correlate positively with creativity, whereas GDD does not. The "positive-constructive" nature of MW may be directly reflected in its content. [?] found that MW that is personally meaningful positively predicts creativity. In task contexts, "meaningfulness" may manifest as task-relatedness. [?] found a significant positive correlation between MW frequency and creative performance only when the stimuli in the incubation task were related to the unresolved creative task. [?] also found that MW during incubation significantly improved creative writing performance only when the writing prompts were consistent before and after the incubation. These findings suggest that task-related MW (MW-r), rather than task-unrelated MW (MW-u), facilitates creative performance. Furthermore, task-related MW is often accompanied by conscious awareness and reporting [?]. From the perspective of intentionality, [?] found that deliberate MW (MW-d) was significantly correlated with creative thinking, while spontaneous MW (MW-s) was not, highlighting the role of attentional control in this relationship.

In summary, the types of MW positively associated with creative thinking tend to be characterized by "planning," "task-relatedness," or "intentionality," all of which involve attentional control (top-down processing) regardless of whether they are defined by content or origin. Integrating dual-process theory with recent research, this study proposes the following core hypothesis: only MW involving top-down cognitive processing can effectively promote creative thinking.

At the cognitive neural level, previous research has suggested that MW and creative thinking may share common neural mechanisms, both being closely associated with the default mode network (DMN) and the frontoparietal control network (FPCN) [?]. Studies [?, ?] have found that the impact of resting-state DMN functional connectivity on creative performance is partially mediated by associative ability, which is considered a core component of the idea generation stage [?]. This suggests that the generation process—including memory retrieval, combination, and association—is grounded in the activity of DMN-related brain regions. The FPCN' s role in creative cognition primarily involves identifying and discarding irrational ideas to ensure new ideas fit the reality of the problem context [?]. Functional connectivity between the DMN and FPCN is a hallmark neural signature of creative thinking. [?] found that dynamic changes in DMN-FPCN connectivity during resting-state scans effectively reflect participants' creative thinking levels. [?] observed that at the start of a creative task, connectivity is primarily between the DMN and the salience network (SN), but as the task progresses, it shifts toward the DMN and FPCN. This aligns with the generation-evaluation process hypothesized by dual-process theory, further validating the dynamic interaction between brain networks during creative thinking. Similarly, the DMN and FPCN play crucial roles in MW: the DMN facilitates MW through memory retrieval, while the FPCN is responsible for controlling and regulating MW content [?]. Furthermore, [?] found that deliberate MW is closely related to FPCN-DMN connectivity, whereas spontaneous MW is linked to connectivity between the DMN and the limbic system. [?] found that PCD and creative thinking share common connectivity patterns within the DMN and FPCN. Therefore, while MW and creative thinking share a neural basis, the relationship varies depending on the type of MW.

MW can be distinguished into trait and state MW, which differ in time scale, manifestation, and neural mechanisms. These differences are also reflected in their underlying neural networks. Trait MW is typically characterized by resting-state functional connectivity, emphasizing a stable tendency for thoughts to deviate from the external environment. State MW is captured in real-time using task paradigms and the experience sampling method (ESM), reflecting transient attentional disengagement during cognitive activities [?]. At the trait level, studies generally find that an individual' s static DMN functional connectivity correlates positively with their MW tendency [?, ?]. Key nodes in these networks include the medial prefrontal cortex (mPFC), posterior cingulate cortex (PCC), angular gyrus (AG), and parahippocampal gyrus (PHG) [?]. Increased coupling between the FPCN and DMN also predicts an individual' s tendency for deliberate MW, suggesting that cross-network coupling may constitute the neural basis for trait MW [?].

Research on state MW focuses more on revealing transient neural responses during cognitive processes. Studies have found that when MW occurs, core DMN regions such as the PCC, mPFC, and temporoparietal junction (TPJ) are activated, reflecting the detachment of thought from the current task goal. Meanwhile, the anterior cingulate cortex (ACC) and insula (INS) are responsible for identifying the MW state [?]. The task-positive network (TPN) and executive control network (ECN) typically show functional inhibition [?, ?]. The ECN focuses on the continuous monitoring and regulation of goal-directed behavior, involving core regions like the middle frontal gyrus (MFG), and is crucial for maintaining task execution and controlling the occurrence of MW [?, ?]. However, [?] found that state MW is also accompanied by activation of the dorsal ACC (dACC) and dorsolateral prefrontal cortex (DLPFC), indicating that MW is not a state of pure cognitive disengagement but involves a degree of executive control. This dynamic balance between networks constitutes the complex neural regulatory mechanism of the MW state [?].

However, the fMRI techniques used in previous studies impose strict restrictions on physical movement, which may affect cognitive task performance [?]. Given that MW is highly susceptible to interference from noise, postural constraints, and physical confinement, and that the authentic expression of creative thinking (especially divergent thinking) requires natural, low-constraint conditions, this study utilizes functional near-infrared spectroscopy (fNIRS) to enhance ecological validity [?, ?]. fNIRS offers advantages such as low noise, compatibility with a seated position, and minimal restriction on head movement. This significantly reduces the inhibitory effects of traditional fMRI environments on MW, particularly during low-load incubation phases (e.g., the SART task), helping to induce spontaneous MW more naturally. Furthermore, this technology allows participants to write or speak freely during creative tasks like the AUT, providing a more ecologically valid environment for capturing the dynamic interaction between MW and creative thinking. Additionally, the higher temporal resolution of fNIRS helps capture rapid dynamic changes in neural activity. By using fNIRS, this study aims to replicate and extend previous fMRI findings while facilitating the generalization of results to real-world settings. Building on prior research, we will use fNIRS to systematically explore "which" types of MW predict creative thinking and "how" they do so, revealing the specific underlying neural mechanisms.

While research on specific types of MW promoting creative thinking is increasing, discussions on the intentionality of MW are mostly limited to the trait level. Furthermore, few studies have explicitly quantified task-related MW or investigated its unique value for creativity. Therefore, Experiment 1 of this study examines the predictive effects of MW tendencies with different valences and contents (PCD vs. GDD) on creative thinking at the trait level, hypothesizing that only PCD—which involves top-down processing—will positively predict creative thinking. We then explore the state-level manifestations of "positive-constructive" MW. Experiment 2 focuses on the key dimensions of task-relatedness (MW-r vs. MW-u) and intentionality (MW-d vs. MW-s), both of which reflect top-down cognitive control in terms of content and origin, respectively. Although task-related MW is often accompanied by intentionality [?], these two dimensions are conceptually and empirically separable, making it necessary to clarify which type more robustly predicts creative thinking. Experiment 1 focuses on resting-state functional connectivity, using exploratory analysis to reveal the deep connections between spontaneous brain activity, PCD/GDD tendencies, and creative thinking ability. Experiment 2 shifts to specific task contexts, capturing brain activity throughout the task to analyze how task-state functional connectivity reflects the occurrence of MW and its commonalities with creative performance. By integrating the "trait-state" longitudinal dimension, the "behavioral-neural" observational dimension, and the "static-dynamic" mechanistic dimension, this study provides a structured investigation.

