THE ACTIVATION OF DEFAULT MODE AND MULTIPLE DEMAND NETWORKS: AN FMRI STUDY ON INTENTIONAL AND UNINTENTIONAL MIND WANDERING

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Shahrzad Falahat

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The Activation of Default Mode and Multiple Demand Networks: An fMRI Study on Intentional and Unintentional Mind Wandering
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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Ausaf Ahmed Farooqui(Advisor)

Zahide Pamir Karatok

Buse Merve Ürgen

Approved for the Graduate School of Engineering and Science:

Orhan Arıkan
Director of the Graduate School

ABSTRACT

THE ACTIVATION OF DEFAULT MODE AND MULTIPLE DEMAND NETWORKS: AN FMRI STUDY ON INTENTIONAL AND UNINTENTIONAL MIND WANDERING

Shahrzad Falahat
M.S. in Neuroscience
Advisor: Ausaf Ahmed Farooqui
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Mind wandering or task-unrelated, self-generated thoughts happen every day in life. These thoughts can either be Unintentional or Intentional. The brain's Default Mode (DMN) and Multiple Demand (MD) networks integrate during Mind Wandering. In this study, we conducted a functional magnetic resonance imaging (fMRI) experiment where Mind Wandering was the task. During this task's think part, an Intentional form of Mind Wandering occurred. Meanwhile, Unintentional Mind Wandering took place during the rest part where participants rested in the fMRI machine. We aimed to see the difference in the pattern of activity in both the Default Mode and Multiple Demand Networks during the Intentional and Unintentional Mind Wandering.

Our results showed that, in the Posterior Cingulate Cortex (PCC) and the left Temporoparietal Junction (TPJ) regions of the Default Mode Network, the think part provokes a stronger response than the rest part. On the other hand, the Multiple Demand network regions responded differently to the different forms of Mind Wandering. Some Multiple Demand regions, such as the left Inferior Frontal Sulcus (IFS) and the pre-Supplementary Motor Area (pre-SMA), represented a more robust response in the think part than the rest part. Meanwhile, the bilateral Intraparietal Sulcus (IPS) regions showed stronger activation in response to the rest part. In addition, we showed that the Language regions have a more pronounced activation in the think part than the rest part. Consequently, the Default Mode Network's regions, some of the Multiple Demand regions, and Language regions respond more robustly to the Intentional form of Mind Wandering than the Unintentional Mind Wandering.

Keywords: Intentional Mind Wandering, Unintentional Mind Wandering, functional magnetic resonance imaging (fMRI), Multiple Demand network (MD), Default mode network (DMN), Language regions.

ÖZET

VARSAYILAN MOD VE ÇOKLU TALEP AĞLARININ AKTİVASYONU: İSTEMLİ VE İSTEMSİZ ZİHİN GEZİNTİSİ ÜZERİNE BİR FMRI ÇALIŞMASI

Shahrzad Falahat
Nörobilim, Yüksek Lisans
Tez Danışmanı: Ausaf Ahmed Farooqui
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Zihin yolculuğu veya bir amaca hizmet etmeyen, kendi kendine üretilen düşünceler hayatta her zaman meydana gelir. Bu düşünceler istemli veya istemsiz olabilir. Beynin Varsayılan Mod (VMA) ve Çoklu Talep (ÇT) ağları zihin yolculuğu sırasında birbirleriyle entegre olurlar. Bu çalışmada, zihin yolculuğu görevi içeren bir fMRI deneyi gerçekleştirdik. Bu görevin düşünme kısmı istemli bir zihin yolculuğundan oluştu. Aynı zamanda, katılımcıların fMRI makinesinde dinlendiği kısım boyunca istemsiz zihin yolculuğu gerçekleşti. Amacımız, Varsayılan Mod ve Çoklu Talep ağlarının istemli ve istemsiz zihin yolculuğu sırasındaki etkinlik örüntüleri arasındaki farkı görmekti.

Sonuçlarımıza göre, Varsayılan Mod Ağı'nın Posterior Cingulate Cortex (PCC) ve sol Temporoparietal Junction (TPJ) bölgeleri, düşünme kısmında dinlenme kısmına göre daha güçlü bir tepki gösterdi. Öte yandan, Çoklu Talep ağı bölgeleri farklı zihin yolculuğu biçimlerine farklı tepkiler verdi. Sol Inferior Frontal Sulcus (IFS) ve pre-Supplementary Motor Area (pre-SMA) gibi bazı Çoklu Talep bölgeleri, düşünme kısmında dinlenme kısmına göre daha güçlü bir yanıt gösterdi. Bu arada, çift taraflı Intraparietal Sulcus (IPS) bölgeleri, dinlenme kısmına daha güçlü bir şekilde tepki gösterdi. Ayrıca, dil bölgelerinin düşünme kısmında dinlenme kısmına göre daha belirgin bir aktivasyona sahip olduğunu gösterdik. Sonuç olarak, Varsayılan Mod Ağı'nın bölgeleri, bazı Çoklu Talep bölgeleri ve dil bölgeleri, istemli zihin yolculuğuna istemsiz zihin yolculuğuna göre daha güçlü bir şekilde tepki veriyor.

Anahtar sözcükler: İstemli zihin yolculuğu, İstemsiz zihin yolculuğu, Fonksiyonel Manyetik Rezonans Görüntüleme, Çoklu Talep ağı(ÇT), Varsayılan Mod

Ağı (VMA), Dil bölgeleri.

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Chapter 1

Introduction

1.1 Mind Wandering

While we must focus on different tasks during everyday activities, sometimes we find ourselves drowning in self-produced thoughts unrelated to these tasks, and one thought leads to another. This situation is called mind-wandering, stimulus-independent thoughts, or task-unrelated thoughts [1] [2]. It can be defined as a shift of attention from external tasks to internal personal thoughts [3]. People usually try to avoid mind wandering when they need to focus on a task. Nevertheless, it happens frequently. On the other hand, when people start to rest and are not involved in a task with cognitive load, they usually wander their minds freely [3].

1.1.1 Intentinal versus unintentional mind wandering

Generally, research defines mind-wandering as unwanted thoughts that occur unintentionally or spontaneously. However, researchers from decades ago have distinguished between intentional and unintentional mind-wandering [4]. Unintentional or spontaneous mind wandering occurs despite people's tendency to focus

on a task without meta-awareness, while intentional or deliberate mind wandering occurs when people deliberately mind-wander freely and avoid external stimuli. For example, when participants are involved in a boring or tedious task, they prefer to occupy their minds with other thoughts. Regarding this, a study found that the amount of intentional mind wandering increases during an easy task compared to a difficult one [5]. Therefore, it was suggested that these regions adjust the amount of mind wandering during a task's easy and difficult conditions. Furthermore, sometimes, when people want to develop a new idea to solve a problem, they deliberately focus on their internal thoughts [6] [7]. Evidence suggests that these two types of mind wandering lead to separate brain and body responses. For instance, spontaneous mind wandering leads to unwanted movements in the body, while intentional mind wandering does not have such an effect [8]. Moreover, a study indicated that the 'non-reactivity to inner experience' factor in the Five Facet Mindfulness Questionnaire (FFMQ) correlates highly with intentional mind wandering [9]. Meanwhile, it negatively correlates with unintentional mind wandering. The differences in brain activities between these two types of mind wandering were also investigated in this fMRI study [6]. The findings revealed individual differences between cortical thickness and functional connectivity between different regions during intentional or unintentional mind wandering. For instance, they found increased functional connectivity between the right IPS and medial temporal lobe during unintentional mind wandering. Hence, even though these two types of mind wandering are highly correlated with each other, they have different brain mechanisms responsible for their occurrence.

1.1.2 Brain regions associated with mind wandering

Default Mode Network (DMN)

Lots of researchers have been investigating mind wandering and regions of the brain that are associated with it [10] [11] [6]. Among them, the most interrelated one is the default mode network (DMN). Generally, the activity of DMN regions in the brain tends to decrease during external tasks [10] and increase during various internal tasks such as self-referential thoughts [12]. The reason behind reduced activity during tasks is that when attentional sources are needed somewhere else, less remains for internal thoughts [10]. In this situation, the prefrontal region usually suppresses the DMN activation during the cognitive task and reduces it [13]. A study reported that participants who reported mind wandering more frequently during a cognitive task had stronger activation in the DMN [14]. Meanwhile, when stimulus-independent thoughts did not occur, there was no DMN activation during the task. Moreover, DMN activation and mind-wandering levels were higher in well-practiced task conditions than in novel and demanding task conditions. On the other hand, reduced activity in DMN leads to better cognitive performance on tasks [15]. These are because mind wandering and executive functions rely on the same attentional sources [16]. Hence, when attention is devoted to one of them, the other gets impaired. In situations where the cognitive task is well-practiced and is done automatically, more attentional sources are left for mind wandering, so it occurs more frequently. It is worth mentioning that these stimulus-independent thoughts benefit humans since they lead to a coherent sense of time [17] [18]. Due to these thoughts, people can time travel between past, present, and future events in their minds.

Multiple Demand and Default Mode network's coorporation

Studies have shown that besides the DMN, the Multiple Demand (MD) network is also required for the occurrence of mind-wandering [19]. In various studies, both these networks have shown higher activation during mind wandering [20] [21] [22] [9]. Studies have shown that during mind wandering, primary sensory cortices are not getting information from the external environment, and response

in these cortices decreases during mind wandering [23]. This occurs mainly because the Default Mode and Multiple Demand networks suppress the activation in these sensory cortices [24].

Language regions

The correlation between language and mind wandering was investigated in a study [25]. It revealed that inner speech plays a significant role in awareness of one's mind wandering. This study also demonstrated a positive correlation between the clarity of thoughts and the awareness level of mind wandering. Participants showed reduced awareness of mind wandering when the verbal working memory was inhibited. Conversely, when the activation of verbal working memory was enhanced, the awareness of mind wandering also increased. Furthermore, In an fMRI study, it was asserted that when participants were engaged in a non-linguistic task, they exhibited greater brain activation during periods of rest when they typically experienced mind wandering, as opposed to when they were actively performing the task [26].

1.2 Default Mode Network (DMN)

Neuroimaging findings from the last few decades revealed that the default mode network (DMN) is a network in the brain that decreases its activation during a wide range of cognitive tasks requiring external attention [27] [10]. This reduced activation corresponds to a decrease in the BOLD signal or blood flow in the regions of this network [27]. When the association between DMN regions strengthens, we observe less engagement in environmental stimuli [28]. On the other hand, DMN activation is associated with task-independent self-relevant, spontaneous thoughts, or mind wandering, which mainly occur during the rest [13]. When attention gets impaired due to task-independent thoughts, the DMN activation rises and disrupts the goal-directed behavior [29].

Moreover, evidence suggests faster and more accurate responses during the task when the DMN activation decreases before a stimulus presentation [30]. Generally, diminished DMN activity leads to enhanced cognitive abilities across different tasks [15]. Hence, when the brain is at rest, a systematic operation gets impaired during goal-oriented external tasks [31].

1.2.1 Regions of the Default Mode Network (DMN)

The regions in the DMN represent the same response pattern during different conditions. For instance, the BOLD activation in all these regions tends to be lower when participants are engaged in external tasks [27]. However, these regions also have a separate role in cognitive functions.

The anterior Prefrontal Cortex (aPFC)

Previous studies have demonstrated that the aPFC region is involved in self-referential processes and self-awareness [32]. It is well known that the self-referential processes are disrupted in participants with Autism Spectrum Disorder (ASD). Based on the neuroimaging results, the connectivity of the aPFC

region with other regions of the default mode network gets disrupted in people with Autism Spectrum Disorder (ASD). In addition, the connectivity of the DMN with other brain regions, such as the fusiform gyrus or somatomotor cortex, is corrupted in these people. Other studies have shown that the connectivity of this region with the anterior insula results in self-perception of body sensations. This mainly occurs because the aPFC region's activation leads to information integration from memory storage and external sensory inputs. The memory-related information is projected from the posterior cingulate cortex (PCC) to the aPFC, while the sensory inputs come from the anterior insula to this region [33].

The medial Prefrontal Cortex(mPFC)

Evidence suggests that the Orbitofrontal cortex serves as a pathway for sensory information, forwarding it to the ventromedial prefrontal cortex (VMPC) [34]. In turn, this region relays this information to various parts of the midbrain. Additionally, the default mode network (DMN) enhances motor task performance by promoting heightened activity in the medial prefrontal cortex (mPFC) [35]. On the other hand, emotional states such as anxiety have been found to impact the functioning of the ventromedial prefrontal cortex (VMPC) [36]. Furthermore, neuroimaging findings revealed that damage to the VMPC region can lead to deficits in social behavior [37]. Meanwhile, the dorsal part of the medial Prefrontal Cortex(dMPFC) participates in evaluating oneself and engaging in internal thoughts [38].

The Posterior Cingulate Cortex (PCC)

Previous research discovered that although the PCC region deactivates during complex feature-matching decision-making, it exhibits stronger functional connectivity with the left dorsolateral prefrontal region of the multiple-demand network [39]. This connectivity remains consistent during rest periods and enhances participants' performance when they engage in semantic tasks. This cooperative interaction between these two regions is also crucial for anticipating and preparing future events and actions [40] [41]. Furthermore, other studies have indicated that the medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC) regions play a role in integrating cognitive and emotional information for decision-making that is relevant to oneself [10] [37] [42] [38].

Temporoparietal Junction (TPJ)

Findings demonstrate that the left Temporoparietal Junction (TPJ) region shows less activation during mind wandering while it increases its neural activation during mindful attention [43]. This region is also involved in social understanding. The increased connectivity between the TPJ and dmPFC leads to understanding other people's mindsets. Overall, the temporoparietal junction's activation contributes to redirecting attention to other people and understanding their emotions [44].

