Self-reported mind-wandering intentionality and functional connectivity:

High spontaneous mind-wandering versus high deliberate mind-wandering

A Bachelor Thesis

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Abstract

Mind-wandering is ever present and affects many areas of our daily life. Earlier research revealed that mind-wandering has a controversial relationship with cognitive control, as it depends on whether thoughts emerge in a deliberate or spontaneous fashion. This Thesis aimed to contribute to a more sound basis about this phenomenon. The central research question was formulated as follows: 'Is there a difference in functional connectivity between people who score high on deliberated mind-wandering and people who score high on spontaneous mind-wandering?'. Based on earlier studies, it was hypothesized that people with high scores on deliberate mind-wandering would show more functional connectivity in the default mode network and control network than people with high scores on spontaneous mind-wandering. The Spontaneous and Deliberate Mind-Wandering (S-D-MW) questionnaire from the N&C protocol of the 'MPI-Leipzig Mind-Brain-Body' dataset has been used to identify people with high scores on deliberate mind-wandering (n=18), high scores on spontaneous mind-wandering (n=18) and high scores on both (n=26), by considering the top 40% per mind-wandering scale. Resting-state fMRI data has been analyzed, focusing on functional connectivity between the left inferior frontal sulcus (LIFS) and right intraparietal sulcus (RIPS) within the default mode network and between the left inferior frontal sulcus (LIFS) and left intraparietal sulcus (LIPS) within the control network. The results confirm the hypothesis, offering neurocognitive evidence for significant differences in functional connectivity between people with different mind-wandering intentions. Further research is recommended in order to solidify the preliminary findings and examine additional cognitive dimensions related to mind-wandering.

Keywords: mind-wandering, functional connectivity, resting-state fMRI, default mode network, control network, left inferior frontal sulcus (LIFS), left intraparietal sulcus (LIPS), right intraparietal sulcus (RIPS).

1. Introduction

We all recognize the feeling of drifting away in our mind, thoughts away from the external world. These thoughts were first described in 1890 by William James as the “stream of consciousness” (James, 1890). Nowadays, more and more research has been conducted about consciousness of the brain. In the last two decades, many studies have examined thoughts that distract us from reality and focused on a task called ‘mind-wandering’. Mind-wandering is ever-present. Research from Killingsworth and Gilbert (2010) suggests we mind-wander around half of our daily life. It affects many areas of our daily life, e.g. education, creativity, workplace functioning, focus, boredom, personality, dealing with problems and pain (Seli et al., 2016; He et al., 2021; Maratelli et al., 2021; Kucyi et al., 2013). Because of this ubiquitous presence, the scope of mind-wandering as a research topic has widened into many different psychological domains.

Mind-wandering as a broad concept, can be described as thoughts being directed internally (Smallwood & Schooler, 2015). Although mind-wandering is regularly considered as one concept, it reaches multiple dimensions in the psychology and neuropsychology. The term mind-wandering is often widely used (Christoff et al., 2018). According to Christoff et al. (2018), researchers use mind-wandering as an umbrella term, giving room for their own interpretation and resulting in conflicting definitions. However, mind-wandering contains several facets that cannot be summed up in one concrete term (Seli et al., 2018).

Despite its broad meaning, two particular differences in mind-wandering have been explored in studies for over two decades. Mind-wandering with and without intention (Seli et al, 2016). Research has shown that mind-wandering is no unitary construct, it occurs with two kinds of intentionality. A distinction is made between deliberate mind-wandering and spontaneous mind-wandering. In short, deliberate mind-wandering is directed, intentional and stimulus dependent. Spontaneous mind-wandering is undirected, unintended and stimulus independent (Seli et al., 2016). While mind-wandering was initially described negatively as the failure of attention on a task, more recent research has shown that it does have benefits in one's daily life. Research suggests that deliberate mind-wandering is associated with beneficial traits that may have a positive effect on beliefs and attitudes such as openness, positive-constructive daydreaming and originality at a divergent thinking task (Agnoli, Vannucci, Pelagatti, & Corazza, 2018; Marcusson-clavertz & Kjell, 2019; Vannucci & Chiorri, 2018). In the meta-analysis performed by Carriere et al. (2013), spontaneous mind-wandering is associated to more negative characteristics of mind-wandering. This includes amongst others difficulty with attention control, shifting between tasks and attentional distraction which leads to impaired performance and is even involved in clinical conditions (Carriere et al., 2013). Spontaneous mind-wandering is, however, not only correlated to negative results. It also appears to promote human flourishing (Baird et al., 2012).