This study anticipates that brain functional network connectivity patterns reflected by fNIRS will effectively predict creative thinking. At both the trait and state levels, we expect that only MW involving top-down cognitive processing will predict creative thinking, and that the neural mechanisms underlying these predictions will differ across different types of MW.

2 Experiment 1: Positive-Constructive Daydreaming (PCD) and Guilty-Dysphoric Daydreaming (GDD)

2.1 The Relationship Between GDD and Creative Thinking and Its Neural Mechanisms

Abstract Guilty-Dysphoric Daydreaming (GDD) refers to a specific type of spontaneous thought process where an individual' s internal mental stream is oriented toward negative emotions, guilt, or failure. While traditional views often associated daydreaming with distractibility or cognitive failure, recent research in cognitive neuroscience suggests that the content of daydreaming significantly impacts creative thinking. This paper explores the conceptual framework of GDD, its distinct characteristics compared to stimulus-independent thought, and its relationship with creative performance. Furthermore, we review the neural mechanisms underlying GDD, focusing on the dynamic interaction between the Default Mode Network (DMN) and the Executive Control Network (ECN). We propose that unlike PCD, GDD may not serve as a cognitive bridge for creative thought, providing a foundation for future research into the enhancement of human creativity.

1. Introduction For decades, daydreaming was primarily viewed through the lens of "mind-wandering" —a phenomenon characterized by a lapse in attention to the external environment, often resulting in decreased performance on ongoing tasks. However, emerging evidence suggests that not all daydreaming is counterproductive. Positive-Constructive Daydreaming (PCD) represents a volitional or semi-volitional shift toward internal processing that is structured around future planning, creative problem-solving, and the simulation of goal-relevant scenarios.

In the context of creativity, PCD is increasingly recognized as a vital cognitive state. Unlike random mind-wandering or GDD, PCD maintains a degree of thematic consistency and intentionality, allowing the individual to explore associative paths that are relevant to a specific creative objective. Understanding the relationship between different types of daydreaming and creativity requires an analysis of both behavioral outcomes and the underlying functional architecture of the brain.

2. Conceptualizing Daydreaming Types Daydreaming is defined by its internal focus and its alignment with the individual's long-term or immediate goals. While it shares the "stimulus-independent" quality of general mind-wandering, it is distinguished by its content and valence.

2.1 PCD vs. GDD Traditional mind-wandering is often unintentional and can lead to "task-unrelated thoughts" (TUTs) that impair performance. In contrast, PCD is frequently intentional. As noted in recent studies, individuals who engage in PCD are often "tuning out" the external world to engage in productive internal deliberation.

2.2 Experiment 1: Construction of LASSO (Least Absolute Shrinkage and Selection Operator) Regression Models for PCD

We conducted an exploratory analysis of the relationship between PCD, creative thinking, and their underlying neural mechanisms. Drawing upon previous research [?, ?, ?], Experiment 1 proposed the following hypotheses: (1) enhanced functional connectivity between the Default Mode Network (DMN) and the Frontoparietal Control Network (FPCN) during the resting state can predict higher levels of creative thinking; and (2) PCD mediates the positive predictive relationship between DMN-FPCN functional connectivity and creative thinking, whereas GDD does not play a significant mediating role. Specifically, we hypothesize that functional connectivity between the DMN and FPCN is associated with a higher frequency of PCD, which in turn effectively predicts creative thinking performance at the trait level.

2.2.1 Participants Seventy-two university students (12 males, 60 females) were randomly recruited for this study. All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of psychiatric disorders or use of psychotropic medication. All questionnaires involved in this experiment were administered online via the Wenjuanxing platform.

Brain imaging data were inspected and preprocessed using the HOMER2 toolkit [?]. After excluding data from three participants due to excessively high signal-to-noise ratios, the final sample consisted of 69 participants (11 males, 58 females; mean age $M = 19.71$ years, $SD = 0.60$ years). Prior to the experiment, all participants were informed about the experimental equipment and procedures and provided written informed consent. Participants received monetary compensation upon completion of the study. The experimental protocol was approved by the Ethics Committee of the Key Laboratory of Modern Teaching Technology, Ministry of Education, Shaanxi Normal University (L20240101-01).

2.2.2 Experimental Materials The Short Imaginal Processes Inventory (SIPI; Huba et al., 1981; Huba & Tanaka, 1983) consists of three subscales: Poor Attention Control (PAC), Positive-Constructive Daydreaming (PCD), and Guilty-Dysphoric Daydreaming (GDD). Each subscale contains 15 items, totaling 45 items. Responses are recorded using a 5-point Likert scale ranging from 1 (definitely not like me) to 5 (definitely like me). The PAC subscale includes 7 reverse-scored items, the PCD subscale includes 5 reverse-scored items, and the GDD subscale includes 2 reverse-scored items. The Generation and Selection Questionnaire (GSQ; Fürst et al., 2016; Fürst & Grin, 2018) was employed to assess trait-level creative thinking, specifically measuring an individual' s capacity for creative idea generation and evaluation. The questionnaire comprises two subscales: the Generation subscale (e.g., "I easily generate a large number of ideas") and the Selection subscale (e.g., "I seek to optimize solutions"). Each subscale consists of 6 items rated on a 5-point Likert scale from 1 (almost never) to 5 (frequently), with all items being positively scored.

2.2.3 fNIRS Data Acquisition In this study, resting-state functional brain imaging data were collected using a functional near-infrared spectroscopy (fNIRS) system (LABNIRS, Shimadzu Corp., Kyoto, Japan). The device utilizes three wavelengths of near-infrared light (780 nm, 805 nm, and 830 nm) with an initial sampling rate of 83 Hz, which was subsequently downsampled to 10 Hz. Based on previous research [?, ?], the regions of interest (ROIs) were defined as the prefrontal cortex (a 2×7 array totaling 14 optodes) and the temporoparietal junction (a 3×3 array on both the left and right sides, totaling 18 optodes). The optode distance was set at 3 cm, resulting in a total of 43 channels. The specific configuration is illustrated in [FIGURE:1].

The study collected 3 minutes of eyes-open resting-state data and 3 minutes of eyes-closed resting-state data to prevent participants from experiencing drowsiness, which can occur during resting periods exceeding 3 minutes [?]. During the eyes-open resting state, participants were instructed to fixate on a white crosshair centered on a black screen. To minimize random fluctuations in psychological states that might occur when participants first arrive at the laboratory, only the data from the eyes-closed resting-state period were selected for subsequent analysis [?].

[FIGURE:1] fNIRS optode arrangement and channel numbering. Note: Red circles represent emitters; blue circles represent detectors; numbers indicate the data channels and their corresponding identifiers.