1.2.2 The Default Mode Network's roles in the brain

Mind Wandering:

Mind wandering is strongly associated with increased default mode network (DMN) activity [14]. The mind can wander spontaneously or on purpose, particularly when the brain is at rest [4]. Meanwhile, when the mind is involved in a task, it might wander unwillingly and think about task-independent subjects. Based on a study, participants who reported more frequent mind wandering during a cognitive task exhibited higher DMN activity [14]. Conversely, no DMN

activation was observed when stimulus-independent thoughts were absent during the task. Additionally, DMN activation and mind-wandering levels were higher in well-practiced task conditions than in novel task conditions. In another study investigating DMN activation during mindfulness attention, it was found that certain DMN regions, such as the medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC), show reduced activation during internal or external mindful attention compared to situations involving the mind wandering [43].

Working Memory:

Activation of the default mode network (DMN) is associated with a comprehensive experience during working memory tasks [45]. Prior research indicated that the DMN is involved in the specificity and details of memory retrieval during working memory tasks [46] [47]. Meanwhile, the DMN and working memory positively correlate during retrieval and coding phases, while an inverse relationship is observed during the maintenance phase [48]. Several studies have demonstrated that the involvement of cingulate regions within the DMN can indicate successful working memory performance [49]. Activation in the anterior cingulate cortex (ACC) and the medial prefrontal cortex (mPFC) predicts the accuracy of working memory tasks, with more deactivation in the mPFC and less deactivation in the ACC. These regions have been shown to influence attentional focus and working memory processes. Overall, the DMN rearranges its regions in response to increased cognitive demands [50].

Light Sleep:

Earlier investigations revealed that the default mode network (DMN) remains active and functionally connected during light sleep [51]. This network, which monitors the environment, conscious awareness, and information processing, is traditionally associated with wakeful rest. However, it was reported that the DMN continues to exhibit correlated brain activity even during reduced levels of consciousness which is a characteristic of light sleep. This suggests that DMN activity is not dependent on wakefulness and can persist during sleep. The presence of correlated fluctuations in the DMN during sleep supports its role in cognitive

processes and suggests that its functioning is not limited to wakefulness. Another study revealed that contrary to the expectation of decreased connectivity as the brain disconnects from the external world, there were minimal changes in functional connectivity in sensory and cognitive networks during early non-rapid eye movement (NREM) sleep [52]. The DMN, associated with subjective awareness, showed no measurable change in connectivity during the transition to sleep; Only the dorsal attention network exhibited increased connectivity during sleep. These findings suggest that functional connectivity remains intact across different arousal levels, including sleep and anesthesia.

Language:

Previous studies have shown that while the multiple demand network (MD) response is associated with meaningful words, DMN activation is associated with nonwords [53]. Meanwhile, a recent study demonstrated that the DMN is engaged in processing semantic information and evaluating the imaginability of words [54]. This suggests that the default mode network can employ semantic information to categorize words as imaginable or unimaginable. Another study revealed a strong association between semantic memory and the default mode network (DMN) regarding both spatial and functional aspects [55]. Specifically, when participants were involved in tasks requiring semantic processing, less deactivation was observed within the DMN compared to tasks involving non-semantic phonological and perceptual processes. This reduction in deactivation primarily occurs in the association cortices of the left hemisphere, suggesting a convergence of functions in these regions during both resting and task-related activities. These identified regions align with those involved in both bottom-up and top-down semantic retrieval during language processing.

Autobiographical memory retrieval and Planning:

The default mode network activates during cognitive functions such as remembering the past event, conceptualizing future scenarios, and imagining fictional events that are currently taking place [56] [57] [58] [59] [58]. These functions mainly rely on retrieving information about people and objects from episodic memory. Therefore, sensory inputs don't participate in these functions.

Divergent thinking:

Divergent thinking includes creating novel ideas with cognitive flexibility and looking for uncommon solutions. The default mode network is important for divergent thinking [60]. Evidence demonstrated that this network contributes to the unplanned and non-linear aspect of divergent thinking. These two functions are important for creative and novel problem-solving. Neuroimaging studies suggest that some regions in the DMN, including the anterior medial prefrontal cortex (aMFC) and posterior cingulate cortex (PCC), show higher activation when participants tell creative stories in a task [61]. These findings highlight the association of DMN with promoting creative or imaginative thinking.

Error Anticipation:

Evidence suggests that the activation of the default mode network is correlated with predicting errors [62]. Based on a study, when a surprising event occurs during a naturalistic film viewing, the DMN regions coactivate with the hippocampus and nucleus accumbens (NAcc). This network participates in updating the prediction of errors, recognizing the mismatches between expected and incoming information, and integrating the incoming information with previous knowledge in memory.

Decision Making:

According to previous research, the default mode network (DMN) exhibits increased activation when individuals make decisions based on past experiences but reduced activation when they make choices based on current circumstances

[57]. This finding supports the notion that individuals rely more on internal mental processes than immediate sensory inputs during decision-making. Other findings suggested that the DMN becomes active in decision-making tasks because of its involvement in internal cognitive processes rather than immediate sensory inputs.

Integration of Information:

The rich-club organization is a neural network in the human brain with highly connected regions that create a tightly interconnected core [63]. These regions consist of bilateral frontoparietal and subcortical regions. This organization is considered a central hub for communication between various regions in the entire brain and enables the coordination and integration of different functional units. Damages to this organization lead to a great disruption in global communication in the brain. Evidence revealed that this club overlaps with the default mode network. However, it extends to other networks as well [63]. This overlap verifies the role of the default mode network in integrating and processing information [64] [65].

1.2.3 Neural hierarchy in the brain

Brain areas can be separated into unimodal and multimodal regions. Unimodal regions involve sensory-motor regions that perceive basic information about objects. Multimodal regions are the ones that integrate this information and lead to perceiving complex features and abstract thinking [66]. DMN is one of these regions managed by memory instead of sensory inputs [28]. Several studies indicated that these regions are far from sensory input regions locationally and functionally [67] [68] [69]. The frontoparietal network separates inner thoughts from environmental inputs and keeps a balance between them [70] [71]]. DMN enhances goal-directed performance via its connectivity to the frontoparietal network [41]. Meanwhile, DMN's interaction with hierarchically lower regions leads to comprehensive cognitive presentation [45].

Intrinsic connectivity networks (ICNs) consist of several networks, such as default mode, frontoparietal, and language networks. These networks can activate according to task requirements [41] [71] [72]. The DMN is the intersection of neural signals from other ICN networks among these regions [64]. It is responsible for integrating and processing information, which leads to cognition. Research has shown that the PCC region of the DMN facilitates communication between different areas. Meanwhile, Ventral and dorsal PCC respond differently to task demands. Dorsal PCC increases its connectivity to DMN in more difficult tasks, leading to increased functional integration. While ventral PCC reduces connectivity, it contributes to changing the focus of attention to external tasks and holding internal thoughts back [73]. Consequently, the default mode network consumes the highest amounts of energy in the cortex and has many connections with other regions [27] [74].

1.2.4 DMN and related disorders

Neuropsychiatric disorders

Neuropsychiatric conditions such as schizophrenia change DMN activity and connectivity between its regions [75]. Patients with schizophrenia exhibited higher frequency oscillations in the default mode than healthy individuals. This might indicate the potential impaired communication between the DMN and other brain regions. Moreover, positive symptom severity was correlated with several DMN regions, including the middle temporal gyrus, medial frontal gyrus, and left posterior cingulate cortex. In addition, patients with schizophrenia and their relatives displayed abnormal functioning of the DMN, characterized by hyperactivation of the medial prefrontal cortex (MPFC) and hyperconnectivity within this network [76]. This suggests a genetic basis for these abnormalities. The findings suggest that hyperactivation and hyperconnectivity of the default network contribute to the cognitive and clinical symptoms of schizophrenia and may eliminate the boundary between internal thoughts and external perceptions.

Traumatic brain injury (TBI)

Evidence indicates that Traumatic brain injury (TBI) can lead to abnormalities in the default mode network (DMN), specifically in the posterior cingulate cortex (PCC) [77]. This disruption in the DMN is associated with cognitive impairments, particularly in sustained attention and the ability to switch from automatic responses to controlled ones. Reduced metabolism within the PCC and structural damage to the cingulum bundles connecting the PCC to other parts of the DMN contribute to these impairments. Furthermore, the failure to control PCC/DMN activity is linked to attentional lapses, which can result from damage to the salience network. Interactions between the salience network and the DMN play a role in rapidly allocating attentional resources. Consequently, damage to the DMN and its connections in TBI patients can lead to cognitive deficits and attentional lapses.

ADHD:

Previous studies reveal that in children with Attention-deficit/hyperactivity disorder (ADHD), the default mode network (DMN) deactivation decreases when they perform a task that demands inhibitory control [78]. Factors such as methylphenidate medication or motivational rewards result in normalized deactivation of the DMN in these children. The threshold for motivation or task importance is higher in children with AHDH than the typical ones. Hence, the reason behind the inability of inhibitory control in ADHD children might be the lack of deactivation in DMN.

1.2.5 DMN activation during on-task condition

Some recent research indicates that the default-mode network (DMN) exhibits increased connectivity with task-positive regions during cognitively demanding tasks, contrary to the previous belief that DMN deactivates during such tasks [79] [39]. In fact, instead of deactivation, the DMN reconfigures its arrangement [79]. Several studies have also shown DMN's activation during cognitive demands

[80] [81] [82] [83], including language comprehension tasks [81]. The medial dorsal prefrontal cortex from this network has been found to contribute to faster task performance by directing attention to external tasks rather than internal thoughts [35]. Additionally, the anterior parts of the DMN exhibit lower activation during rest compared to the task condition [80]. Furthermore, some findings revealed that the DMN's activity increases during faster behavioral responses to external sensory inputs. Meanwhile, it is independent of that inputs [84]. Consequently, extrinsic or intrinsic changes may influence DMN activity in various cognitive conditions [83] [85]. Nevertheless, since most studies have shed light on the importance of DMN during off-task conditions, we will rely on them in this study.

1.3 Multiple Demand network (MD)

During the past few decades, researchers have found a correlation between various cognitive task demands and activation of a set of brain regions [86]. These regions create a network called the multiple-demand (MD) or task control[87] or central executive network [88]. The multiple-demand network activates during a wide range of cognitive tasks, such as executive functions, problem-solving, and choosing a response. Even minor damages to these regions lead to disruption in many tasks [89] [90]. Generally, activation in MD regions gets stronger as the task requires extra demands such as timing pressure and complexity [91]. Based on the adaptive coding theory, MD network's regions code various characteristics of cognitive tasks and regulate their activity based on these features and demands swiftly [92]. Hence, as these demands increase, multiple demand regions represent a stronger activation [93] [94]. Generally, the MD network integrates and synchronizes information to do the cognitive task [95]. This network is connected to various brain regions and has been shown to adjust its activity based on these cognitive tasks [92].

1.3.1 The Multiple Demand Network's regions

Multiple demand regions are mainly located in the frontoparietal lobe of the brain. All of these regions show increased activation during external cognitive tasks as a network. Nevertheless, each has a different role in cognitive processes.

Inferior Frontal Sulcus (IFS)

Previous findings suggest that the right Inferior Frontal Sulcus (IFS) is important for verbal guidance. This region shows a more significant response in situations where participants try to apply what they recently learned instead of memorizing the items only. In addition, the IFS is vital for editing task sets and protecting the essential rules from disruption. Therefore, this region is important for generating proper responses for future tasks [96]. Another important study

revealed the role of IFS in hierarchical structures in a sentence. This is due to the function of IFS in the verbal form of working memory. The left IFS is important for dedicating working memory resources to syntactic processing when the sentence is complex [97].

The pre-Supplementary Motor Area (pre-SMA)

Based on previous studies, the pre-SMA (pre-supplementary motor area) plays a role in response inhibition. It regulates motor behaviors and contributes to choosing a proper response. In short, it promotes goal-directed behavior by combining sensory information from the bottom-up and incentive information from top-down resources [98]. Another research claims that this region activates when participants encounter a conflict in information. The higher levels of conflict provoke a more intense response in pre-SMA region [99].

The Intraparietal Sulcus (IPS)

Evidence suggests that the Intraparietal Sulcus (IPS) regulates arm and eye movement by involving attentional and visuomotor mechanisms. This role of the Intraparietal Sulcus (IPS) is consistent with other species as well [100]. Furthermore, the activations in this region affect cognitive functions such as spatial orientation. Neuroimaging findings revealed that some frontal and parietal cortex regions, including IPS, activate during the reorientation of visuospatial attention [101]. A study investigated the effect of the IPS region in processing task-related information. It showed that when the functional connectivity between the ventral and occipital regions of the temporal lobe increases, the memory load also increases. The IPS has been shown to modulate this functional connectivity during various tasks [102].

The Anterior Cingulate Cortex (ACC)

An important study demonstrated the crucial role of the anterior cingulate cortex (ACC) in decision-making processes, as well as error detection during cognitive tasks [103]. Another study further supported this finding, establishing a connection between the left anterior cingulate cortex and conflict monitoring

in tasks driven by specific goals [104]. Neuroimaging evidence revealed that this region shows more robust activation during the concrete semantic processing compared to the abstract one [105].

1.3.2 The Multiple Demand's Roles in Cognition

Even though each of the Multiple Demand network's regions has a specific role in cognitive processes, they coactivate and cause integrated responses toward stimuli [91].