Although the number of mind-wandering studies has increased in recent decades, little is known about the underlying brain regions involved. A network that is often associated with spontaneous thoughts is the default mode network, also known as the DMN (Poerio et al., 2017). Poerio et al. (2017) suggest that the DMN allows memory representations to form a conscious experience. In addition, it supports experiences that are unrelated to the environment. Previous research by Golchert et al. (2017) suggests that there are differences in the neural basis of cognitive functioning. Deliberate mind-wandering generates more activity in and between the default mode network and the control network, whereas spontaneous mind-wandering generates more activation in the limbic areas. Moreover, potential involvement of the control network (FPN), the limbic network and the salience network are mentioned.

As there are different kinds of intentionality of mind-wandering, it is important to further examine the nature of these differences using fMRI. To contribute to a more sound basis about the phenomenon of mind-wandering, this study will further investigate differences and similarities in functional connectivity between deliberate and spontaneous mind-wandering.

Therefore, in this study resting-state fMRI data will be analyzed to identify the functional connectivity between associate brain networks during deliberate mind-wandering and spontaneous mind-wandering. Mind-wandering will be measured with the 'Spontaneous and Deliberate Mind-Wandering Questionnaire (S-D-MW)'. This study will explore brain regions related to two large-scale networks: the default mode network (DMN) and the control network (FPN, frontoparietal network). These brain regions include the intraparietal sulcus and the inferior frontal sulcus.

This study will answer the following research question: 'Is there a difference in functional connectivity between people who score high on deliberated mind-wandering and people who score high on spontaneous mind-wandering?'. Based on previous research by Golchert et al. (2017), the hypothesis is that people with high scores on deliberate mind-wandering would show more functional connectivity in the default mode network and the control network than people with high scores on spontaneous mind-wandering.

2. Methods

2.1 Dataset

To answer the research question of this thesis, the 'MPI-Leipzig Mind-Brain-Body' (MPILMBB) data set was used to gather MRI and behavioural data (Babayan et al., 2020; Harvard Dataverse, 2020). In this study 318 people participated. Two protocols were used to gather this dataset: the Leipzig Mind-Body-Brain Interactions protocol (Lemon; Babayan et al., 2019) and the Neuroanatomy & Connectivity protocol (N&C; Mendes et al., 2019). The Lemon protocol focused on structural imaging and the N&C protocol focused on resting-state fMRI.

The participants relevant for this thesis took part in only the N&C protocol or the N&C and Lemon protocol, since Spontaneous and Deliberate Mind-Wandering (S-D-MW) questionnaire is only used in the N&C protocol.

The S-D-MW questionnaire was used in this study to provide the behavioural data from the N&C questionnaires (N&C; Mendes et al., 2019). The S-D-MW questionnaire measures two trait level tendencies of mind-wandering: spontaneous mind-wandering (S-MW) and deliberate mind-wandering (D-MW). The scales consist of four items. A five-point Likert scale is used to score each item from 1 (= "almost never") to 5 (= "very often"). As the questionnaire measures two trait level tendencies it can be divided in two parts. The S-MW scale captures experiences of unintentional mind-wandering and the D-MW scale assesses intentional mind-wandering. Cronbach's alpha revealed a good reliability for both spontaneous mind-wandering (German translation α=0.81, English original α =0.88) and deliberate mind-wandering (German translation α =0.81, English original α =0.90).

The structural imaging data used in this thesis is the high resolution structural scan (quantitative T1-weighted). It is collected by the N&C protocol or the LEMON protocol, depending on the subject. The structural and functional data from the N&C protocol was found in subfolder 'ses-02' from the MPILMBB data set. The key elements of the N&C protocol are four 15-minute eyes-open rs-fMRI. In this thesis only the first eyes-open rs-fMRI (Anterior-Posterior phase encoding direction) was used due to time limitations. The MRI-scanner used for the MPILMBB dataset is the Siemens Verio 3 Tesla MRI-scanner, equipped with a 32-channel Siemens head coil. The MRI-scanner remained stable during the scans. Data was obtained from the OpenfMRI database. During the eyes-open rs-fMRI scans, participants were instructed to remain awake with their eyes open and to fixate on a crosshair.

