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Your Brain on Meditation: Rebalancing of Attention Networks

Master's thesis

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Contents

Abstract

Meditation is an age-old practice with a recent surge in societal and scientific interest. Here, benefits on attention are laid out, zooming in on rebalancing of brain-wide networks. Attention is defined as a goal-oriented behavioral state with direction of cognitive resources towards a subset of stimuli. Lapses and deficits in attention are unwanted in daily life, and are the subject of a variety of psychiatric disorders. Practicing meditation aids in a variety of attention dependent tasks, mainly revolving around top-down, executive functioning. These benefits can be traced towards interactions between three networks: the Default Mode Network (DMN), Central Executive Network (CEN), and Salience Network (SN). The CEN is recruited when performing external tasks, while the DMN is active during internal mentation and mind-wandering. The SN offers a mediating role by updating other brain areas via salience determinance, and resolving cognitive conflict. Attention consists of a constant interplay between these networks. Lapses in attention coincide with insufficient activation of the CEN, alongside insufficient deactivation of the DMN. Meditation has the ability to rebalance this interplay by skewing involvement toward the CEN. The fundamental component of meditation of repeatedly reorienting and maintaining attention likely plays a role, with practice leading to improvements in cognitive control. Underlying these findings are alterations in functional connectivity between brain regions, and increased network stability. Indeed, repeated practice gradually leads to changes in wiring via induced neuroplasticity. Findings on these principles have implications for disorders related to attention, such as ADHD, PTSD, depression and anxiety. Furthermore, the use of meditation might be of aid in wake of the recent COVID-19 pandemic. Overall, meditation provides an inexpensive and solitarily performable technique with salutary effects on attention. Its increase in popularity does not seem unwarranted.

Abbreviations

OOM Open Monitoring Meditation. **FAM** Focused Attention Meditation. **MBT** Mindfulness-Based Therapy. **MBSR** Meditation Based Stress Reduction Program. **ANT** Attention Network Test. **DMN** Default Mode Network. **CEN** Central Executive Network. **SN** Salience Network. **TNM** Three Network Model. **RTvar** Variation in reaction time. **FC** Functional Connectivity. **SCA** Seed-based Correlation Analysis. **ICA** Independent Component Analysis. **SART** Sustained Attention to Response Task. **ERP** Event-Related Potential. **ITC** Inter Trial Coherence. **EM** Experienced Meditators. *For brain regions see Figure 5.*

1. Introduction

In religious context, meditation has existed for thousands of years. The practice originates from eastern cultures, and forms one of the core fundamentals of Buddhism and Hinduism. Secular variants of the same techniques took wind in western society in the early 20th century [38]. Simultaneously, the topic became subject to active scientific analysis.

A recent resurgence again reveals itself, with meditation moving away from its religious and spiritual demeanor to reach a more mainstream appliance. This is reflected in the countless apps for guided meditations that are currently available on phones. In recent years these have seen growth in activity; downloads and subscriptions have risen sharply (Figure 1).

For many people, meditation offers an easy, solitary method to work on their mental health [38]. A large increase in practitioners is for example seen coinciding with the recent COVID-19 pandemic [5] (Figure 1). Numerous companies and universities actively promote the practice, including Google and Harvard [40, 44].

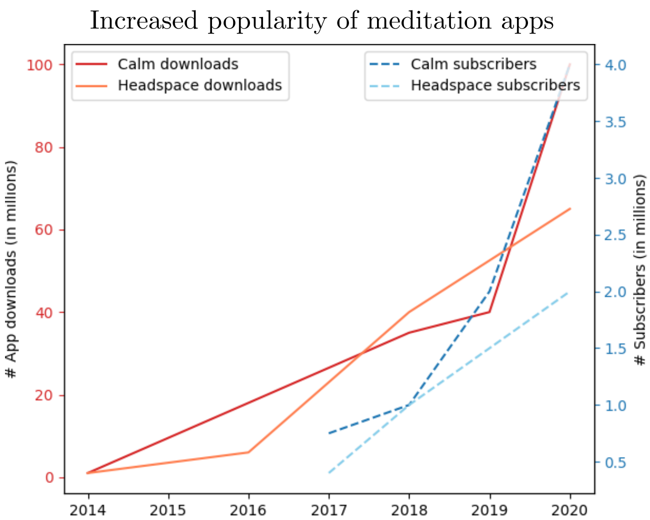

Figure 1: Total downloads and paid subscriptions for *Headspace* and *Calm*. These apps are the biggest meditation apps on mobile platforms as of 2021. Both metrics have been steadily rising over the past years. *Data from: businessofapps.com/data/app-statistics and forbes.com*

In parallel with the practices reaching a mainstream audience, research into meditation has become more widespread (Figure 2). With this, a scientifically sound foundation on the positive effects of the practice has emerged. Benefits have been found on among others: anxiety, stress, depression, PTSD, substance abuse, and the topic of this article: attention [26, 5].