Conflict Discrimination:

Conflict discrimination refers to the ability to recognize and solve conflicting information during a task. During these kinds of tasks, participants need to choose between several responses. These responses are usually contradictory, and participants must recognize them as accurately as possible. A good example of this task is the Stroop effect task. When participants discriminate between conflicts, the multiple demand regions show great activation [86]. This role of the multiple demand network in conflict discrimination reflects its participation in response inhibition and error monitoring as well. This network enables participants to make the right choices during conflicting situations [86].

Task Familiarity:

Previous findings suggest that the multiple-demand network's activation is associated with task familiarity [86]. It regulates the coding of task-relevant information based on the demands of a task. According to the adaptive coding hypothesis, the multiple-demand network represents the task-relevant information in a way that responds to task demands [106]. For instance, when the task becomes more challenging, the multiple-demand network increases the amount of the coding of task-relevant information while in the visual cortex, the amount of this coding decreases. This flexibility arises during alternating periods of high

and low perceptual challenges. When the task is well-practiced, the multiple-demand network reduces its activation, but its resources get dispersed, and the coding of task-relevant information disappears. These results indicate that the multiple-demand network is a flexible system essential for goal-directed behavior by adaptively representing task-relevant information.

The Monitoring Phase in Working Memory:

The monitoring phase in working memory requires the multiple demand network for cognitive control, maintenance of representations, updating and manipulation of information, and attentional allocation. The activation of this network results in more accurate and adaptive usage of information during the monitoring phase [86] [107]. Moreover, a study explored how the multiple-demand network is related to executive abilities and fluid intelligence [108]. The researchers examined the activity of the MD network in a large group of participants and its correlation with performance on a spatial working memory task. The study revealed a positive correlation between the activation level in the MD network and performance on the spatial working memory task. They conclude that there is a significant correlation between the activation level in the multiple-demand network and the performance of working memory tasks. Moreover, they found that the multiple-demand network tends to have greater activation during more challenging tasks. This shows that multiple-demand network activation is related to better and faster performance during a working memory task.

Fluid Intelligence:

Several studies revealed that the multiple demand network's activity is correlated to fluid intelligence [109]. Neuroimaging evidence suggests that extensive damage to MD regions leads to disrupted fluid intelligence. The role of the multiple demand network in fluid intelligence was also supported by an article that studied the differences between the MD region and language region's lesions in affecting fluid intelligence [110]. They found that while MD's activation influence fluid intelligence, language regions have no impact on it.

Cognitive Control:

Control regions in the brain affect how different processes are done and ensure they are done properly [111]. The multiple demand regions should operate during several stages, such as initiating and continuing a task and detecting unexpected errors [112]. Brain imaging studies have found that the multiple demand regions are associated with these cognitive controls in different kinds of cognitive tasks. Furthermore, the MD regions interact with other control systems, namely the cingulo-opercular and the frontoparietal systems, during the cognitive control.

Attention:

Based on the theories of attention, different brain networks compete for attention, and when attention is devoted to one of them, the activity of the other one gets disrupted [113]. Several research shows that MD might be important for top-down attentional control and directing the focus of attention toward external stimuli [113] [114] [115]. Studies have found that MD regions adjust their activity to the task difficulty. This is mainly because when a task becomes more complicated, the MD region needs to respond to these demands by changing the focus of attention to integrating helpful information for doing the complex task [95] [116]. Moreover, the multiple-demand network participates in visual attention, which involves selecting and prioritizing relevant visual stimuli for processing while filtering out irrelevant or distracting information. By coordinating and regulating attentional processes, the multiple-demand network helps individuals selectively attend to relevant visual information and adaptively allocate attention based on task demands and goals [86].

Categorizing Information:

Perceptual categorization occurs when similar-looking stimuli from different categories are treated differently, while distinct stimuli within the same category are treated similarly. A previous study on monkeys used a morphing system to generate stimuli spanning two categories (cats and dogs) and precisely define the category boundary citefreedman2001categorical. Monkeys participated in a task

where they needed to determine whether a sample and test stimulus belonged to the same category or not. The findings suggest that the activation of multiple demand regions varied significantly when the two categories were dissimilar. In contrast, the activation remained the same inside each category. These findings suggest that the multiple-demand network is affected by learning and is important for the perceptual categorizing of information.

Language:

While numerous researchers have provided evidence that language and the multiple demand network are distinct networks [117], it has been revealed that the multiple demand network's activation is associated with language perception [118]. Based on previous findings, impairments to regions within the multiple-demand network create significant perceptual difficulties for participants. These individuals were unable to perceive words when the accompanying sound was ambiguous. Conversely, damage to language regions in these participants led to challenges in comprehending the meaning of words, often referred to as semantic difficulties. A different study indicated regions associated with multiple demands (MD) exhibit stronger activation when a sentence is easily comprehensible than when it is not [119]. Additionally, individual words elicit greater activation in MD regions than words within a sentence structure. Conversely, language regions demonstrate an opposite response pattern, showing increased activation for complete sentences. Therefore, it can be inferred that the activation of MD regions during language processing is likely attributed to their involvement in cognitive demands . The multiple-demand network plays a role in vocabulary learning [120]. Vocabulary learning includes obtaining, storing, and retrieving words and their meanings from memory. Increased activities in this network cause better performance in vocabulary learning. The activation of this network is important due to its involvement in working memory, cognitive control, and semantic processing. In fact, the multiple-demand network dedicates the attentional sources to vocabulary learning.

An fMRI study revealed that bilingual individuals display stronger neural responses in multiple demands (MD) regions when they engage in various cognitive

tasks, such as spatial working memory, compared to monolingual individuals [121]. Additionally, bilingual participants exhibited more significant differences in brain activity between low and high cognitive loads during the tasks. These findings suggest that bilingual people might have better cognitive abilities than monolinguals. Another important research on Broca's region separated it into two different subregions: one of them activates during language processing. At the same time, the other one might be a part of the MD network and respond to various cognitive tasks. These two regions were side by side in different individuals [122]. Generally, these findings indicate that the MD and language regions are highly correlated.

1.4 Anticorrelated networks in the Brain

During the past few decades, many researchers have found that our brain can be divided into two anticorrelated networks: The default mode and the multiple-demand network [123] [124]. Previous findings revealed that the multiple demand network shows a stronger BOLD activation during a cognitive task, while the default mode network reduces its activity [49]. In contrast, when the brain is at rest, the multiple-demand network decreases its activity, while the default mode network has a more robust activation. Therefore, the default mode network is a task-negative network, while the multiple demand network is a task-positive network [49]. The default mode network can also be called intrinsic since it activates during self-generated thoughts or internal awareness [125]. On the other hand, the multiple-demand network could be called the extrinsic network due to its activity during external tasks or external awareness [126]. Generally, increased activity in each of these networks suppresses the activity in the other one. Previous research has shown that stronger activations in multiple demand networks during a working memory task reduce DMN activation. This mainly occurs because, during cognitive control, the attentional sources get devoted to multiple demand regions [127] [128]. These regions might contribute to executive performance by suppressing DMN activities. A study indicated that DMN activation leads to disrupted cognitive performance and more appearance of attentional lapses during the task [15]. Meanwhile, this disruption is concurrent with less MD activation. In addition, when cognitive demands increase during a task, DMN regions reduce their BOLD activity level while MD regions get more activated [93] [94]. Moreover, increased anticorrelation between these two networks is concurrent with better behavioral performance in a task [124]. Overall, it can be said that each of these anticorrelated networks has a unique role in brain functions.

1.4.1 DMN and MD networks' Coactivation

Even though the default mode and multiple demand networks were shown to be anti-correlated with each other, several studies have shown that their interaction during various conditions contributes to the occurrence of these experiences:

Natural Visual and Auditory Stimuli Processing

It has been discovered that the default mode and multiple demand networks' collaboration contribute to movie watching in a natural condition [21]. During this contribution, the attentional focus alters quickly between external stimuli and internal thoughts. When the external stimuli in the movie were exciting and included actions, the MD regions activated more intensely. On the contrary, when the scenes in the movie were tranquil, greater activation was observed in the DMN network. Therefore, the interaction between these two networks correlated with the cognitive experience of watching a movie.

Semantic Processing

During semantic information processing, there is a noticeable coactivation and coordination between the DMN and MD network, where accessing and manipulating stored knowledge is required [22]. This coactivation could indicate the synchronization between internally directed processes associated with memory retrieval and externally directed processes associated with attention and cognitive control. The multiple-demand network's role lies in representing and keeping track of task goals, while the DMN is responsible for representing and processing semantic information related to those goals. Generally, these networks collaborate to combine various inputs and support cognitive control processes when the performing tasks involve semantic retrieval.

Future Planning

When an upcoming problem in the future needs to be solved, we need cognitive stimulation to create mental images and imagine different steps for dealing with that problem and solving it. Research indicates that cognitive stimulation is associated with the default mode network activity, while goal-directed behavior is correlated with the multiple demand network [40]. The multiple-demand network has a role in determining different steps to conduct a task, setting a goal, and keeping the plans in mind for the next step. Meanwhile, the activation in the default mode network leads to self-generated plans and evaluation of these plans. So it can be said that the brain needs to exert both the default mode and multiple demand networks. The contribution between these networks helps people to imagine different situations, assess the relevance of scenarios, consider their current mental state, and develop strategic plans to solve problems besides providing cognitive control to solve the task [129].

Multistep Tasks

Behavioral tasks can be divided into several steps that lead to achieving a specific goal. These tasks can be called multistep tasks. Even though the default mode and multiple demand networks have separate roles during the multistep task, their coactivation reflects each step's position and content [130]. The MD network follows the specific cognitive processes in each task step, while the DMN connects these processes to a broader context. The structure of a task episode evokes a response in both networks. However, the MD network responds more to specific steps, while the DMN shows more robust activation during episode boundaries. Taken together, the DMN and MD networks work together to control and organize task sequences and reflect the hierarchical nature of goal-directed behavior.

Creativity

Evidence revealed that both default mode and multiple demand networks are crucial for creativity and creative cognition [60]. Novel ideas can be generated by exerting episodic memory and self-generated thoughts by the DMN. On the other hand, the MD has a role in external attention and cognitive control mechanisms such as working memory and task-set switching. It also uses top-down modulation to assess and adapts candidate ideas with specific task objectives. Hence, when the task goal is vague, or there is no top-down modulation, the corporation between these two networks decreases.

Mind Wandering

Mind wandering is an intricate situation where people focus on their internal self-generated thoughts. Evidence suggests that during mind wandering, both multiple demand and default mode networks increase their activation [9] [11]. Each of these networks has its specific role in the occurrence of mind wandering. The default mode network is important for creative self-generated thought during mind wandering. On the other hand, the multiple demand network is vital in dedicating attention sources to these internal thoughts instead of external stimuli.

1.5 This study

In this study, we aimed to investigate the difference in brain activities in response to intentional and unintentional forms of mind wandering. We designed an fMRI experiment where mind wandering was the task. The part where the mind-wandering task took place was called the think part. In this part, we asked participants to wander their minds as much as possible. They were instructed to think about their memories from the past consecutively. This part can be considered deliberate or intentional mind wandering [4]. The important consideration here was whether or not the participants experienced episodes of mind blanking. Because during intentional mind wandering that they are required to think about something; sometimes, their mind might go blank, and they can't think about anything. After the think part, we asked them, " How much could you think?" They rated their answer from one to four. One corresponded to large portions of mind blanking or the answer: "I couldn't think that much," and four corresponded to small portions or "I could think a lot." Another important consideration was the intentionality of mind wandering. During the think part, it was important that participants could follow their thoughts. That thought would be vague if they thought about something they didn't intend to. To find out about this, after the first question, we asked them, "How vivid were your thoughts." Like the first question, they rated their answer from one to four. One for a large portion of spontaneous thoughts or, as they might say," my thoughts were not so vivid," and four for a small portion of unwanted thoughts corresponding to the answer: "my thoughts were vivid." After they responded to the second question, the rest began. During this part, participants rested in the fMRI machine without doing anything. Usually, when the brain is at rest, the mind wanders freely and unintentionally [4]. Hence, we could investigate the brain activities during unintentional mind wandering in this part.

Previous evidence revealed that during intentional mind wandering, there is a corporation between the Default Mode and Multiple Demand networks [9]. The higher rate of intentional mind wandering in participants is associated with

more incorporation between regions of these two networks. In contrast, in participants who had a higher rate of unintentional mind wandering, they observed thinner cortical regions in both Default Mode and Multiple Demand networks. Accordingly, we investigated the difference between intentional and unintentional wandering forms in the default mode network and multiple demand regions of interest. We speculated see a significant difference in the activation of both Multiple Demand and Default Mode Network regions during the think and rest parts. Previous research has suggested that there is a distinction between intentional and unintentional mind wandering. Considering the previous research, we expected to see a more robust activation in both DMN and MD networks during the think part where intentional mind wandering occured compared to the rest part where unintentional mind wandering took place [9].

Evidence suggests that the exact shape of Multiple Demand network regions varies among participants [131]. Concerning this matter, we needed to detect the multiple demand regions in participants' brains. Some of the participants conducted an n-back task prior to our think-rest experiment. Based on previous findings, this task leads to high activation in the multiple demand network regions [86]. After detecting these regions, we examined their activities during the rest and think parts of the experiment and compared them. We anticipated to see the same response pattern here as the multiple demand network regions in all participants.