2.2.4 fNIRS Data Analysis **Data Preprocessing** Following previous research [?], this study utilized oxyhemoglobin (HbO) concentrations as the basis for all subsequent analyses. Preprocessing and filtering were conducted using the HOMER2 package [?]. First, raw data signals were converted into optical density signals. Motion artifacts were then detected using the `hmrMotionArtifactByChannel` function and corrected using the `hmrMotionCorrectSpline` function. Finally, the signals were band-pass filtered to retain frequencies between 0.01 and 0.10 Hz. Channels with excessive noise for each participant were flagged, and any channel with a marking rate exceeding 50% was removed [?]. Based on the HOMER2 preprocessing results, data from channels 2, 5, 15, 18, and 20 were excluded from further analysis.

Construction of Functional Connectivity Networks This study investigated the relationship between creative thinking and both static and dynamic functional connectivity. For static functional connectivity, the connectivity matrix used channels as nodes. The edge values were defined as the Fisher Z-transformed Pearson correlation coefficients of the time-varying blood oxygen levels between channels. For each participant, this resulted in a 38 × 38 functional connectivity matrix. For dynamic functional connectivity, we employed sliding window correlation (SWC; [?]) to calculate brain functional connectivity across different time intervals during the resting state. Based on prior research, the window length was set to 60 seconds with a step size of 1 second [?]. Similar to the static connectivity approach, functional connectivity matrices were obtained for each window by calculating the Fisher Z-transformed Pearson correlation coefficients between channels. Subsequently, the dynamic functional connectivity index, referred to as functional connectivity variability (FCV; [?]), was calculated as the standard deviation of the connectivity values for the same channel pair across different time windows. Finally, the dynamic functional connectivity matrix was constructed using these FCV values. The specific construction process is illustrated in [FIGURE:2].

Network-Based Predictive Analysis LASSO regression model construction and leave-one-out cross-validation (LOOCV) were performed using MATLAB 2021a. First, a LASSO regression model was constructed using edge values significantly correlated with creative thinking ($p < 0.05$, uncorrected) as independent variables and trait-level creative thinking as the dependent variable. This step served to extract features from the functional connectivity values, and the edges identified through this feature extraction were used for subsequent analyses. To determine the optimal regression model, LOOCV was used to find the optimal regularization parameter λ. Specifically, the λ value that minimized the mean square error (MSE) between the predicted and observed values was selected to balance model fit and complexity, ensuring optimal generalization capability. The overall significance of the model was determined using a 10,000-iteration permutation test [?]. Based on the LASSO regression results, edges with non-zero regression coefficients in the optimal model were identified as selected features. Using these as independent variables, several mediation models were constructed, with different types of trait-level mind-wandering as mediators and trait-level creative thinking as the dependent variable. The construction of the LASSO regression model is shown in [FIGURE:3].

[FIGURE:2] Flowchart of functional connectivity matrix construction. Note: RSFC: Resting-state functional connectivity; FCV: Functional connectivity variability.

[FIGURE:3] Construction process of the LASSO regression model.

2.3 Results

2.3.1 Behavioral Results Pearson correlation analysis was conducted on the three subscales of the SIPI questionnaire: Poor Attention Control (PAC), Positive-Constructive Daydreaming (PCD), and Guilty-Dysphoric Daydreaming (GDD). The results indicated a significant negative correlation between PAC and PCD ($r = -0.29, p = 0.015$) and a significant positive correlation between PAC

Figure 4

Figure 1: Figure 4

Figure 5

Figure 2: Figure 5

and GDD ($r = 0.48, p < 0.001$). The correlation between PCD and GDD did not reach statistical significance ($r = -0.14, p = 0.261$).

2.3.2 Creative Thinking Prediction Models Based on Resting-State Functional Connectivity

Based on resting-state functional connectivity, both static and dynamic functional connectivity between the Default Mode Network (DMN) and the Frontoparietal Control Network (FPCN) significantly predicted creative idea generation as well as creative idea evaluation. When λ was set to 0.1481, the static functional connectivity between the DMN and FPCN achieved the best predictive performance for creative idea generation ($MSE = 10.55$), with the predicted values explaining 53.48% of the variance in the observed values. When λ was set to 0.1085, the dynamic functional connectivity between the DMN and FPCN showed the best predictive performance for creative idea generation ($MSE = 10.31$), with an explained variance of 68.17%. The predictive models for creative idea generation based on static and dynamic functional connectivity are shown in

and

, respectively. Permutation tests with 10,000 iterations indicated that both models significantly predicted creative idea generation performance ($p_1 < 0.001$; $p_2 < 0.001$). In the predictive models for idea generation, functional connections between the DMN and FPCN carried greater weight; detailed edge weights for the static and dynamic models are provided in Appendix 1, Tables S1 and S2.

When λ was set to 0.1528, the static functional connectivity between the DMN and FPCN achieved the best predictive performance for creative idea evaluation ($MSE = 10.92$), explaining 61.40% of the variance. When λ was set to 0.1085, the dynamic functional connectivity between the DMN and FPCN reached its optimal predictive performance for creative idea evaluation ($MSE = 10.31$), explaining 68.17% of the variance. The predictive models for creative idea evaluation based on static and dynamic functional connectivity are illustrated in [FIGURE:6] and [FIGURE:7], respectively. Permutation tests (10,000 iterations) confirmed that both models significantly predicted creative idea evaluation performance ($p_1 < 0.001$; $p_2 < 0.001$). In the predictive models for idea evaluation, functional connections within the FPCN exhibited higher weights; specific edge weights for the static and dynamic models are listed in Appendix 1, Tables S3 and S4.

Predictive model of creative idea generation based on static functional connec-

Figure 4

Figure 3: Figure 4

Figure 5

Figure 4: Figure 5

tivity.

Predictive model of creative idea generation based on dynamic functional connectivity.
Note: The upper panels display specific functional connections and their corresponding nodes within the predictive models. Red nodes represent brain regions associated with the Frontoparietal Control Network, while blue nodes represent regions associated with the Default Mode Network. Red edges indicate functional connections with positive weights, and blue edges indicate those with negative weights. The bottom-left panels show scatter plots of predicted versus observed values for creative idea generation. The bottom-right panels show the results of the permutation tests, where the vertical line represents the observed MSE value. L: Left; R: Right; SMG: Supramarginal Gyrus; STG: Superior Temporal Gyrus; IFG: Inferior Frontal Gyrus; DLPFC: Dorsolateral Prefrontal Cortex; ANG: Angular Gyrus; SFG: Superior Frontal Gyrus; FG: Fusiform Gyrus; Freq.: Frequency of MSE occurrences in permutation tests; MSE: Mean Squared Error.

[FIGURE:6] Predictive model of creative idea evaluation based on static functional connectivity.
[FIGURE:7] Predictive model of creative idea evaluation based on dynamic functional connectivity.
Note: L: Left; R: Right; SMG: Supramarginal Gyrus; STG: Superior Temporal Gyrus; IFG: Inferior Frontal Gyrus; DLPFC: Dorsolateral Prefrontal Cortex; ANG: Angular Gyrus; SFG: Superior Frontal Gyrus; MTG: Middle Temporal Gyrus; FG: Fusiform Gyrus; Freq.: Frequency of MSE occurrences; MSE: Mean Squared Error.