The eyes-open rs-fMRI scans were run in axial orientation, using T2∗ -weighted gradient-echo echo planar imaging (GE-EPI) with multiband acceleration, sensitive to blood oxygen level-dependent (BOLD) contrast. N&C open-eyes rs-fMRI data was obtained using an echo time for acquisition of 39.4 ms. Other parameters used for the open-eyes rs-fMRI were as follows: voxel size=2.3 mm isotropic; FOV=202 × 202 mm2; imaging matrix=88 × 88; 64 slices with 2.3 mm thickness; TR=1400 ms; flip angle=69°; echo spacing=0.67 ms; bandwidth=1776 Hz/Px; partial fourier 7/8; no pre-scan normalization; multiband acceleration factor=4; 657 volumes; and duration=15 min 30 sec.

Imaging data from both protocols, N&C T1-weighted structural data and LEMON T1-weighted structural data, were obtained using a 3D MP2RAGE sequence with the following parameters: voxel size =1.0 mm (isotropic); FOV=256 × 240 × 176 mm; TR=5000 ms; TE=2.92 ms; TI1=700 ms; TI2=2500 ms; flip angle 1=4°; flip angle 2=5°; bandwidth=240 Hz/Px; GRAPPA acceleration with iPAT factor 3 (32 reference lines); pre-scan normalization; and duration =8.22 min.

2.2 Participants

The N&C protocol was used for scanning 199 participants. Eventually, 111 participants have been successfully pre-processed, yielding usable data for further analyses in this thesis.

In order to focus on participants with high scores on deliberate mind-wandering and spontaneous mind-wandering, thresholds were implemented based on the D-MW, respectively S-MW, scores. These thresholds were selected by considering the upper 40% for both scales, thereby securing a relatively large group size while not weakening the difference between the group with high scores and the rest. Based on these thresholds, 44 participants were classified as scoring high on deliberate mind-wandering and also 44 participants were classified as scoring high on spontaneous mind-wandering.

2.3 Regions of interest

As described in the introduction, typically various regions tend to be involved in mind-wandering. Multiple regions of interest (ROIs) were chosen based on existing literature. To examine whether there is a difference in functional connectivity between people who score high on deliberated mind-wandering and people who score high on spontaneous mind-wandering, ROIs in two large-scale networks typically related to different types of mind-wandering were selected. Based on the domain research from Golchert et al. (2017) this thesis selected three specific ROIs which are linked to the large-scale default mode network (DMN) and the control network (FPN): the left inferior frontal sulcus (LIFS) with xyz coordinates = -41, 23, 29; the left intraparietal sulcus (LIPS) with xyz coordinates = -37, -56, 41; and the right intraparietal sulcus (RIPS) with xyz coordinates = + 37, −56, 41, see Table 1. According to Golchert et al. (2017), the connectivity between LIFS and RIPS overlaps with the DMN and the connectivity between LIFS and LIPS overlaps with the FPN.

Table 1.

Regions of interest and corresponding MNI coordinates.

		MNI coordinates		
Seed		X	Y	Z
Inferior Frontal Sulcus (IFS)	Left	-41	23	29
Intraparietal Sulcus (IPS)	Left	-37	-56	41
Intraparietal Sulcus (IPS)	Right	37	-56	41

2.4 Data processing

Data processing was performed in Matlab (R2021) using Conn Toolbox version 20 (Nieto-Castanon, 2020) and SPM version 12 (SPM, 2020). In the pre-processing phase, images were processed based on a repetition time of 1.4 seconds and continuous acquisition type. The data processing in general could be divided into three phases: pre-processing, model fitting and statistical inference. Functional and structural data were pre-processed in one session. The pre-processing pipeline consisted of several steps. For the functional data, these steps include: realignment for movement and volume correction, slice timing correction – manually defined, co-registration, functional outlier detection (global-BOLD-signal z-value threshold 5, subject-motion threshold 0,9mm) and lastly Gaussian smoothing (kernel 8mm full-width at half maximum (FWHM)). For the anatomical data the following steps were preformed: direct normalization of MNI-space and segmentation into grey matter, white matter and CSF. After pre-preprocessing the data was controlled for potential confounding factors, which included: white matter, CSF, realignment, scrubbing and effect of rest. A band-pass filter of 0.008-0.09 Hz was used to denoise the data. In addition, a linear regression was used to estimate and remove confounds. A seed-based functional connectivity analysis was performed for the ROIs mentioned earlier, using the following options: ROI-to-ROI analysis only, bivariate correlation and hrf weighted.