The inner speech is an indispensable part of mind wandering. Research has shown that language regions responsible for verbal working memory are essential for awareness of mind wandering [25]. Furthermore, the default mode and multiple demand regions both participate in language processes [54] [118]. The default mode network shows high activation during semantic processing and categorizes the words as meaningful and nonmeaningful [54]. On the other hand, the multiple-demand network's activation is associated with language perception [118]. Due to the importance of language regions in mind-wandering and the activity levels in the default mode and multiple demand regions, we investigated the language regions during the think and rest parts of the experiment. However, there is an individual difference in language regions among participants. Hence,

we did a language localization task called the sentence completion task on some participants to find their language regions in the brain [132]. Afterward, we investigated these regions' activities during our experiment's think and the rest parts. We hypothesized that the language regions have a stronger activation during the intentional form of mind wandering where participants have meta-awareness [25].

Chapter 2

Methods

2.1 Participants

The study included 18 Turkish participants (10 females), with a mean age of 22.167 and a standard deviation of 3.47. All of these participants were right-handed. Their vision was normal or corrected with MR-compatible glasses during the study. Through Bilkent University's email system, we recruited participants in the study. Participants were compensated for their participation with either a monetary award or course credit. They signed the required paperwork before the experiment in order to give their informed permission. For the participant's safety, it was made sure that they could use the fMRI machine before the inquiry. The Bilkent Ethics Committee gave the study its approval.

2.2 Experimental Design

Our experiment was an fMRI experiment with one run and one session. This experiment had 20 blocks and consisted of 4 main parts, including the think part, the first question, the second question, and the rest part. Moreover, the

biggest part appeared at the beginning and end of the experiment for 60 seconds. During this part, we asked participants to rest in the fMRI machine for a while without doing anything (see Figure 2.1). At the end of each block, participants were asked to press a button to continue to the next block (see Figure 2.6).

Figure 2.1: Think-rest experiment. Biraz dinlenin (Translation: Rest for a while). This was the big rest part at the beginning and end of the experiment. Participants rested for one minute in the fMRI machine.

Think: In this part, participants were asked to wander their minds as much as possible by thinking about their memories in the past and moving from one thought to another. This part continued for 30 seconds (see Figure 2.2).

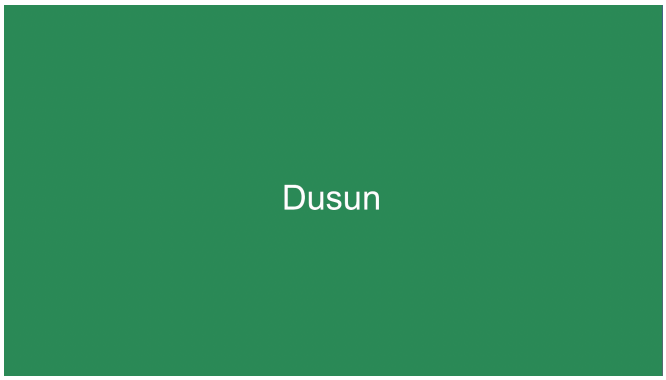

Figure 2.2: Think-rest experiment. Dusun (Translation: Think). In this part, participants were asked to wander their minds by thinking about one thought after another for 30 seconds.

First question: After the think part, the first question appeared on the screen. We asked participants how much they could think. This question aimed to find out whether participants have experienced mind blanking during the think

part or not. They needed to rate their thinking from one to four. One for "I couldn't think that much" and four for "I thought a lot." They gave their answers by pressing the corresponding button on the button box from one to four (see Figure 2.3).

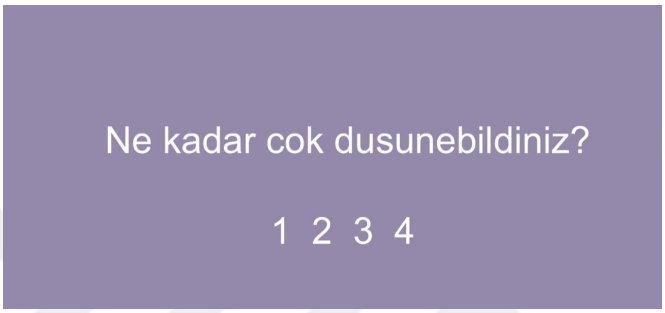

Figure 2.3: Think-rest experiment. Ne kadar cok dusunebildiniz (Translation: How much could you think?"). This question aimed to find out if participants experienced episodes of mind blanking or not. They rated their answer from one to four by pressing the buttons on the button box in the fMRI machine. 1 corresponded to "I couldn't think a lot", and 4 corresponded to "I thought a lot".

Second question: After participants answered the first question by pressing the buttons on the button box, the second question appeared on the screen. We asked them how vivid their thoughts were. This question aimed to investigate the amount of intentional mind wandering. As for the first question, they needed to rate the vividness of their thoughts from one to four. One for "not vivid that much" and four for "so vivid." (see Figure 2.4) If they rate this part as "not vivid," it could be said that they were not that successful in detecting their thoughts during the mind-wandering, and their mind-wandering was spontaneous rather than intentional.

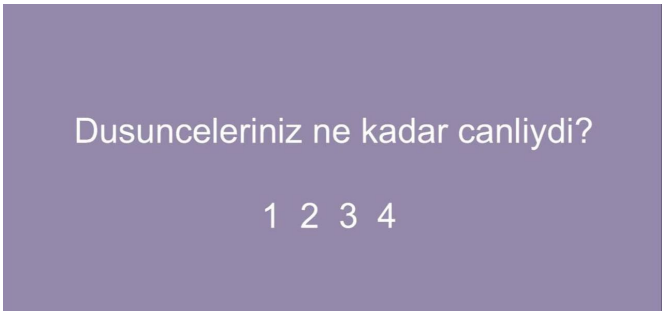

Figure 2.4: Think-rest experiment. Dusunceleriniz ne kadar canliydi? (Translation: How vivid were your thoughts?). The second question was asked to see if the participants' thoughts were intentional and vivid or not. They evaluated their response from 1 to 4 with a button box in the fMRI machine. 1 corresponded to "my thoughts were not vivid" and 4 corresponded to "my thoughts were so vivid".

Rest: After answering the second question by pressing the buttons on the button box, the rest part began. This part's duration varied between 16 to 25 seconds. Participants rested in the fMRI machine without doing anything during this part (see Figure 2.5).

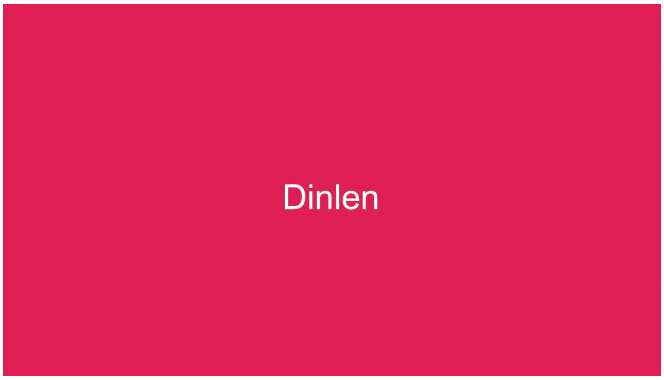

Figure 2.5: Think-rest experiment. Dinlenin (Translation: Rest). In this part, participants rested in the fMRI machine without doing anything. The duration of this part was between 16 to 25 seconds in each block.

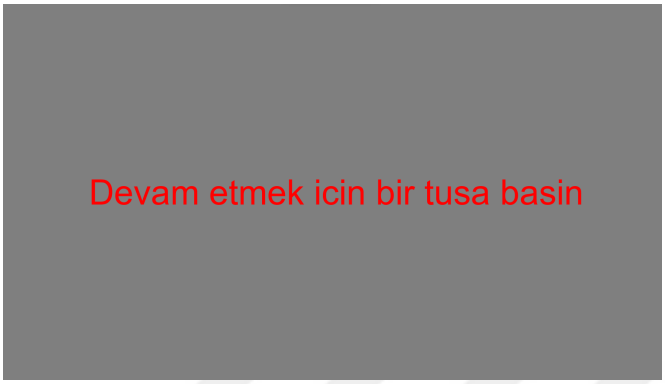

Figure 2.6: Think-rest experiment. Devam etmek icin bir tusa basin (Translation: Press a button to continue). Participants were able to move to the next block by pressing a button on the button box.

2.3 Procedure

We explained the task to the participants before the experiment started in the fMRI machine. They did a practice version of the experiment on a computer. Instead of using the button box, they used the keyboard's 1, 2, 3, and 4 keys. After they learned how to do the task, we gave them earplugs to reduce the noise of the fMRI machine during the scan. After they lay down inside the machine, we placed foam pads around their necks to stabilize their heads and minimize head movements. Additionally, we instructed the participants to remain still throughout the scan. To enhance their comfort, a pad was positioned beneath their knees. Finally, we connected the head coil, and a mirror was positioned above it, allowing the participants to view the entire screen by adjusting it. A button box containing four buttons was provided to the participant's right hand, and they were instructed to use their index finger to provide their responses.

2.4 Apparatus

The fMRI scans were performed at the National Magnetic Resonance Research Center (UMRAM) located at Bilkent University. We used a 3T Siemens TimTrio

MR scanner equipped with a 32-channel phased array head coil. The MR-compatible stimuli screen used during the scans had a resolution of 800x600 pixels and was a 32-inch LCD screen with a 60 Hz refreshing rate. The screen brand used was called TELEMED. Participant responses were recorded using a fiber optic button box, specifically the fORP 904 fMRI trigger and response system from Current Design. The experimental stimuli were created and presented using MATLAB and the Psychophysics Toolbox, developed by Denis G. Pelli and David H. Brainard. Before the start of the main experiment, we got a T1-weighted anatomical image with the following parameters: TR=2600 ms, TE=2.92 ms, flip angle=8°, FoV read=256 mm, FoV phase=87.5%, 176 slices with 1×1×1 mm3 resolution. A T2-weighted EPI acquisition sequence was employed with the following settings during each run: TR=2000 ms, TE=30ms, flip angle=78°, 64 x 64 matrix, FoV read=192 mm, 32 slices with a thickness of 3.0 mm, 3×3×3 mm3 resolution.

2.5 Behavioral Data Analysis

2.5.1 First question

The first question appeared after the think part of the experiment. We aimed to explore how much participants could think during the think part by asking the first question (See figure 2.3). The participants rated their answers from one to four with the button box. We separated their response into low and high. The 1 and 2 ratings were categorized as low, while the 3 and 4 ratings were categorized as high. Afterward, we calculated the fraction and percentage of high and low ratings in participants.

2.5.2 Second question

After participants answered the first question, the second question appeared on the screen. This question asked about the vividness of the participants' thoughts during the think part (See figure 2.4). Like the first question, they rated their answer from one to four by pressing the buttons on the button box here. We considered 1 and 2 responses low and 3 and 4 high. Then, we found the percentage and fraction of low and high ratings in our participants.

2.6 fMRI Analysis

fMRI analysis was conducted by the SPM12 toolbox in Matlab(2022a) [133].

2.6.1 Preprocessing

We first needed to do preprocessing to prepare the neuroimaging data for analysis. The preprocessing was done by SPM12 GUI in Matlab(2022a). We did a

realignment for motion correction on these data by setting the last volume as the reference point. Hence they had a standard orientation. Later on, we did a slice-time correction on the EPI volumes. We determined the 32nd slice as the reference slice. We did a coregistration to align the functional images with anatomical ones. Moreover, a segmentation was included to separate different brain tissue types. The next step was a nonlinear spatial normalization. This normalization was done by the Montreal Neurological Institute (MNI) space and led to the resampling of the voxels to the size of 2x2x2 mm. Hence, the time course of each voxel was subjected to high-pass filtering with a cutoff duration of 90 s to analyze the data further. Finally, we did the smoothing with an 8 mm full-width half-maximum Gaussian kernel.

2.6.2 First Level Analysis

General Linear Models (GLMs) were used for statistical first-level analysis. Separate event regressors were used to model the think and the rest parts. These regressors represented the stimulus-to-response time and were convolved with a single basis function that modeled the canonical hemodynamic response (HRF). The model's parameter estimates for each regressor were obtained by fitting the model to the data using a least-squares method.

2.6.3 Whole Brain Analysis

Using SPM in Matlab(2022a), a group-level statistical analysis was used for the whole brain analysis to see if there was a significant difference between the think and the rest parts of the experiment in 18 participants. The think part was determined bigger than the rest part. A voxel-wise statistical test and a general linear model were used to make this comparison. The threshold for uncorrected multiple comparisons was $p < 0.001$. Corrective False Discovery Rate (FDR) was applied for multiple comparisons with a threshold of $q < 0.05$.

2.6.4 Regions of Interest

To investigate the activity difference between the think and rest parts in specific brain regions from the Default Mode and Multiple Demand networks in all 18 participants, we conducted an ROI analysis using the MarsBar toolbox of SPM in Matlab(2022a).

Due to interpretability and proper volume effect, the regions of interest were made as spheres with a 10mm radius in MNI space. The locations were as follows: The multiple-demand regions included the bi-lateral Intraparietal Sulcus (IPS; ±37 -56 41), the bilateral pre-Supplementary Motor Area (pre-SMA; ±5 18 50), the bilateral Anterior Cingulate Cortex (ACC; ±5 31 24), and the bi-lateral Inferior Frontal Sulcus (IFS; ±41 23 29). These coordinates were priori anatomical regions of interest based on [114]. The Default Mode Network regions of interest were the Posterior Cingulate Cortex (PCC; 1 -61 38), the Bi-lateral Temporoparietal Junction (TPJ; (±52 -54 23), the bilateral anterior Prefrontal Cortex (aPFC; ±24 58 18), and anterior Medial Prefrontal Cortex (aMPFC; 1 55 26). These priori Default Mode regions were defined based on [42] [134] [135] [136] [137]. The beta values show the alternations in the strength of neural activity in response to a specific condition. After finding the beta values of the regressors for these 18 participants, we conducted a paired t-test to determine if there was a significant difference between the think and the rest parts in these regions of interest in participants. We did this analysis by the Statistics and Machine Learning Toolbox in Matlab(2022a). Since our regions of interest from the DMN and MD networks were priori regions from previous studies and what we did was a preplanned analysis, we set the p-value <0.05 to reduce the change of Type II error.