2.3.3 Specificity Testing of Prediction Models This study employed Steiger' s Z-test to compare the model fit by examining the correlations between various predicted values and the actual observed values of creative thinking. The results of these tests are presented in and . The findings indicate that the predictive models for creative thinking exhibit high specificity, regardless of whether they are based on static functional connectivity or dynamic functional connectivity [**?**, **?**].

Specificity of prediction models based on static functional connectivity. | | Generation Prediction | Evaluation Prediction | Steiger' s Z | | :–| :–: | :–: | :–: | | Generation Observed | 0.73*** | 0.32** | 3.60*** | | Evaluation Observed |

0.29** | 0.78*** | -4.49*** | Note: *$p < 0.05$,* ***$p < 0.01$,*** $p < 0.001$.

Specificity of prediction models based on dynamic functional connectivity. | | Generation Prediction | Evaluation Prediction | Steiger' s Z | | :–| :–: | :–: | :–: | | Generation Observed | 0.83*** | 0.40*** | 4.91*** | | Evaluation Observed | 0.38** | 0.81*** | -4.71*** | Note: *$p < 0.05$,* ***$p < 0.01$,*** $p < 0.001$.

2.3.4 Mediating Effects of Different Types of Mind-Wandering Between Resting-State Functional Connectivity and Creative Thinking

Mediation analyses were conducted using static functional connectivity as the independent variable, Positive-Constructive Daydreaming (PCD) as the mediating variable, and creative idea generation and evaluation as the dependent variables. A bootstrap sampling procedure with 5,000 iterations was employed for significance testing. The results indicated that PCD fully mediated the relationship between the static functional connectivity of the bilateral superior temporal gyrus (STG) and creative idea generation ($\beta = 1.14$, 95% CI $[0.19, 2.58]$), as shown in [FIGURE:8]. Furthermore, PCD partially mediated the relationship between the static functional connectivity of the dorsolateral prefrontal cortex (DLPFC) and the inferior frontal gyrus (IFG) and creative idea evaluation ($\beta = 0.11$, 95% CI $[0.03, 0.21]$), as illustrated in [FIGURE:9].

Mediation analyses were also performed using dynamic functional connectivity as the independent variable, PCD as the mediator, and creative idea generation and evaluation as the dependent variables, utilizing 5,000 bootstrap samples. The results demonstrated that PCD fully mediated the relationship between the dynamic functional connectivity of the superior frontal gyrus (SFG) and the left middle temporal gyrus (MTG) and creative idea generation ($\beta = -2.54$, 95% CI $[-5.13, -0.69]$), as shown in [FIGURE:10]. However, no significant mediating effect of PCD was found in the relationship between dynamic functional connectivity and creative idea evaluation.

Additionally, corresponding analyses were conducted using Guilty-Dysphoric Daydreaming (GDD) as the mediating variable. No significant mediating role for GDD was observed in the relationship between resting-state functional connectivity and creative thinking.

[FIGURE:8] The mediating role of PCD in the relationship between bilateral STG static functional connectivity and creative idea generation.
[FIGURE:9] The mediating role of PCD in the relationship between left DLPFC and right IFG static functional connectivity and creative idea evaluation.
[FIGURE:10] The mediating role of PCD in the relationship between left MTG and SFG (FP) dynamic functional connectivity and creative idea generation.
Note: L: Left; R: Right; STG: Superior Temporal Gyrus; MTG: Middle Temporal Gyrus; SFG (FP): Superior Frontal Gyrus (Frontal Pole); DLPFC: Dorsolateral Prefrontal Cortex; IFG: Inferior Frontal Gyrus; PCD: Positive-Constructive Daydreaming.

Experiment 1 used resting-state fNIRS to replicate and deepen the results of previous fMRI studies, systematically investigating the functional connectivity between the DMN and FPCN and trait mind-wandering as predictors for creative idea generation and evaluation. These findings provide preliminary validation for the central hypothesis of this study at the trait level: specifically, that mind-wandering predicts enhanced creative performance only when it involves top-down processing.

Correlation analysis revealed a significant negative correlation between Poor Attention Control (PAC) and Positive-Constructive Daydreaming (PCD). Individuals with higher levels of trait PCD may exhibit higher levels of attentional control engagement. This finding suggests that PCD likely involves top-down cognitive processing, providing preliminary behavioral evidence in support of our hypothesis.

In the resting state, both static and dynamic functional connectivity between the Default Mode Network (DMN) and the FPCN significantly predict creative thinking. Specifically, in the predictive model for creative idea generation, the functional connectivity between the DMN and FPCN carries greater weight, and the generation process depends on the dynamic functional connectivity between these two networks. Conversely, in the predictive model for creative idea evaluation, internal functional connectivity within the FPCN carries greater weight.

Mediation analysis further demonstrated that PCD fully mediated the relationship between static functional connectivity (between bilateral STG) and creative idea generation, as well as the relationship between dynamic functional connectivity (between the Frontal Pole, FP, and the left MTG) and creative idea generation. Additionally, PCD partially mediated the relationship between the static functional connectivity of the left DLPFC and the right IFG and creative idea evaluation.

The planning and intentional content control inherent in PCD reflect its involvement in top-down cognitive processing. Individuals with a high PCD tendency often perceive mind-wandering as a positive experience and are more willing to engage in mind-wandering intentionally within specific task contexts [**?**]. The content of deliberate mind-wandering (deliberate MW) may involve unfinished tasks or upcoming goals; thus, the dimensions of deliberation and task-relatedness in mind-wandering may overlap to some extent [**?**]. Consequently, Experiment 2 further explores the relationship between these two dimensions—intentionality and task-relatedness—and creative thinking, as well as their underlying cognitive and neural mechanisms.

3 Experiment 2: Deliberate Mind-Wandering and Task-Related Mind-Wandering Predict Creative Thinking

3.1 Cognitive Neural Mechanisms

Experiment 1 only examined the characteristics of mind-wandering and creative thinking at the trait level through resting-state functional connectivity. However, previous research has failed to clarify the relationship between mind-wandering and creativity at the state level. The PCD framework is most likely to manifest in specific task contexts through the dimensions of task-relatedness and deliberation in mind-wandering [**?**, **?**]. Specifically, task-relatedness and deliberation reflect the involvement of top-down processing within the mind-wandering state at the levels of content and etiology, respectively.

Therefore, to further characterize the relationship between different types of mind-wandering and creative thinking beyond the scope of Experiment 1, Experiment 2 focuses on the incubation process of creative thinking. This experiment distinguishes mind-wandering by its etiology into deliberate mind-wandering (MW-d) and spontaneous mind-wandering (MW-s), and by its content into task-unrelated mind-wandering (MW-u) and task-related mind-wandering (MW-r). This approach allows for a more focused exploration of how these distinct types of mind-wandering relate to creative thinking. Additionally, this study utilizes functional Near-Infrared Spectroscopy (fNIRS), which offers high ecological validity, to explore the cognitive neural mechanisms by which mind-wandering predicts creative thinking performance following an incubation period.