2.5 Statistical analysis

Two independent t-tests have been performed in SPSS (version 27.0.1), to validate the correct grouping of participants in terms of high scores on deliberate mind-wandering and spontaneous mind-wandering. First, the sample has been tested for the assumptions for independent t-tests, i.e. correct scale of measurement, normal distribution, independence of observations and homogeneity of variances. Afterwards two independent t-tests with alpha 0.05 have been performed to check if there was a significant difference between the group classified as scoring high and the rest, for both types of mind-wandering.

For the two demographic variables ‘gender’ and ‘age’, descriptive statistics were generated. In order to check if the groups differ significantly in terms of gender and age, two Chi-square tests with alpha 0.05 have been performed.

Two one-way ANOVA tests have been performed to examine the effect of different types of mind-wandering on the functional connectivity. One ANOVA for each of the two dependent variables, which are the functional connectivity between LIFS and RIPS and the functional connectivity between LIFS and LIPS. The sample has been tested for the assumptions for ANOVA, i.e. correct scale of measurement, normal distribution, independence of observations and homogeneity of variances. In addition, the sample was checked for outliers on the functional connectivity scores. For this outlier analysis the default boundaries have been used, i.e. the first quartile minus three times the interquartile range and the third quartile plus three times the interquartile range. The ANOVA tests have been performed using an alpha of 0.05.

3. Results

Not all assumptions for the independent t-tests were met. For both deliberate and spontaneous mind-wandering, data was not normally distributed. Because of the large sample size, the t-tests are robust against this violation. In addition, for deliberate mind-wandering Levene's test for equality of variances revealed that equal variances could not be assumed. Nevertheless, this did not change the conclusion of the test when looking at the test scores for equal variances not assumed. The independent t-tests confirmed a significant difference between the group with high scores and the rest, for both deliberate mind-wandering ($t_{108.972} = 14.43$, $p < 0.001$, sd = 0.11, CI = 1.35 – 1.78) as well as spontaneous mind-wandering ($t_{109} = 15.86$, $p < 0.001$, sd = 0.10, CI = 1.42 – 1.83). For deliberate mind-wandering, the group with high scores includes 44 participants with an average score of 4.08 (sd = 0.46), the rest group includes 67 participants with an average score of 2.52 (sd = 0.68). For spontaneous mind-wandering, the group with high scores also includes 44 participants with an average score of 3.82 (sd=0.50), the rest group includes 67 participants with an average score of 2.19 (sd = 0.55).

In total 26 participants were classified as scoring high on both types of mind-wandering. Based on these results, three groups were identified for further research in this thesis: People who score high on deliberate mind-wandering (High_D-MW), people who score high on spontaneous mind-wandering (High_S-MW) and people who score high on both types of mind-wandering (High_Both).

For these three groups, descriptive statistics were computed in terms of gender and age. See Table 2 and Table 3. The Chi-square tests revealed no significant difference between the groups for gender nor age.

Table 2.

Distribution of gender per group.

	High_S-MW		**High_D-MW**		**High_Both**		**Total**	
Gender	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Female	9	50%	6	33%	10	38%	25	40%
Male	9	50%	12	67%	16	62%	37	60%
Total	18	100%	18	100%	26	100%	62	100%

Table 3.

Distribution of age (in 5 year intervals) per group.

	High_S-MW		**High_D-MW**		**High_Both**		**Total**	
Age	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
20-25	7	39%	9	50%	10	38%	26	42%
25-30	8	44%	3	17%	11	42%	22	35%
30-35	0	0%	2	11%	2	8%	4	6%
35-40	0	0%	2	11%	2	8%	4	6%
40-45	0	0%	2	11%	1	4%	3	5%
55-60	1	6%	0	0%	0	0%	1	2%
65-70	2	11%	0	0%	0	0%	2	3%
Total	18	100%	18	100%	26	100%	62	100%

Two one-way ANOVA tests have been performed. For both tests, all one-way ANOVA assumptions were met, including Tests of Normality and Levene's Test of Equality of Error Variances. One outlier was detected in functional connectivity between LIFS and LIPS. This participant (sub-010078) was taken out for subsequent tests and analyses. For all three groups, the mean functional connectivity between LIFS and RIPS in the default mode network and LIFS and LIPS in the control network were calculated, see Figure 1 and Figure 2.