2.6.5 Individual MD regions of Interest

Due to the different shapes of the multiple demand network regions in different participants, we needed to determine the Individual MD regions in each participant. 13 participants did an n-back task prior to our experiment in the fMRI machine. Previous research showed that this task leads to activation in the Multiple Demand network regions [86]. The n-back that was used here was two-back versus zero-back. It was conducted on previous runs of our fMRI session for another project. In this experiment's zero-back condition, participants saw images one after another on the screen. They needed to decide whether the image they see is the same as the previous one. In the two-back conditions, participants decided if the image they saw was the same as the two images back in the sequence. In order to compare the MD regions' activation in the two-back versus zero-back conditions, we did the preprocessing and first-level analysis on this n-back task by using GUI SPM in Matlab(2022a). We examined the contrast of activation in brain activities in the two-back condition versus the zero-back condition. Then, we found each participant's functional Multiple Demand regions by doing a single-subject ROI analysis. MarsBaR and Anatomy toolboxes in SPM in Matlab(2022a) were used for this purpose. We found the Multiple Demand regions of interest as 10-mm spheres in MNI space based on the anatomical ROIs, including the bilateral Intraparietal Sulcus (IPS), bilateral Inferior Frontal Sulcus (IFS), and bilateral pre-supplementary motor area (pre-SMA) regions. The coordinates were found as global and local maximums adjacent to these regions. After finding these regions, we defined them as functional regions of interest in the think-rest experiment for each participant and conducted an ROI analysis so we could see the difference in activation between the think and the rest parts. After creating ROI bar graphs for each participant, to display the results, we took the average beta values of individual Multiple Demand regions of interest in the think and rest parts of these participants and show them in Figure 3.4 using Matlab(2022a).

In addition, to show the contrast between the think and the rest parts in

the participants that did the n-back task, we demonstrated some of the participant's brain activity in the think and the rest parts in the Multiple Demand regions of interest in their subjective space including sub06's left inferior frontal sulcus (IFS, and right intraparietal sulcus (IPS), sub04's left intraparietal sulcus (IPS), Sub02's left pre-supplementary motor area (pre-SMA), sub17's right inferior frontal sulcus (IFS), and right pre-supplementary motor area (pre-SMA). These regions are shown in Figure 3.5.

2.6.6 Individual Language Regions of Interest

9 participants conducted a sentence completion task before they did the think-rest experiment. This task was done by these participants before our run at the fMRI session. Previous neuroimaging studies found that this task activates the language regions in the brain [132]. During this task's first condition, participants saw a sentence with a blank word they needed to fill in. Moreover, they were asked to read the whole sentence quietly to themselves. During the second condition, a sentence consisted of non-words. They were asked to read these non-words and fill in the blank in the sentence with the last non-word. To see the activation in the language regions, we needed to compare brain activity in sentences with meaningful words with non-words. We did the preprocessing and first-level analysis on each participant in the sentence completion task. We set the contrast as meaningful words minus meaningless words. Then, by conducting an individual functional ROI analysis, we looked at the activation of language regions in these participants using MarsBaR and Anatomy toolboxes in SPM in Matlab(2022a). The coordinates were set as the global locals and global maximums in the whole brain. Afterward, we defined these regions as regions of interest in the think-rest experiment and analyzed each participant's ROI in the think and rest parts. After investigating the ROI bar graphs in each of them, we divided the brain's language regions into the left Frontal, Parietal, and Temporal lobes for better demonstration. We had 16 functional ROIs of participants in the left Frontal regions, 9 for the left parietal, and 9 for the left temporal regions in the brain. We took the average of the beta values in the language regions in

each lobe among participants and displayed them in Figure 3.6. To see if there was a statistically significant difference between the think and the rest parts in the average of language regions, we conducted a paired t-test. This analysis was done by the Statistics and Machine Learning Toolbox in Matlab(2022a).

Chapter 3

Results

3.1 Behavioral results

3.2 First question

In the first question, we investigated the amount of mind blanking in participants (see 2.3). We separated the responses to this question into low and high ratings. We considered the 1 and 2 ratings low, indicating high amounts of mind blanking. The 3 and 4 ratings were considered high, showing small amounts of mind blanking. Based on our results, 214 out of 270 answers by participants had high ratings, and 56 answers had low ratings. Hence, 79 percent of answers by our participants were high ratings, and only 21 percent were low. So, it can be said that most participants did not experience episodes of mind blanking during the think part.

3.3 Second question

The amount of intentional mind wandering or vividness of thoughts during the think part was investigated during the second question. The 1 and 2 ratings were considered low, corresponding to low vividness of thoughts and low amounts of intentional mind wandering. The 3 and 4 ratings were considered high-rating responses corresponding to vivid thoughts and high amounts of intentional mind wandering during the think part. Based on our results, out of 270 rating responses by participants, 210 ratings were high, and 60 ratings were low. So,77.53 percent of answers were rated high, and 22.47 percent were rated low. It means that most of our participants had vivid and intentional thoughts during the think part of the experiment.

3.4 fMRI results

3.4.1 Whole Brain Analysis

A group-level statistical analysis was conducted in all 18 participants to see if there was a significant difference in whole brain activation between the think and the rest parts of the experiment. Results revealed a statistically significant difference between the think and rest parts in various brain regions in these participants ($q < 0.05$, FDR-corrected). The statistical map in Figure 3.1 shows the activity contrast between the think and the rest parts (think-rest) in brain regions such as some of the DMN regions, including the Medial Prefrontal Cortex (mPFC) and Temporoparietal Junction (TPJ) as well as some of the MD regions, including Intraparietal Sulcus (IPS), Inferior Frontal Sulcus (IFS), Anterior Cingulate Cortex (ACC), and pre-Supplementary Motor Area (pre-SMA). Compared to the right hemisphere, these brain activities are more apparent in the left hemisphere. The t values shown in the statistical map are between 2 and 5, from black to yellow. The statistical brain maps for each participant are shown in Figures 5.1, 5.2, 5.3.

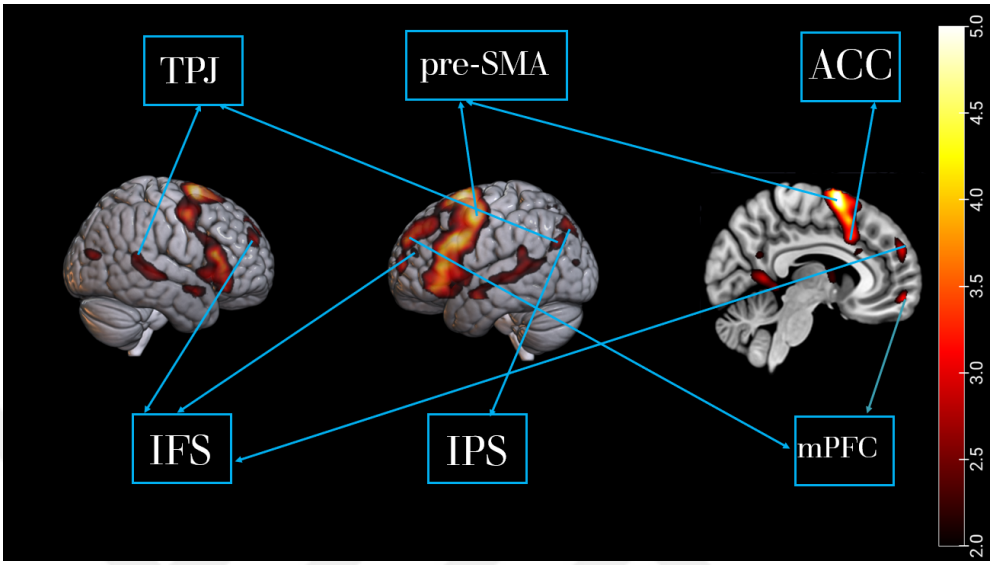

Figure 3.1: The statistical map. Whole Brain Activity results for the contrast between the think and the rest parts (think - rest) in 18 participants ($q < 0.05$, FDR-corrected). We also see the activation in some MD regions, such as IFS, IPS, pre-SMA, and ACC. Also, some DMN regions, including the TPJ and mPFC, are displayed. The t values shown in the statistical map are between 2 and 5, from black to yellow.

3.4.2 Regions of Interest

We did an anatomical ROI analysis on our participants to see the difference in activation between the think and the rest parts. Our regions of interest were the bilateral Temporoparietal Junction (TPJ), the Posterior Cingulate Cortex (PCC), the anterior Medial Prefrontal Cortex (aMPFC), and the bilateral anterior Prefrontal Cortex (aPFC) from the Default Mode Network (see Figure 3.2). The Multiple Demand regions of interest included the bilateral Intraparietal Sulcus (IPS), the bilateral Inferior Frontal Sulcus (IFS), the bilateral Anterior Cingulate Cortex (ACC), and the bilateral pre-supplementary Motor Area (pre-SMA) (See Figure 3.3).

3.4.2.1 The Default Mode Network

We used a paired sample t-test to determine if there is a significant difference in the activation of Default Mode Network regions of interest in the rest and think parts of the experiments. The results showed that there is a statistically significant difference between the think and rest parts in the Left Temporoparietal Junction (TPJ) ($t(17)= 2.47$, $p = 0.024$) (not corrected for multiple comparisons) and the Posterior Cingulate Cortex (PCC) ($t(17)= 2.63$, $p = 0.018$) (not corrected for multiple comparisons) regions of the Default Mode Network. These regions had a stronger response in the think part compared to the rest part. In other DMN regions of interest, including Left anterior Prefrontal Cortex (aPFC) ($t(17)= 1.53$, $p = 0.265$), Right anterior Prefrontal Cortex (aPFC) ($t(17)= -1.82$, $p = 0.086$), Right Temporoparietal Junction (TPJ) ($t(17)= 0.71$, $p = 0.48$), and anterior Medial Prefrontal Cortex (aMPFC) ($t(17)= 1.87$, $p = 0.08$), there was no significant difference between the think and the rest parts. The summary of the statistical results is shown in table 3.1. Based on a statistical approximation, the beta values in Figure 3.2 show the strength of activation or deactivation in the DMN regions of interest during the think part in comparison with the rest part. The rest part provokes more deactivation in the Default Mode Network regions than the think part in the Posterior Cingulate Cortex (PCC) and the Left Temporoparietal Junction (TPJ) regions. Among these regions, the difference in activation between the think and the rest parts is more pronounced in the Posterior Cingulate Cortex (PCC). In other DMN regions of interest, there was no significant difference between the think and the rest part.

Name	Side	MNI coordinates	t statistic	p	significance level
PCC	Right	1 -61 38	2.63	0.018	*
TPJ	Left	-52 -54 23	2.47	0.024	*
TPJ	Right	52 -54 23	0.71	0.480	
aPFC	Left	-24 58 18	1.53	0.265	
aPFC	Right	24 58 18	-1.82	0.086	
aMPFC	Right	1 55 26	1.87	0.080	

Table 3.1: The Default Mode Network regions of interest. We see the coordinates of some DMN regions, including PCC, Bilateral TPJ, Bilateral aPFC, and aMPFC, and their statistical values in the difference of their activation in the think part compared to the rest part of the experiment (not corrected for multiple comparisons). (*p <0.05)

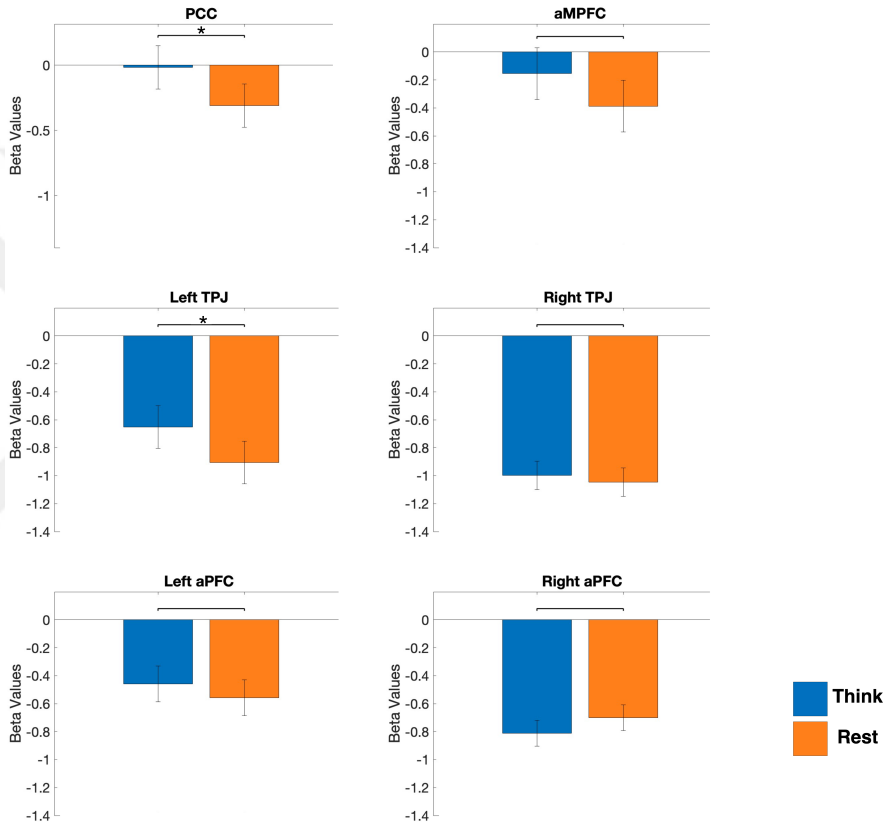

Figure 3.2: ROI results. The Default Mode Network regions of interest include PCC, Bilateral TPJ, Bilateral aPFC, and aMPFC. In the x-axis, we see our events, including the think and the rest part. The y-axis shows the beta values the general linear model (GLM) calculated. They represent the changes in brain activities in response to think and the rest parts in 18 participants. The difference in activation between think and the rest parts is statistically significant in PCC and left TPJ regions of DMN. In other DMN regions, there is no significant difference between the think and the rest parts. Error bars indicate SEM across participants. (*p <0.05)