Experiment 2 proposes the following hypotheses: 1. Only MW-d and MW-r will significantly predict creative task performance following incubation, while MW-s and MW-u will show no significant predictive effects. 2. The specific content of mind-wandering may be more critical to creative performance than its etiology; thus, MW-r is expected to be a more effective predictor of post-incubation creative performance than MW-d. 3. During the task state, individuals' creative performance will be positively correlated with both static and dynamic functional connectivity between the Default Mode Network (DMN) and the Frontoparietal Control Network (FPCN). 4. Mind-wandering during the incubation period will predict brain network connectivity during the subsequent creative thinking task.

3.2 Methods

3.2.1 Participants The study first determined the required sample size using G*Power software [**?**]. Based on an a priori effect size analysis for multiple regression, a minimum of 55 participants was required to achieve a medium effect size ($f^2 = 0.15$) at a significance level of $\alpha = .05$. Consequently, 70 university students were randomly recruited for this study (11 males, 59 females). All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of mental disorders or psychiatric medication use.

Due to the failure of seven participants to complete the entire experiment, subsequent data analysis was conducted on the remaining 63 participants (11 males, 52 females; mean age $M = 19.20$ years, $SD = 0.62$ years). Prior to the experiment, all participants were informed about the experimental apparatus and procedures and provided written informed consent. Participants received monetary compensation upon completion of the study. The experimental protocol was approved by the Ethics Committee of the Key Laboratory of Modern Teaching Technology, Ministry of Education, Shaanxi Normal University (L20240101-01).

3.2.2 Experimental Materials

(1) The Short Version of the Imaginal Processes Inventory (SIPI) was identical to that used in Experiment 1. In the present study, the Cronbach' s α coefficients for the three subscales—Poor Attention Control (PAC), Positive-Constructive Daydreaming (PCD), and Guilty-Dysphoric Daydreaming (GDD)—were 0.86, 0.71, and 0.80, respectively.

(2) The Novelty Seeking and Augmentation Questionnaire (NSAQ) was employed to measure the covariate of individual tendencies toward novelty seeking [**?**]. The questionnaire consists of 19 items: 14 items measure the tendency for novelty seeking, defined as an individual' s inclination to seek out fresh stimuli or explore new environments; the remaining 5 items measure the tendency for augmentation, defined as the inclination to seek further understanding of known entities. In this study, the Cronbach' s α coefficients for the novelty seeking and augmentation subscales were 0.88 and 0.82, respectively.

3.2.3 fNIRS Experimental Task and Procedure The Alternative Uses Task (AUT; [**?**]) was utilized to measure individual creative thinking. The AUT requires participants to generate as many unconventional uses as possible for common objects (e.g., “What is a creative use for a brick?” Answer: “Grinding it into powder to use as pigment”). Following previous research protocols [**?**, **?**], the stimulus materials used in the AUT sessions before and after the incubation period were identical. The specific stimuli used in this study were “knife,” “chopsticks,” and “newspaper,” with the presentation order fully randomized between the pre-test and post-test. The AUT consisted of three blocks; in each block, participants were given 1.5 minutes to brainstorm several unconventional uses for a common object and report them orally. These responses were recorded using a digital voice recorder for subsequent analysis.

The experiment employed the Object Characteristics Task (OCT) as a control task [**?**]. The OCT task typically requires participants to report as many characteristics of a common object as possible within 1.5 minutes. For example, participants might be asked, “What are the characteristics of a key?” The OCT materials used in this experiment included: keys, wires, and plastic bags. After collecting the responses, duplicate and irrational answers (e.g., “The key is wet”) were removed. A participant' s OCT score for each material was quantified by the number of valid answers provided in that trial, and the overall OCT performance was quantified using the mean OCT score across all trials.

This study employed both objective and subjective quantification methods to systematically and comprehensively evaluate performance on the Alternative Uses Task (AUT). To provide an objective assessment, we utilized an automated scoring model developed by [?], which is based on the JIEBA Chinese word segmentation tool [?] and the Word2Vec algorithm [?]. This model evaluated participants' AUT performance across three dimensions: fluency, flexibility, and uniqueness. The final scores for these dimensions were derived from a principal component analysis (PCA) of the results across three blocks. Although such natural language processing (NLP) scoring methods can overcome certain drawbacks of traditional AUT scoring, they often fail to address another core evaluative dimension of creative thinking: appropriateness. Therefore, to characterize individual AUT performance as comprehensively as possible, this study also employed the Consensus Assessment Technique (CAT; [?]) for subjective quantification. Three researchers in the field of creativity were recruited as raters to score the creativity of each response on a 7-point scale based on originality and appropriateness. To avoid order effects, the materials were presented to the raters in a randomized order. A participant' s creativity performance for each block was calculated as the average of their two highest-scoring responses [?], and the final performance measure was the PCA value derived from the performance across the three blocks.

The Sustained Attention to Response Task (SART; [?]) was adopted as the distractor task during the incubation period [?, ?, ?, ?]. The incubation period was situated between two creative thinking tasks. The SART is a task with low cognitive resource demands and is frequently used to induce mind-wandering [?]. In this task, participants were required to press the "Q" key when they saw a non-target stimulus and to withhold their response when they saw a target stimulus. The stimuli used in this study were meaningless geometric figures randomly selected from the Raven' s Standard Progressive Matrices (see Appendix 3). Target and non-target stimuli were distinguished by the geometric features of these figures (e.g., whether they were bilaterally symmetrical). Different geometric features served as the criteria for differentiation in different blocks, with corresponding prompts presented before the start of each block. The target stimulus features for the four blocks in this task were: symmetrical, containing a circle, asymmetrical, and not containing a circle.

The experiment utilized thought probes to detect participants' mind-wandering during the SART task [?, ?]. Each probe consisted of two questions, the first being: "What were you thinking about just before this question appeared?" This question provided four response options: 1) the current task (i.e., the SART); 2) the previous creativity task; 3) neither of the above; and 4) I don' t know. In this study, the judgment of "task-related/unrelated" was made with direct reference to the SART task currently being performed by the participants. Therefore, the "previous creativity task" option was specifically included to accurately capture mind-wandering related to the Alternative Uses Task (AUT), hereafter referred to as MW-r.

Only when participants selected option 2 or 3 did the screen present a second question: "Did you think of this intentionally or unintentionally?" This question had two options: 1) intentional and 2) unintentional. Based on the participants' choices, their thoughts during the SART were initially classified into six categories: 1) focused on the current task; 2) intentional and task-related (referring to the AUT, as below); 3) unintentional and task-related; 4) intentional and task-unrelated; 5) unintentional and task-unrelated; and 6) blank. Deliberate mind-wandering (MW-d) was defined as the sum of categories 2 and 4; spontaneous mind-wandering (MW-s) as the sum of categories 3 and 5; task-related mind-wandering (MW-r) as the sum of categories 2 and 3; and task-unrelated mind-wandering (MW-u) as the sum of categories 4 and 5.