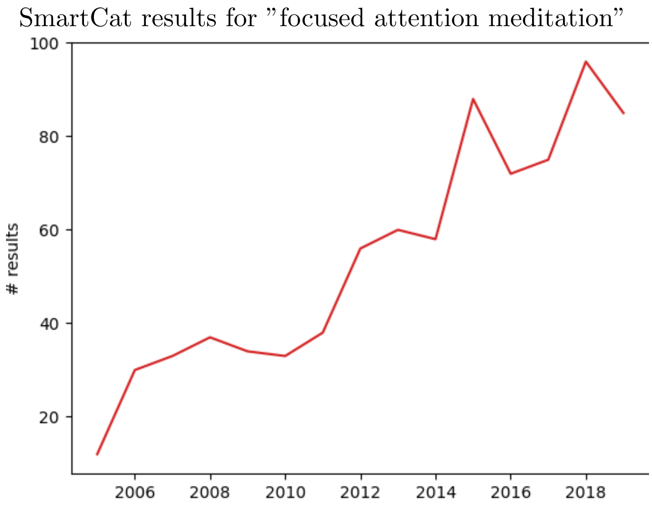

Figure 2: The number of published articles on focused attention meditation per year through time. A clear increase in number of articles can be seen. Only peer reviewed journal articles were included from *SmartCat*, the database of University of Groningen: *rug.on.worldcat.org*

Meditation and attention have an obvious connection. Indeed, respondents regularly report improving their concentration as one of the main reasons for practicing meditation [38, 26]. Furthermore, attention is the topic of a variety of psychiatric disorders, including those mentioned above.

In this paper, the effects of meditation on different aspects of attention are laid out. It aims to provide an overview of a neurobiological basis for meditation benefits. In doing so, the paper will explore in what ways this mental health fad can teach us something about networks present in our brains. This will be done through the scope of the Default Mode Network, often associated with mind-wandering [25, 51]. Other networks core to attention such as the Central Executive Network and Salience Network will be investigated. Finally, implications for relevant psychiatric disorders will be laid out. Changes in network wiring due to meditation will be analyzed using data from modern imaging techniques such as fMRI and EEG.

1.1. What is mindfulness?

The term mindfulness is rather esoteric due to its roots in long existing religions. In essence, it describes a state of being based on awareness and maintaining attention toward the present moment. The goal thereby is to become more aware of one's own thoughts, feelings and sensations, while keeping the mind away from distractors. Then, where mindfulness is the school, meditation is the practice. In a meditation session, the practitioner aims to train their mindfulness. These terms are often used interchangeably in mainstream language.

Two similar meditative techniques with regard to concentration and attention repeatedly surface in the methodology of scientific articles [1, 26, 25, 35]. Usually the techniques are performed while sitting, and with eyes closed. Both forms revolve around noticing and awareness, and repeatedly reorienting attention:

Open Monitoring Meditation (OMM): The general gist of OMM is to notice whatever arrives in consciousness, without acting on it. This includes internal states, and sensations with an external origin. The idea is to not pay close attention to any particular sensation, or to follow a train of thought. Instead, you only acknowledge their existence, while keeping attention open. One returns to the open mind upon realisation of being lost in thought.

Focused Attention Meditation (FAM): This method consist of paying close attention to an object in the mind, and trying to notice every detail thereof. In a practice, the object is for example often your own breathing. The goal is then to fully cover each breath with your attention. Once again, the practitioner returns to attention whenever invariably the mind wanders.

In reality differing forms of meditation are largely overlapping in ideas and execution. Due to this, clinical research often describe them with an encompassing name of mindfulness-based therapies (MBTs) [10]. Treatments often consist of recurring sessions spanning multiple weeks. For instance, many articles use an adapted form of the Mindfulness Based Stress Reduction program (MBSR) [26]. This program offers a standardized 8 to 12-week training into mindfulness. Group sessions are given weekly, and generally last 1–2 hours. In addition to these classes, home practices are expected. Second, multi-day retreats are sometimes engaged in, and with that the subject of research. Participants here are expected to meditate for multiple hours per day, usually spanning a total of 3–10 days. Retreats are often reserved for experienced meditators due to their intensive nature.

2. Attention, and the Attention Network Test

Attention is defined as selective concentration on a subset of incoming information, while ignoring the rest. As such, it is the direction of limited cognitive resources toward a desired subject. Attention can be described as a goal-oriented behavioral state.

Everybody recognizes temporary lapses in attention. While reading you catch yourself daydreaming, and you suddenly realise a paragraph has gone by without registering anything. You forget what you were planning to do, or you lose a train of thought while writing an essay. Less harmless forms of attentive lapses can be found in accidents such as in traffic or harmful work-related incidents [51]. Furthermore, attention has an obvious link to memory; that what is paid close attention to is more likely to get consolidated. In line with this, learning disabilities are seen in around 20–30% of ADHD diagnosed children [48]. Lapses in attention show a relation to the amount of memory failures, and lead to cognitive errors [11]. Maintaining concentration is beneficial both for one's productivity and quality of life.