3.4.2.2 The Multiple Demand Network

We used a paired sample t-test to determine if there is a significant difference in Multiple Demand Network regions of interest's activations in the rest and think parts of the experiment in our participants. The results have shown that there is a statistically significant difference between the think and rest parts in the left Inferior Frontal Sulcus (IFS) ($t(17)= 4.44$, $p <0.0001$) (not corrected for multiple comparisons), the left Intraparietal Sulcus (IPS) ($t(17)= -2.15$, $p= 0.045$) (not corrected for multiple comparisons), the Right Intraparietal Sulcus (IPS) ($t(17)= -3.65$, $p= 0.002$) (not corrected for multiple comparisons), the left pre-Supplementary Motor Area (pre-SMA) ($t(17)= 6.06$, $p <0.0001$), and the right pre-Supplementary Motor Area (pre-SMA) ($t(17)= 4.17$, $p <0.0001$) (not corrected for multiple comparisons) regions. The activity difference between the think and the rest parts is non-significant in the left Anterior Cingulate Cortex (ACC) ($t(17)= 1.11$, $p = 0.28$), the right Anterior Cingulate Cortex (ACC) ($t(17)= -0.072$, $p = 0.94$) and the right Inferior Frontal Sulcus (IFS) ($t(17)= 0.94$, $p= 0.36$) regions of the Multiple Demand network. These statistical results are summarized in table 3.2. However, the regions from the Multiple Demand Network have different patterns of activity in the think and the rest parts. Some of these regions, including the left Inferior Frontal Sulcus (IFS) and bilateral pre-supplementary Motor Area (pre-SMA), have a more robust activity in the think part than the rest part. In contrast, the bi-lateral Intraparietal Sulcus (IPS) regions have a stronger activity in the rest part. In the right Inferior Frontal Sulcus (IFS) and the bilateral Anterior Cingulate Cortex (ACC) regions, there was no significant difference between the think and the rest parts. Based on statistical estimation, the beta values in Figure 3.3 represent the activation or deactivation of the MD regions of interest during the think part compared to the rest part of the experiment. Among these Multiple Demand Network regions of interest, the difference in activation between the think and the rest part is more pronounced in the left inferior frontal sulcus (IFS) region.

Name	Side	MNI Coordinates	t statistics	p	Significance Level
IPS	Left	-37 -56 41	-2.15	0.045	*
IPS	Right	37 -56 41	-3.65	0.002	**
IFS	Left	-41 23 29	4.44	p<0.0001	***
IFS	Right	41 23 29	0.94	0.36	
pre-SMA	Left	-5 19 50	6.06	p<0.0001	***
pre-SMA	Right	5 19 50	4.17	p<0.0001	***
ACC	Left	-5 31 24	1.11	0.28	
ACC	Right	5 31 24	-0.072	0.94	

Table 3.2: The Multiple Demand network regions of interest: In this table, we see the coordinates and statistical values of MD regions (not corrected for multiple comparisons) (*p <0.05, **p <0.01, ***p <0.001).

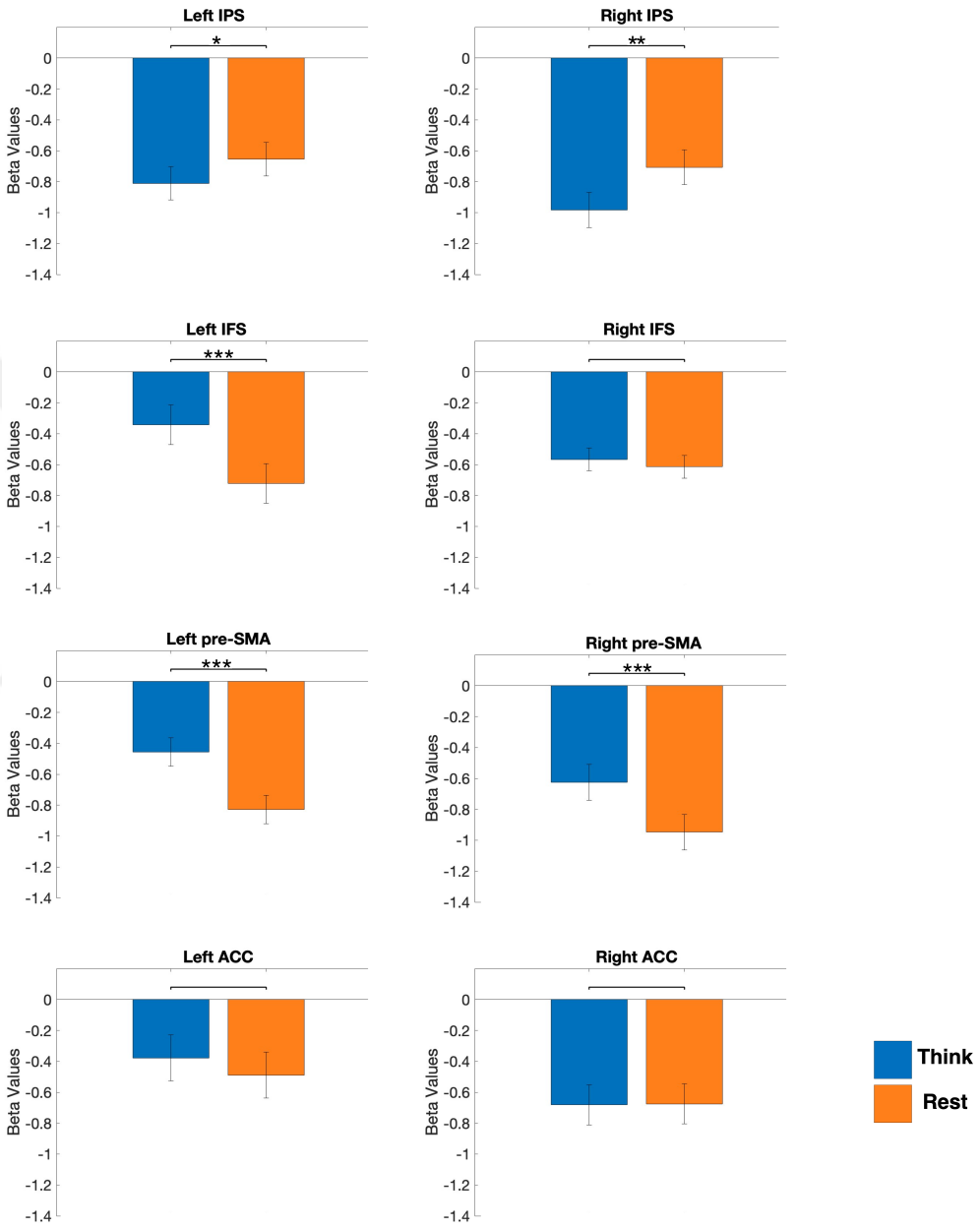

Figure 3.3: ROI results. The Multiple Demand Network regions of interest include bilateral IPS, Bilateral IFS, Bilateral pre-SMA, and Bilateral ACC brain regions. In the x-axis, we see our events, including the think and the rest part. The y-axis shows the beta values representing changes in brain activities in response to the think and the rest conditions in 18 participants. While the left IFS and bilateral pre-SMA regions show higher activation in think part, the bilateral IPS regions represent higher activation in the rest part. (*p <0.05, **p <0.01, ***p <0.001)

3.4.3 The average activity of Multiple Demand regions in Subjective ROIs

We intended to investigate the difference in brain activities between the think and rest parts in participants' subjective Multiple Demand regions of interest. These regions included the bilateral Intraparietal Sulcus (IPS), bilateral Inferior Frontal Sulcus (IFS), and bilateral pre-supplementary Motor Area (pre-SMA). 13 participants conducted an n-back task before the think-rest experiment. Previous studies have shown that this task provokes a strong activation in the multiple demand regions [86]. Hence, after doing first-level and subjective ROI analysis on these participants, we detected the functional Multiple Demand network regions in each of them. After defining these regions as the regions of interest, we examined the difference in activation between the think and rest parts in each participant. For easy demonstration, we took the average of these participants' activation in their functional MD regions of interest in the think and the rest parts and showed them in Figure 3.4. Based on this figure, we can see that the activity in these participants' functional Multiple demand regions of Interest is consistent with the anatomical regions of interest results in all 18 participants. While the bilateral pre-Supplementary Motor Area (pre-SMA) and bilateral Inferior Frontal Sulcus (IFS) regions have a stronger response in the think part, in the bilateral Intraparietal Sulcus (IPS) regions, the rest part leads to a stronger activation compared to the think part. Figure 3.5 presents the activity contrast between the rest and the think parts of some participants' subjective Multiple Demand regions of interest.

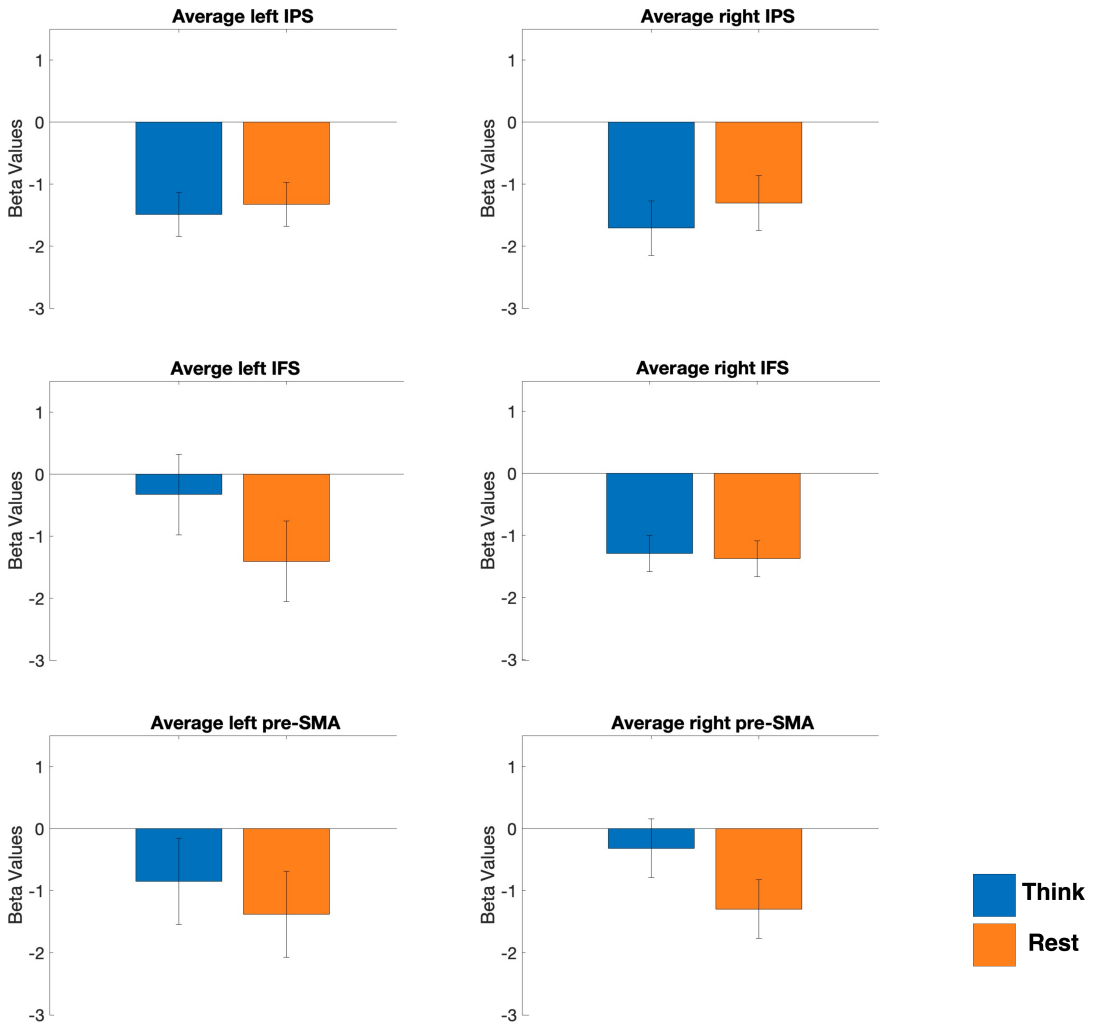

Figure 3.4: Individual MD ROIs. Functional MD ROIs are represented, including the bilateral IFS, bilateral IPS, and bilateral pre-SMA regions. In the x-axis, we see our events, including the think and the rest part. The y-axis shows the average beta values in some participants. The average difference in activation between the think and the rest parts in individual functional MD regions of interest is shown. The Bilateral pre-SMA and Bilateral IFS regions have stronger activation in the think part, while the Bilateral IPS regions show higher activation in the rest part.