Before the formal experiment began, all participants completed the Short Imaginative Processes Inventory (SIPI), the Novelty Seeking Scale, and the Self-Improvement Questionnaire via the Wenjuanxing platform. After participants were informed of the basic experimental procedures, a practice session was conducted. During the practice phase, participants were first presented with an example of the AUT along with a corresponding creative answer (e.g., "What is a creative use for a brick? Answer: Grind it into powder to use as pigment"), followed by the stimulus materials from the SART. In the formal experiment, participants were first required to complete the AUT. After completing the initial AUT and before starting the SART, they were informed that they would need to complete the same AUT again after the SART. Subsequently, they completed the SART with embedded thought probes, followed by the second AUT, and finally a control task. The overall experimental procedure is shown in [FIGURE:11]. This paradigm design [?, ?] quantifies the incubation effect through the difference between pre-test and post-test AUT performance. It has been validated by multiple studies as an effective method for exploring the relationship between mind-wandering (MW) and divergent thinking [?, ?]. It should be emphasized that this study does not aim to distinguish between the classical stages of creativity; rather, it focuses on the dynamic measurement of state MW and its predictive role in immediate creative performance. In this context, the post-test AUT serves primarily as a "creative output detector" to capture the immediate impact of MW activity during the incubation period on creative thinking.

The SART task employed in this study consisted of 4 blocks, each containing 120 trials, of which 108 were non-target trials and 12 were target trials. In each trial, the stimulus presentation time was 2000 ms, with an inter-stimulus interval of 1000 ms. All trials were presented randomly. Within the SART task, thought probes were inserted in a pseudo-random manner every 15 to 25 trials. Participants wore fNIRS equipment throughout the entire experiment.

[FIGURE:11] Overall procedure of Experiment 2. Note: AUT: Alternative Uses Task; SART: Sustained Attention to Response Task.

3.2.4 fNIRS Data Acquisition This study employed functional Near-Infrared Spectroscopy (fNIRS) technology, consistent with the methodology described in Experiment 1. The optode arrangement also remained identical to that used in Experiment 1.

3.2.5 Data Analysis Regarding the behavioral data, we first explored the correlations among the four distinct types of mind-wandering examined in this experiment. Subsequently, we conducted a hierarchical regression analysis to predict post-test creative thinking performance. In this model, demographic variables (age and gender), novelty seeking, pre-test creative thinking performance, and mind-wandering dimensions (intentional vs. unintentional and task-related vs. task-unrelated) were entered as independent variables.

To determine whether intentionality or task-relevance serves as a more effective classification for predicting post-incubation creative thinking, we utilized Leave-One-Out Cross-Validation (LOOCV) to analyze the relationship between predicted and observed values across different models. The differences between these relationships were then compared using Steiger' s Z-test. Finally, all types of mind-wandering were incorporated into a single LASSO regression model to identify which specific type of mind-wandering most robustly predicts post-test creative thinking performance.

Consistent with Experiment 1, this study employed LASSO regression to construct a predictive model of creative thinking based on task-state functional connectivity, incorporating both static and dynamic functional connectivity. Since the Alternative Uses Task (AUT) in this study consisted of three blocks, the functional connectivity values used for model construction and subsequent analysis were derived by applying Principal Component Analysis (PCA) for dimensionality reduction across the corresponding values of these three blocks. The construction of the functional connectivity matrix is illustrated in [FIGURE:12]. Predictive models were then developed based on these matrices. To ensure the consistency of the predictive models across the pre- and post-incubation periods, both pre-test and post-test data were integrated into the dataset during the construction process. Furthermore, to ensure model specificity, we conducted predictive analyses specifically for Original Cognitive Task (OCT) performance. Finally, hierarchical regression analyses were performed using the pre- and post-test functional connectivity values corresponding to predictors with non-zero weights in the model. In these analyses, demographic variables were entered in the first step, pre-test functional connectivity in the second step, and mind-wandering in the third step, with the corresponding post-test functional connectivity serving as the dependent variable.

[FIGURE:12] Flowchart of functional connectivity matrix construction. Note: FC: functional connectivity; dFC: dynamic functional connectivity; PCA: principal component analysis.

3.3 Results

3.3.1 Behavioral Results The mean accuracy for the SART task was 0.92 (SD = 0.06). Correlations between SART error rates and various types of mind-wandering (MW) were analyzed. The results indicated that the SART error rate was significantly positively correlated only with MW-u ($r = 0.25, p = 0.049$). The proportions of mind-wandering are presented in . Correlation analysis revealed that task-related mind-wandering (MW-r) was highly positively correlated with deliberate mind-wandering (MW-d) ($r = 0.93, p < 0.001$), and task-unrelated mind-wandering (MW-u) was highly positively correlated with spontaneous mind-wandering (MW-s) ($r = 0.85, p < 0.001$). After controlling for baseline Alternative Uses Task (AUT) performance and potential confounding variables, results indicated that only MW-r significantly predicted post-incubation AUT performance in terms of originality ($\beta = 0.27, p < 0.01$), flexibility ($\beta = 0.19, p < 0.05$), and composite scores ($\beta = 0.20, p < 0.05$). In contrast, MW-d only significantly predicted post-incubation AUT originality ($\beta = 0.22, p < 0.05$), failing to significantly predict flexibility ($\beta = 0.15, p > 0.05$) or composite scores ($\beta = 0.16, p > 0.5$). Since no significant effects of MW-r or MW-d were observed for post-incubation fluency, this dimension was excluded from subsequent analyses.

Leave-one-out cross-validation (LOOCV) was employed to test the stability of the predictive models. The results showed that for originality, MW-r effectively predicted post-incubation AUT originality after controlling for pre-test scores ($r = 0.28, p = 0.027$). To ensure the robustness of the LOOCV, a 5,000-iteration permutation test was conducted, confirming that the LOOCV results were stable ($p = 0.013$). However, the predictive model based on MW-d exhibited poor stability ($r = 0.22, p = 0.087$). Regarding flexibility, neither MW-r nor MW-d passed the LOOCV (MW-r: $r = 0.20, p = 0.115$; MW-d: $r = 0.13, p = 0.324$). Similarly, for composite scores, neither dimension passed the LOOCV (MW-r: $r = 0.20, p = 0.116$; MW-d: $r = 0.14, p = 0.272$). Steiger' s Z-test performed on the LOOCV results revealed a marginally significant difference between the predictive effects of MW-r and MW-d on AUT originality ($t = 1.35, p = 0.089$). Because the predictive models for flexibility and composite scores failed to meet the stability requirements of LOOCV, these dimensions were excluded from further analysis.