Figure 1.

Mean functional connectivity LIFS – RIPS by group, with 95% CI.

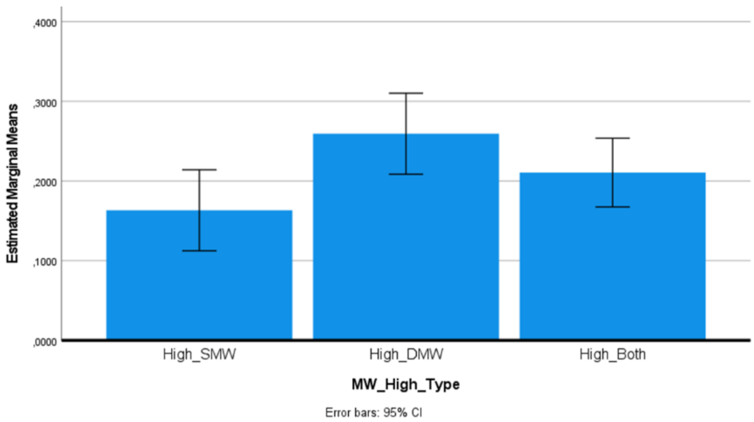
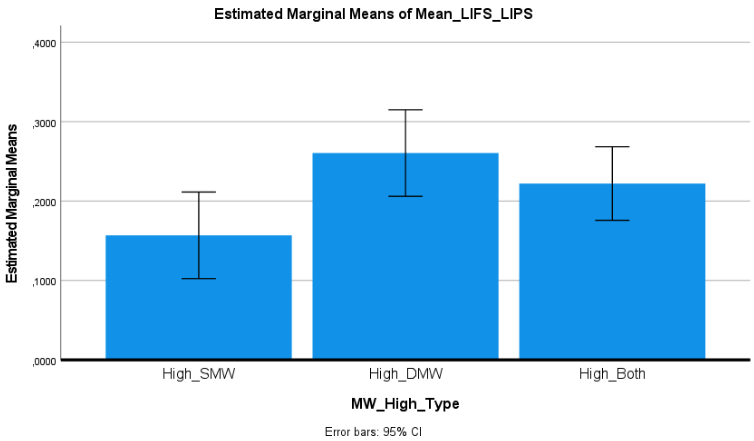


Figure 2.

Mean functional connectivity LIFS – LIPS by group, with 95% CI.



Functional connectivity between LIFS and RIPS

The ANOVA demonstrated that the effect of mind-wandering type was significant for the functional connectivity between LIFS and RIPS ($F(2,58) = 3.58$, $p = 0.03$, $\eta^2 = 0.11$). The group with high scores on deliberate mind-wandering showed a higher connectivity than the group with high scores on spontaneous mind-wandering. The group with high scores on both types of mind-wandering showed a functional connectivity which lies in between the aforementioned groups. The Eta squared shows a medium to strong effect.

Functional connectivity between LIFS and LIPS

For the functional connectivity between LIFS and LIPS, a statistically significant effect of the grouping variable was found too ($F(2,58) = 3.71$, $p = 0.03$, $\eta 2 = 0.11$). The highest connectivity was observed for the group of people with high scores on deliberate mind-wandering. The group of people with high scores on both types of mind-wandering showed a functional connectivity which is lower than the group of high deliberate mind-wandering, though higher than the connectivity observed in the group with high spontaneous mind-wandering. Based on the Eta squared it can be concluded that the effect size is medium to strong.