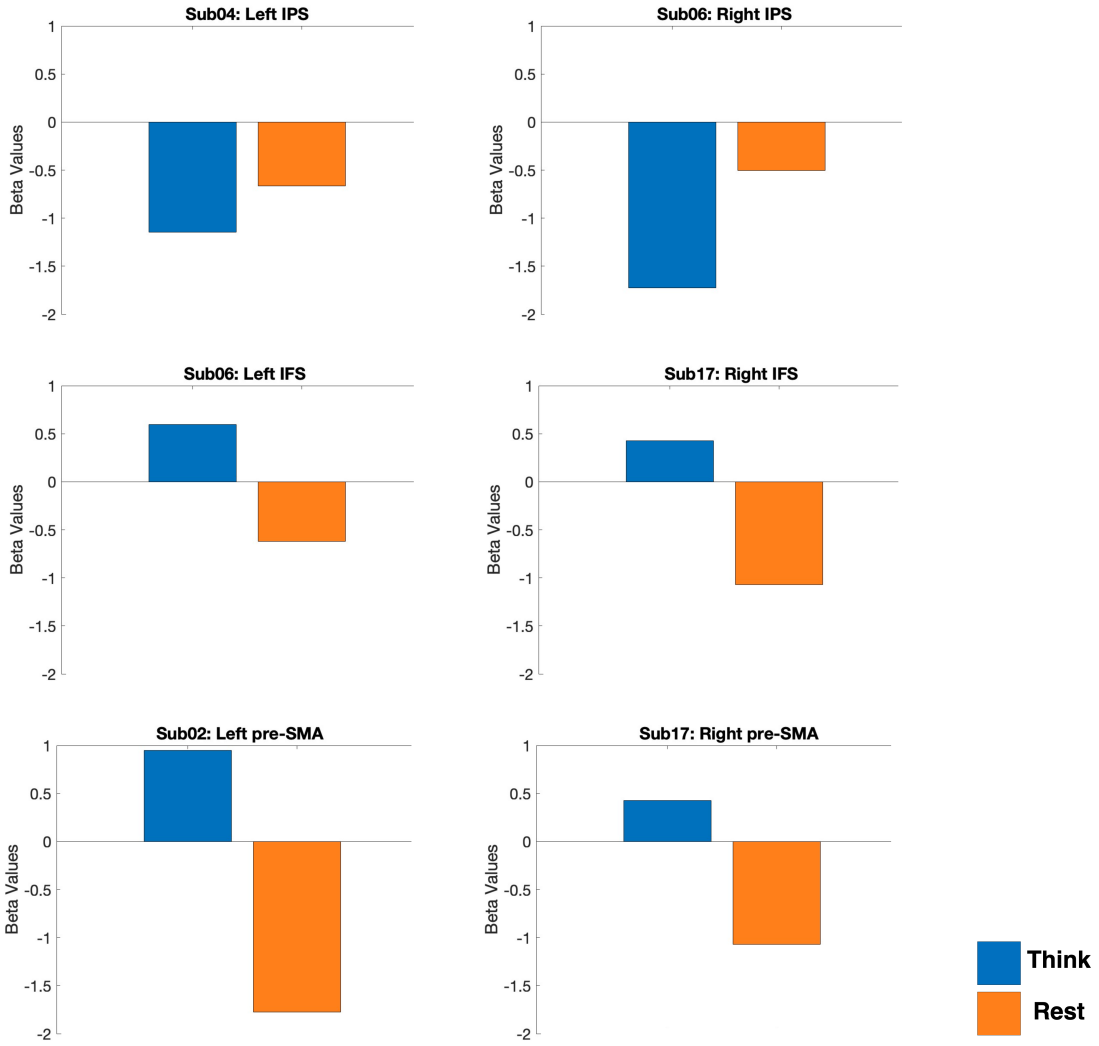

Figure 3.5: Sample of Participants with individual MD ROIs. The difference in activation between think and rest parts in some participants' subjective MD regions of interest. In the x-axis, we see our events, including the think and the rest part. The y-axis shows the beta values in these participants. The Bilateral pre-SMA and Bilateral IFS regions have stronger activation in the think part, while the Bilateral IPS regions show higher activation in the rest part.

3.4.4 The average activity in the Language ROIs in the subjective space

Due to the importance of the language regions in mind wandering, we decided to look into the activation in the language regions during the think and the rest parts of the experiment. 9 participants conducted a Sentence Completion task that activated the language regions [132]. After doing the required analysis on each participant, we defined the language regions as the functional regions of interest in the think-rest experiment. Afterward, we could see the difference in activation between the think and the rest parts in the language regions of each participant. To display the results, we divided the language regions in the brain into three main parts: Left frontal, Left Parietal, and Left Temporal lobes. Then, we took the average activation in the language regions during the think and the rest part in these nine participants for each part and displayed them in Figure 3.6. Moreover, to see if the activity difference between the think and the rest parts in the average language regions in each lobe is statistically significant, we conducted a paired sample t-test. Based on our results, there is a statistically significant difference between the think and the rest parts in the activity of the average of language regions in the left frontal lobe ($t(8)= 4.71$, $p= 0.0015$) (not corrected for multiple comparisons), left Parietal lobe ($t(8)= 7.92$, $p <0.0001$) (not corrected for multiple comparisons), and left Temporal lobe ($t(8)= 2.20$, $p= 0.05$) (not corrected for multiple comparisons). In all the language regions in the three lobes, we see a stronger activation in the think part compared to the rest part. The difference in the activity between the think and the rest parts is most pronounced in the average language regions in the left Parietal lobe.

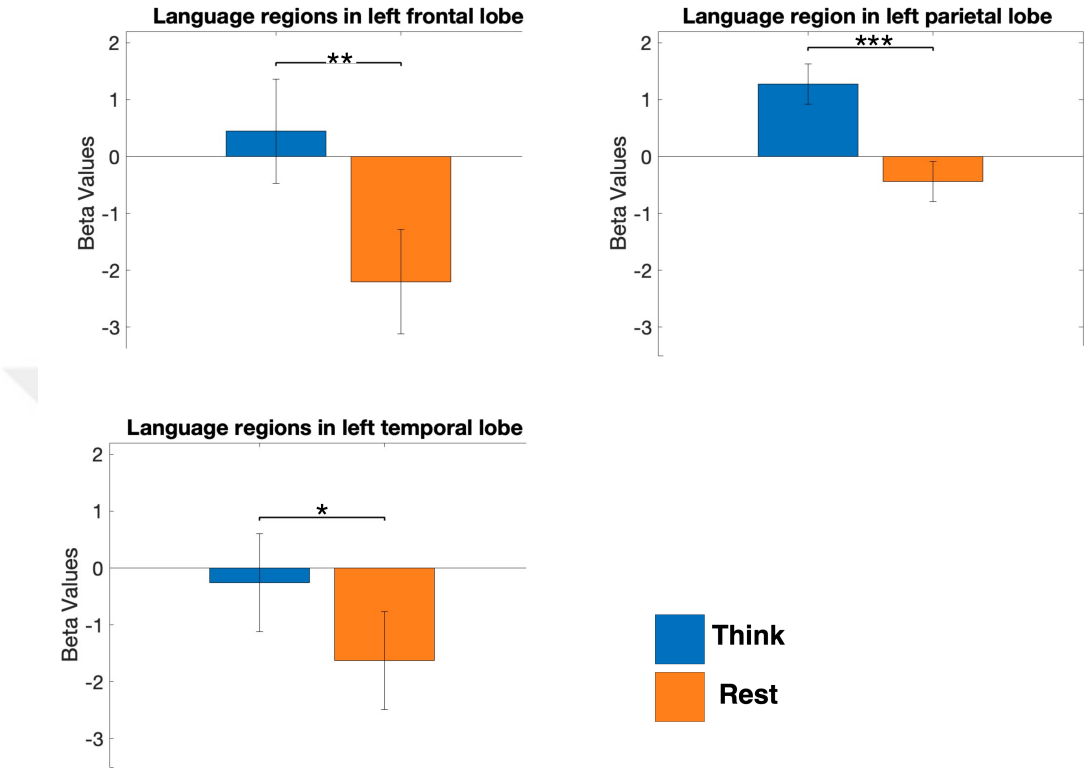

Figure 3.6: Language ROIs. The difference in average activity between think and rest parts in participants' subjective Language regions of interest, including the language regions in the left frontal, left parietal and left temporal lobes. In the x-axis, we see our events, including the think and the rest part. The y-axis shows the average beta values in some participants. In all language ROIs, we observe higher activation in the think part compared to the rest part. (*p <0.05, **p <0.01, ***p <0.001)

3.5 fMRI Result Summary

In this study, we performed a whole-brain analysis on 18 participants to see the difference in activation of whole brain regions in the think part of the experiment in contrast with the rest part. Our results revealed a significant difference between these two conditions. Furthermore, based on anatomical ROI analysis, the Posterior Cingulate Cortex (PCC) and the Left Temporoparietal Junction (TPJ) regions of the DMN had significantly higher activation in the think part than the rest. However, in other regions of DMN, such as the right Temporoparietal Junction (TPJ), bilateral anterior Prefrontal Cortex (aPFC), and anterior Medial Prefrontal Cortex (aMPFC) regions, there was no significant difference between the think and the rest parts. Regions of interest within the MD network represent various patterns of activation. In the bilateral pre-Supplementary Motor Area (pre-SMA) and left Inferior Frontal Sulcus (IFS) regions of the MD network, the activity was higher in the think part. In the bilateral Intraparietal Sulcus (IPS) regions of the Multiple Demand networks, the activity was more pronounced in the rest part compared to the think part. Moreover, in the right Inferior Frontal Sulcus (IFS) and the bilateral Anterior Cingulate Cortex (ACC), there was no significant difference between these two parts. These results were consistent with the functional multiple-demand network regions of interest in some participants' subjective ROIs. In the bilateral IFS and bilateral pre-SMA regions, the average activation was higher in the think part while in the bilateral IPS regions, the average activation was stronger during the rest part. Lastly, functional language regions of interest in the left frontal left parietal and left temporal lobes displayed significantly stronger activation during the think part compared to the rest part in a subset of nine participants.

Chapter 4

Discussion

In this study, we intended to investigate the different brain responses to intentional and unintentional mind wandering. Most studies on mind wandering and related brain regions have not separately investigated these two forms of mind wandering [1] [3]. However, some other studies have shown that these two forms of mind wandering lead to different responses in various brain regions [9] [6]. Regarding this, we designed an fMRI experiment where mind wandering was a task. During this task, participants were asked to wander their minds and think about their memories one after another. This part was called the think part, where intentional mind wandering took place. During the other part of our experiment, participants rested in the fMRI machine without doing anything. This was the part where unintentional mind-wandering could have taken place. Hence, we were able to investigate the difference in activation in various brain regions by comparing these two parts of the experiment. Our results on whole brain analysis showed a significant difference in the activation of brain regions between the think and rest parts. This indicates that intentional and unintentional mind wandering results in different brain activities, as mentioned in previous findings [6] [9].

Previous findings revealed that the activation of the Default Mode Network is highly associated with the occurrence of mind wandering [14]. Nevertheless, there

was no clear boundary between intentional and unintentional mind wandering in most studies [14] [2]. Here, we defined some DMN regions as regions of interest (ROI) and looked into their activation during intentional and unintentional mind wandering. Based on our results, the Posterior Cingulate cortex(PCC) and the Left Temporoparietal Junction (TPJ) regions had significantly higher activation during the think part compared to the rest part. Nevertheless, in most DMN regions, there was no significant difference between these two parts. Hence, most of the default mode network regions responded similarly to two forms of mind wandering. This is consistent with prior studies that showed the role of DMN in internal self-generated thoughts or, as we call mind-wandering [27] [14].

Based on the prior research, in addition to the DMN, the Multiple Demand (MD) network also shows stronger activities in response to mind wandering. Even though the DMN and MD networks are defined to be anti-correlated [123] [124], during some special situations, such as mind wandering, they have been shown to cooperate with each other [9] [11]. Accordingly, we also examined the difference in activation of MD regions during the intentional and unintentional forms of mind wandering. Many studies have claimed that the regions within the MD network represent the same response pattern to various cognitive tasks [86] [138]. Despite that, we found different activation patterns in MD regions in response to two forms of mind wandering. The left inferior frontal sulcus (IFS) and the pre-Supplementary Motor Area (pre-SMA) showed more robust activation during the think part. On the other hand, the bilateral intraparietal sulcus (IPS) regions had stronger activation during the rest part, where the unintentional form of mind wandering took place. Finally, there was no significant difference between the two forms of mind wandering in the right inferior frontal sulcus (IFS) and the Anterior Cingulate Cortex (ACC) regions.

Some studies have revealed an individual difference in multiple demand regions activation in participants [139]. In fact, these regions have dissimilar shapes in different participants [131]. Due to this, in some participants, an n-back task was conducted. This task has been shown to cause great activation in the MD regions [86]. We checked the bilateral Inferior Frontal Sulcus (IFS), bilateral Intraparietal Sulcus (IPS), and bilateral pre-Supplementary Motor Area (pre-SMA) regions of

interest in these participants. Our results in this part were consistent with the activation pattern in anatomical MD regions of interest. While the bilateral pre-Supplementary Motor Area (pre-SMA) and bilateral Inferior Frontal Sulcus (IFS) had stronger activation in the think part, the bilateral intraparietal sulcus (IPS) regions represented a more robust activation in the rest part. So, it can be inferred that the functional MD regions of interest in each participant respond differently to intentional and unintentional forms of mind wandering.

The inner speech is associated with the awareness of mind wandering [25]. During the rest periods, where participants usually engage in internal thoughts or mind wandering, stronger activation was observed in the language regions [26]. Hence, due to the importance of language regions in mind wandering, we investigated the activity of language regions during the think-rest experiment. First, in some participants, a language task called sentence completion was performed to find the language regions throughout the brain. These language regions were detected in the left hemisphere, in the Frontal, Parietal, and Temporal regions. Based on our results, the activity in these regions was stronger in the think part compared to the rest part. This is consistent with previous studies because participants had meta-awareness during intentional mind wandering and were aware of their inner speech [25].