Finally, LASSO regression was utilized to compare the relative weights of MW-r and MW-d within the regression model. The results indicated that the LASSO regression model achieved the minimum error (MSE = 0.56) when the L2 penalty coefficient was 0.0165. At this point, the weight for MW-r was 0.057, while the weight for MW-d was 0. This suggests that MW-r is a more important predictor of post-incubation AUT originality than MW-d; consequently, the MW-d dimension was excluded from subsequent fNIRS data analysis. Given that the behavioral results demonstrated that the predictive effect of MW-r on creative thinking is primarily concentrated in the originality dimension, subsequent predictive models based on task-state fNIRS functional connectivity were constructed using originality as the dependent variable.

Correlations between mind-wandering and SART error rates. | | MW-r | MW-u | MW-d | MW-s | | :–| :–: | :–: | :–: | :–: | | SART Error Rate | 0.12 | 0.25* | 0.15 | 0.21 | Note. MW-r: task-related mind-wandering; MW-u: task-unrelated mind-wandering; MW-d: deliberate mind-wandering; MW-s: spontaneous mind-wandering. ($*p < 0.05$)

Descriptive statistics of mind-wandering during the SART. | Type | Frequency (Total) | Frequency (MW) | | :–| :–: | :–: | | MW-r | 0.14 | 0.38 | | MW-u | 0.23 | 0.62 | | MW-d | 0.16 | 0.43 | | MW-s | 0.21 | 0.57 | | MW-Total | 0.37 | 1.00 | Note. MW-r: task-related mind-wandering; MW-u: task-unrelated mind-wandering; MW-d: deliberate mind-wandering; MW-s: spontaneous mind-wandering; MW-Total: all mind-wandering; Frequency (Total): proportion relative to all thought probes; Frequency (MW): proportion relative to all mind-wandering episodes.

3.3.2 Predictive Models of Creative Thinking Based on Task-State Functional Connectivity The results showed that both the static and dynamic functional connectivity models between the DMN and FPCN could significantly predict originality characteristics. The static functional connectivity prediction model is illustrated in [FIGURE:13]. When λ is set to 0.0244, the static functional connectivity achieves its optimal predictive performance for originality (MSE = 0.51), with the predicted values explaining 61.65% of the variance in the observed data. A permutation test with 10,000 iterations demonstrated that this model significantly predicts performance in creative idea generation ($p < 0.001$).

The dynamic functional connectivity prediction model is shown in [FIGURE:14]. When λ is 0.0106, the model reaches its peak predictive performance (MSE = 0.55), and the predicted values account for 71.13% of the variance in the actual values. A 10,000-iteration permutation test indicated that this model significantly predicts creative idea generation performance ($p < 0.001$). Static and dynamic functional connectivity weights for each edge in the connectivity models are provided in Appendix 1, Tables S5 and S6. We applied both prediction models to the Object Characteristics Task (OCT) scores for fitting. The results demonstrate that both models can predict OCT performance to a certain extent ($r_{static} = 0.27, p_{static} = 0.031$; $r_{dynamic} = 0.30, p_{dynamic} = 0.020$). Furthermore, Steiger' s Z-tests for both models indicated that their predictive power for originality was significantly greater than their predictive power for overall OCT performance ($Z_{static} = 4.16, p_{static} < 0.001$; $Z_{dynamic} = 4.54, p_{dynamic} < 0.001$). These findings suggest that both models possess high specificity in predicting originality performance.

[FIGURE:13] Prediction model of divergent thinking originality based on static functional connectivity.
[FIGURE:14] Prediction model of divergent thinking originality based on dynamic functional connectivity.

Note: L: Left; R: Right; SMG: Supramarginal Gyrus; STG: Superior Temporal Gyrus; IFG: Inferior Frontal Gyrus; DLPFC: Dorsolateral Prefrontal Cortex; ANG: Angular Gyrus; SFG: Superior Frontal Gyrus; MTG: Middle Temporal Gyrus; FG: Fusiform Gyrus; Freq.: Frequency of each MSE in the permutation test; MSE: Mean Squared Error.

3.3.3 Prediction of Functional Connectivity During Creative Thinking Processes by MW-r Hierarchical regression was conducted using the pre-test and post-test functional connectivity values of the predictors with non-zero weights in the predictive model as independent variables. The independent variables were analyzed with demographic variables in the first step, pre-test functional connectivity in the second step, and MW-r in the third step, with the corresponding post-test functional connectivity as the dependent variables. The results (, [FIGURE:15]) indicated that during creative thinking following the incubation period, static functional connectivity between the left inferior frontal gyrus (IFG) and the left supramarginal gyrus (SMG), as well as static functional connectivity between the bilateral IFG, decreased as a function of increased task-related mind-wandering (MW-r) during the incubation phase. Conversely, the dynamic functional connectivity between the right IFG and the right dorsolateral prefrontal cortex (DLPFC) increased as MW-r increased.

Regression Analysis of MW-r on Functional Connectivity During Post-Incubation Creative Thinking. | Predictor | IFG.L -SMG.L | IFG.L -IFG.R | DLPFC.R -IFG.R^{a} | | :– | :– | :– | :– | | **Step 1** | | | | | Gender | 0.29^{*} | -0.27^{*} | 0.30^{*} | | F | 4.02^{*} | 2.87^{*} | 5.64^{*} | | **Step 2** | | | | | Pre-Incubation Connectivity | 0.30^{*} | -0.33^{*} | 0.09^{*} | | F | 4.65^{*} | 4.11^{*} | 3.60^{*} | | **Step 3** | | | | | MW-r | 0.49^{***} | 0.65^{***} | 0.29^{*} | | F | 8.23^{***} | 10.03^{***} | 5.74^{*} | | ΔR^2 | $14.5\%^{***}$ | $13.9\%^{***}$ | $5.74\%^{*}$ | Note: Pre: Pre-incubation; Pos: Post-incubation; L: Left; R: Right; IFG: Inferior Frontal Gyrus; SMG: Supramarginal Gyrus; DLPFC: Dorsolateral Prefrontal Cortex; MW-r: Task-related Mind-Wandering; ^{a} Results based on dynamic functional connectivity analysis; $*p < 0.05$, $***p < 0.001$.

[FIGURE:15] Prediction of Functional Connectivity During Post-Incubation Creative Thinking by MW-r. Note: The upper panel (a) displays results based on dynamic functional connectivity analysis; the lower panel displays the corresponding estimated marginal means. L: Left; R: Right; IFG: Inferior Frontal Gyrus; SMG: Supramarginal Gyrus.

Experiment 2 utilized task-state fNIRS technology to systematically investigate the predictive role of DMN and FPCN functional connectivity and state-level mind-wandering on divergent thinking. Behavioral results indicated that, compared to MW-d, MW-r exerted a stronger predictive effect on the uniqueness performance in the Alternative Uses Task (AUT) following an incubation period. Functional connectivity analysis revealed that both static and dynamic task-based functional connectivity could effectively and positively predict the uniqueness of divergent thinking. Specifically, MW-r during the incubation period was found to negatively predict the static functional connectivity between the left inferior frontal gyrus (IFG) and the left supramarginal gyrus (SMG), as well as bilateral IFG, during the subsequent creative task. Furthermore, it positively predicted the dynamic functional connectivity between the right IFG and the right dorsolateral prefrontal cortex (DLPFC) during the creative task.