4. Discussion

This thesis examined functional connectivity in the default mode network and the control network of people with different types of mind-wandering. Although the number of mind-wandering studies has increased in recent decades, little is known about the underlying brain regions involved. Golchert et al. (2017) identified neural correlates of deliberate and spontaneous mind-wandering, though did not contrast these two types of mind-wandering explicitly. Therefore the aim of this thesis was to contribute to a more sound basis about the phenomenon of mind-wandering, by investigation differences in functional connectivity between deliberate mind-wandering and spontaneous mind-wandering. The central research question was formulated as follows: ‘Is there a difference in functional connectivity between people who score high on deliberated mind-wandering and people who score high on spontaneous mind-wandering?’. Based on earlier studies, the hypothesis was that people with high scores on deliberate mind-wandering would show more functional connectivity in the default mode network and the control network than people with high scores on spontaneous mind-wandering.

Resting-state fMRI data has been analyzed, focusing on the functional connectivity between ROIs in the aforementioned two large-scale networks. Based on research from Golchert et al. (2017), three specific ROIs were selected: the left inferior frontal sulcus (LIFS), the left intraparietal sulcus (LIPS) and the right intraparietal sulcus (RIPS). Connectivity between the LIFS and RIPS is related to the default-mode network, connectivity between the LIFS and LIPS is related to the control network.

Statistical analyses revealed significant differences in functional connectivity between people with high self-reported scores on deliberate mind-wandering and people with high self-reported scores on spontaneous mind-wandering, both in the default mode network and the control network. More specifically, people with high scores on deliberate mind-wandering had a higher functional connectivity between LIFS and RIPS (overlapping with the default mode network) and between LIFS and LIPS (overlapping with the control network). The findings reported in this thesis provide evidence which is in line with earlier research by Christoff et al. (2016) and Seli et al. (2016), which showed that executive control is important to constrain cognition in such a way that inner experiences unfold more deliberately. Moreover, the beneficial results for deliberate mind-wandering in this study are consistent with earlier studies that suggest that deliberate mind-wandering is associated with beneficial traits that may have a positive effect on beliefs and attitudes (Agnoli, Vannucci, Pelagatti, & Corazza, 2018; Marcusson-clavertz & Kjell, 2019; Vannucci & Chiorri, 2018). Intriguingly, the differences between the group with high self-reported spontaneous mind-wandering and high-self reported deliberate mind-wandering were almost identical for the functional connectivity in both networks (DMN and FPN). This thesis strengthens the research on mind-wandering intentionality and functional connectivity, by providing neurological evidence for a significant difference in functional connectivity between spontaneous mind-wandering and deliberate mind-wandering.

The results should be considered in light of a number of limitations of this study. First, since this study focused on the comparison between people which score high on mind-wandering, thereby excluding participants with low scores, the original sample size was reduced. The results, which reveal significant effects, therefore should be interpreted with caution. Second, the resting-state fMRI data showed that participants can have high self-reported scores on both types of mind-wandering. Hence, a third group was added in addition to people who score high on deliberate mind-wandering and people who score high on spontaneous mind-wandering, namely those who score high on both. Their functional connectivity scores were in between the groups of people who score high on one of the mind-wandering types. In other words, the findings show differences across people who differ in the relative levels of deliberation which they experienced and reported during mind-wandering, at the trait-level. To better contrast the two types of mind-wandering, further research could explicitly focus on objective time series analysis and state-related changes, in which participants are engaged in spontaneous mind-wandering and deliberate mind-wandering over time. This is in line with recommendations for further research as shared by Golchert et al. (2017). Third, this study investigated only one functional connectivity combination between ROIs for each of the two large-scale networks. More extensive analysis of various connectivity combinations within the default mode network and control network could offer additional support, alternative insights or more sophisticated explanations. Fourth, the two large-scale networks explored in this thesis are typically related to deliberate mind-wandering (Golchert et al., 2017). In order to further investigate potential higher functional connectivity for people with spontaneous mind-wandering, regions within the limbic network shall be investigated. Research by Golchert et al. (2017) namely implicated greater involvement of the limbic network in spontaneous mind-wandering. In addition, the medial temporal lobe may play an important role initiating spontaneous mind-wandering (Smallwood, 2013).

In conclusion, this thesis offers neurocognitive evidence of differences in functional connectivity between people with different intentions of mind-wandering. Using resting-state fMRI, this study showed that deliberate mind-wandering is associated with higher functional connectivity in the default mode network and control network in comparison to spontaneous mind-wandering. Further research is recommended in order to solidify the preliminary findings and to examine additional dimensions related to the interesting concept of mind-wandering.

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