Overall, these results indicate that intentional and unintentional mind wandering provoke separate responses in different brain regions. Therefore, future studies would benefit from defining these two types of mind wandering separately. Furthermore, previous findings revealed that mind wandering and mindfulness are associated with separate activities in brain regions [43]. However, mindfulness might be correlated with the intentional form of mind wandering [9]. On the grounds of this, the brain activities corresponding to intentional mind wandering and mindfulness should be studied in future works.

Previous studies stated that the DMN shows higher activation and stronger connectivity within its regions in patients with neuropsychiatric disorders [75]. On the other hand, other findings on DMN revealed higher activation and increased connectivity between its regions during mind wandering [14]. Regarding this,

mind wandering could be explored in these patients. For instance, future studies can investigate the form of internal thoughts mixed with the external world in these patients and determine if these thoughts are intentional or unintentional. Furthermore, a lack of attention was observed in patients with TBI [77]. This disrupted attention is associated with disrupted functions in DMN and salience networks. Due to the importance of attention during intentional mind wandering, this form of mind wandering could be disrupted in these patients. This issue could be investigated in future research.

We had some limitations in our study. First of all, we did not have any questions about the rest part of the experiment. The existence of spontaneous or unintentional thoughts during mind wandering was based on assumption. However, it was also possible that participants engaged in self-generated thoughts intentionally. For example, they might do future planning while they were asked to rest. For future work, it would be better to have a question part about the occurrence of unintentional thoughts during the rest part. However, asking these questions at each block during the fMRI session would affect the intentionality of mind wandering and make the participants aware of their internal thoughts. Therefore, these questions need to be asked after the fMRI session.

Secondly, there was no statistical fMRI analysis of the experiment's first and second questions. For further studies, the different brain regions' activation could be investigated during the high rates of mind blanking versus low rates at the first question. Moreover, the similarities in brain activities can be explored between the second question, where we asked about intentional mind wandering and the think part of the experiment.

The current study shed light on the importance of investigating the two forms of mind wandering seperately. Moreover, we found a novel activity pattern in the anatomical and functional MD network's regions since they responded differently to two forms of mind wandering.

Chapter 5

Supplementary material

5.1 Individual brain maps

The statistical brain maps for all participants are represented in figures 5.1, 5.2, 5.3, showing the contrast between the think and the rest parts of the experiment (think - rest). To make this comparison, we exerted a voxel-wise statistical test and a general linear model.

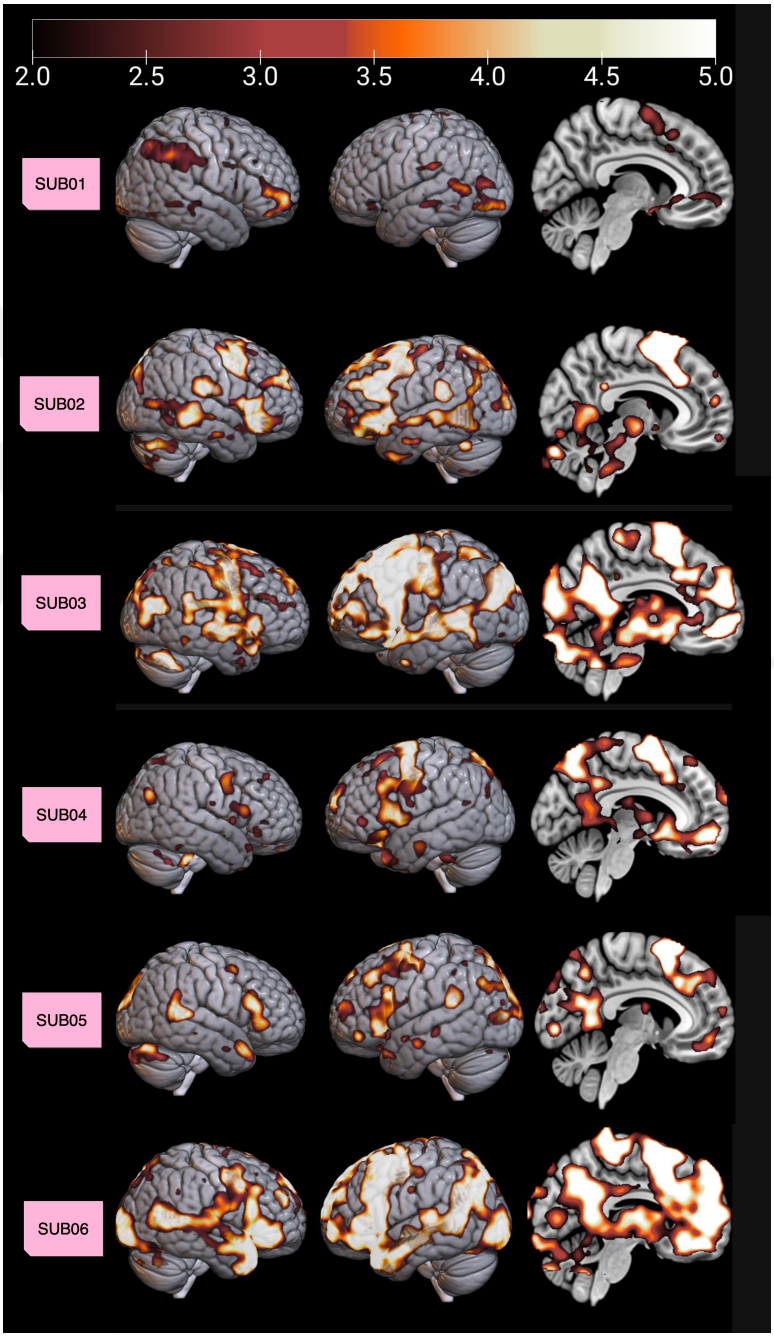

Figure 5.1: The statistical maps. The brain activations show the contrast between the think and the rest parts of the experiment (Think-Rest) in participants 1 to 6 ($q < 0.05$, FDR-corrected). The t values shown in the statistical map are between 2 and 5, from black to yellow.

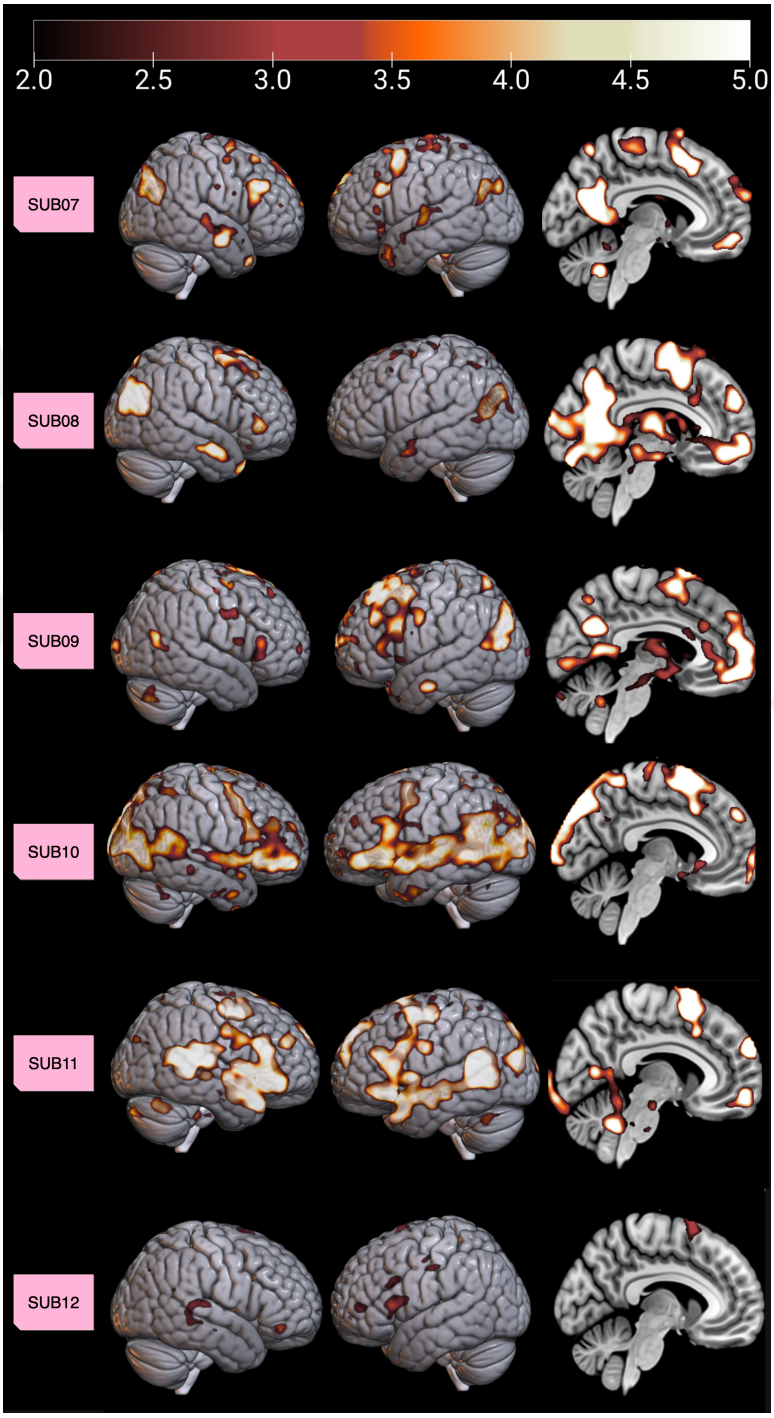

Figure 5.2: The statistical maps. The brain activations show the contrast between the think and the rest parts of the experiment (Think-Rest) in participants 7 to 12 ($q < 0.05$, FDR-corrected). The t values shown in the statistical map are between 2 and 5, from black to yellow.

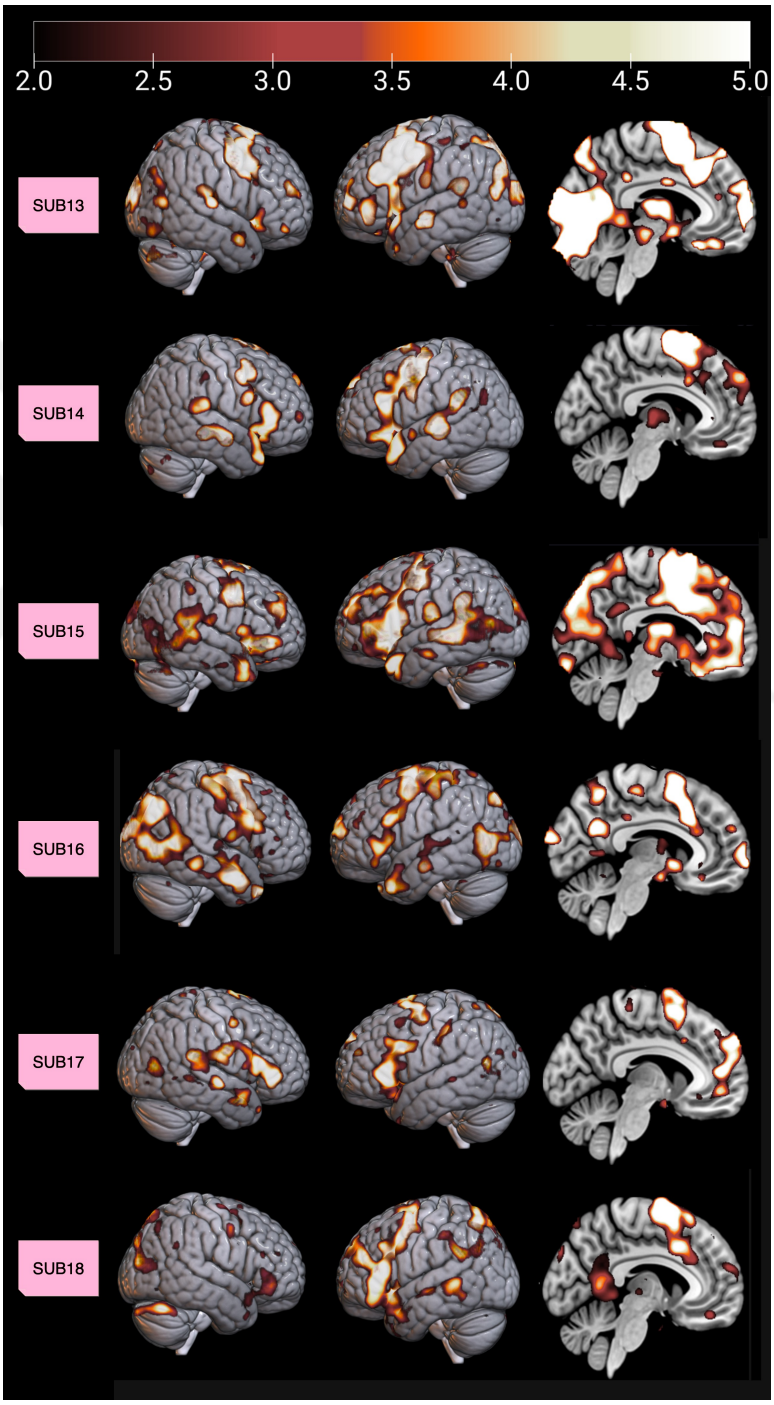

Figure 5.3: The statistical maps. The brain activations shows the contrast between the think and the rest parts of the experiment (Think-Rest) in participants 13 to 18 ($q < 0.05$, FDR-corrected). The t values shown in the statistical map are between 2 and 5, from black to yellow.

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