4 General Discussion

This study utilizes functional Near-Infrared Spectroscopy (fNIRS), a technique with high ecological validity, to explore the relationship and underlying neural mechanisms between mind-wandering (MW) and creative thinking at both trait and state levels. Experiment 1 reveals the predictive role of trait-level MW—specifically Positive-Constructive Daydreaming (PCD)—on self-perceived creativity and its associated neural mechanisms. Building upon these findings and further considering the heterogeneity of mind-wandering at the state level, Experiment 2 demonstrates that specific types of MW during an incubation period (namely, task-related mind-wandering, MW-r) predict subsequent divergent thinking performance in the Alternative Uses Task (AUT), along with its corresponding neural mechanisms.

Building on previous research [**?**, **?**, **?**], this study further demonstrates that both static and dynamic functional connectivity between the Default Mode Network (DMN) and the Frontoparietal Control Network (FPCN) significantly predict creative thinking in both resting and task states. This confirms that brain activity patterns during creative processes captured by fNIRS can effectively predict individual creative performance. Experiment 1 found distinct predictive models for creative idea generation versus evaluation in the resting state. In the prediction model for idea generation, functional connectivity between the DMN and FPCN carried greater weight, and this process relied primarily on dynamic functional connectivity between these networks [**?**]. Conversely, in the prediction model for idea evaluation, functional connectivity within the FPCN carried more weight, and the process relied mainly on the stability of DMN-FPCN connectivity. Mediation analysis in Experiment 1 showed that PCD mediated the positive prediction of idea generation by functional connectivity between bilateral superior temporal gyri (STG), the negative prediction of idea generation by connectivity between the frontal pole (FP) and the left middle temporal gyrus (MTG), and the positive prediction of idea evaluation by connectivity between the left dorsolateral prefrontal cortex (DLPFC) and the right inferior frontal gyrus (IFG). Experiment 2 found that both static and dynamic functional connectivity between the DMN and FPCN during the task state significantly predicted AUT originality. Furthermore, MW-r during the incubation period positively predicted creative originality by decreasing static functional connectivity between the left IFG and the left supramarginal gyrus (SMG) and bilateral IFG, while increasing dynamic functional connectivity between the right IFG and the right DLPFC.

At the network level, the DMN is the primary brain network supporting the generation of spontaneous thoughts [**?**, **?**], while the FPCN supports higher-order cognitive functions such as cognitive control and attentional allocation [?]. The process of creative idea generation requires the reprocessing of prior experiences [?]. During this process, the degree of constraint an individual imposes on their thought content changes over time, with alternating cycles of generation and evaluation eventually leading to novel creative ideas [?]. The coupling of the FPCN and DMN signifies the reorganization of prior knowledge and preliminary decision-making [?, ?]. In contrast, the evaluation of creative ideas relies more heavily on top-down cognitive control, where individuals must maintain sustained attentional control over spontaneous thought content to optimize and refine existing ideas.

Building on the detailed characterization of the shared neural mechanisms between mind-wandering and creative thinking, this study systematically explores the subtle differences in how different types of mind-wandering predict creativity. Experiment 1 found that PCD mediated the positive prediction of creative idea generation by the static functional connectivity of the bilateral STG. The bilateral STG are core nodes of the DMN [?, ?] and are involved in cognitive processes such as breaking mental sets, forming novel representations, and future prospection [?]. This suggests that PCD may involve cognitive activities related to overcoming fixations, generating novel ideas, and imagining the future, consistent with previous findings [?, ?]. Experiment 1 also found that PCD mediated the negative prediction of idea generation by the functional connectivity between the FP and the left MTG. The left MTG is considered a key region for the semantic representation of abstract words [?], while the FP is critical for distant associations [?]. Stable functional connectivity between the left MTG and FP may indicate that during PCD, individuals use existing knowledge as material for distant associations, combining seemingly unrelated concepts to generate novel ideas [?]. Once these novel ideas are consciously captured [?], they eventually form creative viewpoints. Additionally, the study found that PCD mediated the positive prediction of idea evaluation by the functional connectivity between the left DLPFC and the right IFG. Both are core nodes of the FPCN; the left DLPFC is associated with attentional control switching [?], while the right IFG primarily functions to inhibit irrelevant interference during information retrieval in creative thinking [?]. Their functional connectivity during mind-wandering may represent the allocation of surplus cognitive resources to other tasks, such as optimizing and enhancing existing creative ideas. Although mediation analysis in Experiment 1 revealed potential neural pathways through which resting-state connectivity influences creativity via PCD at the trait level —providing a more advanced mechanistic hypothesis than simple correlation— one must consider the inherent neural overlap between PCD, relevant brain connectivity, and creativity. Consequently, future research should adopt causal validation approaches, such as using non-invasive brain stimulation (e.g., TMS or tDCS) to target these networks, or longitudinal designs to track dynamic changes in PCD and creative performance following interventions, thereby clarifying the causal direction of the "functional connectivity-PCD-creativity" chain. In summary, PCD facilitates the generation of novel future-oriented ideas and long-term distant associations, benefiting idea generation. Simultaneously, due to the involvement of cognitive control, PCD may be controllable, allowing individuals to optimize their creative ideas during these periods.

Experiment 2 revealed the predictive role of MW-r on task-state brain functional connectivity during the creative thinking process. After controlling for pre-test values, MW-r significantly and negatively predicted the static functional connectivity between the left inferior frontal gyrus (IFG) and the left supramarginal gyrus (SMG), as well as between the bilateral IFG, during the creative thinking process. Both the IFG and SMG are core nodes of the frontoparietal control network (FPCN). Brain activity in the left IFG may weaken an individual' s capacity for remote association [**?**], while activity in the left SMG is involved in the directed retrieval of episodic memory to match problem contexts with existing knowledge and experience [**?**]. A decrease in functional connectivity between these two regions may signify a reduced reliance on prior knowledge and experience, leading individuals to generate novel ideas through remote associations—a process conducive to enhancing creative thinking performance. In contrast, the primary role of the right IFG during creative thinking is to inhibit irrelevant interference during information retrieval [**?**]. Increased functional connectivity between the bilateral IFG may reflect an individual' s over-focus on the problem itself and restricted associative capacity, thereby negatively impacting the uniqueness of the final ideas. MW-r during the incubation period helps individuals detach from fixation on the current problem, enabling them to engage in remote associations in subsequent tasks and thus enhancing the creativity of the final ideas. Research also indicates that MW-r positively predicts the dynamic functional connectivity between the right IFG and the right dorsolateral prefrontal cortex (DLPFC). The right DLPFC is a region responsible for the overall control of attention [**?**]; functional connectivity between these two areas may imply that the individual is focusing attention on the current task while continuously excluding external

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