A variety of psychiatric affections are known to alter certain aspects of attention [42]. Most well known are ADHD, OCD, and ASD. Some less obvious conditions are also associated with alterations in attention networks. For example, anxiety disorders are seen as an inability to inhibit fear and worry about the future, and depression as recursive negative ideation. Furthermore, PTSD is seen as a strong attentional bias towards triggering stimuli [19].

Many disciplines from pedagogy to psychology, and from neuroscience to philosophy are interested in the topic of attention. It stretches subjects like working memory, sensations, thoughts, and consciousness. With the march of modern brain imaging techniques, neuroscientists have built comprehensive frameworks of attentional processes.

2.1. Types of attention

A general framework on the functional components of attention was presented by Knudsen [30], and is shown in Figure 3. This model distinguishes between two general streams of information: bottom-up and top-down. Bottom-up represent sensory information that is filtered for importance in a process called salience determinance. With a high enough signal strength, the stream enters attention networks. The information eventually competes for space in the working memory, where it is used for decision-making. Otherwise, a top-down voluntary cognitive control is performed to allocate attention. This is represented by behavioral orientation, and sensitivity control over incoming stimuli.

In the clinical model of attention, multiple types are discerned [45]. These include sustained: maintenance of attention on one subject, spanning longer periods of time; focused, or selective: the ability to discern importance between multiple subjects, and to prioritize one; alternating: a cognitive switch necessary for alternating between tasks or subjects.

In line with these types, Posner and Rothbart [41] describe three networks of attention, shown in Table 1. They were defined using brain imaging in behavioral and genetic studies to create a neuroscientific basis for the psychology framework of attention. Each network represents cooperating brain structures with a function to facilitate a specific aspect of attention. Associated with the networks and their functions is the often used Attentional Network Test (ANT) [42, 20]. A specific test was designed for each network, so that they can be tested independently. The computer based test measures reaction time on a varying presentation of cued stimuli, including content determinance via congruent/incongruent stimuli (Executive), spatial location (Orienting), and temporal-onset (Alerting) [20]. Research on attention often uses the ANT and the corresponding networks.

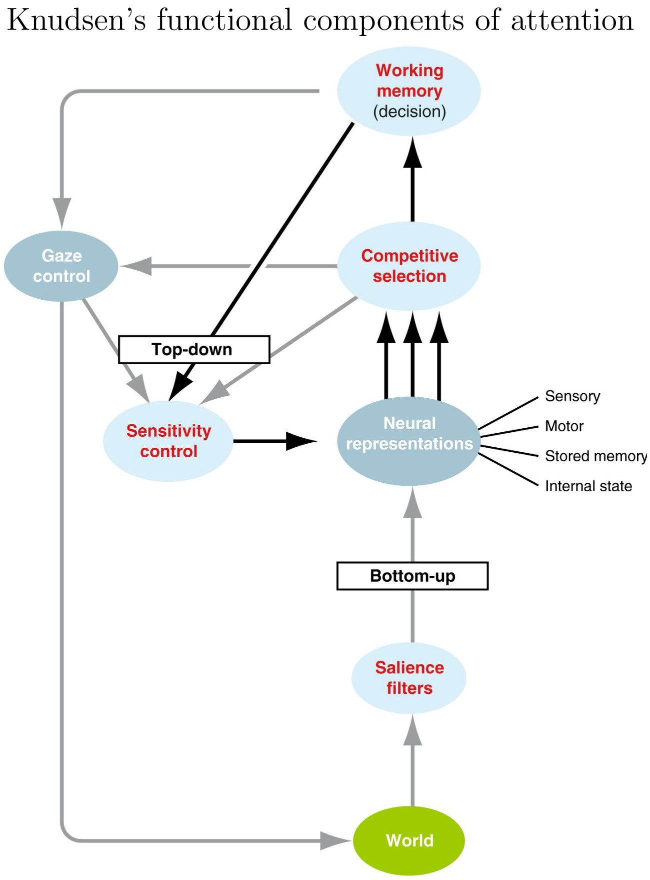

Figure 3: Sensory information from the world enters the brain and is transported further. Neural networks determine importance via salience filters (bottom-up). For example, infrequent or dangerous stimuli are responded differentially towards. Information is then further processed and incorporated with representations about emotional state, movements and memories. Via a processes of competitive selection, signals with the highest strength are given access to the working memory. This in turn regulates behavior and decision-making. Biases to signals are given from the working memory to neural representations via a top-down process called sensitivity control. Similarly, orienting behavior such as gaze control is determined. Red text represents processes of attention. The loop of top-down control is shown as dark arrows. *Figure from Knudsen [30].*

Table 1: The three ANT networks and their contents as defined by Posner and Rothbart [41]. *Table adapted from Posner et al. [42].*

	Function	Structures	Primary modulator
Alerting	A constant state of vigilance and sensitivity toward an incoming stream of stimuli.	Locus coeruleus Frontal and parietal cortex Thalamus	Norepinephrine
Orienting	Selecting the relevant parts out of a stream of sensory input. This represents both top-down and bottom-up influence on orienting behavior.	Superior parietal Temporal parietal junction Frontal eye fields Superior colliculus	Acetylcholine
Executive	Controlling voluntary responses represented by top-down control of conflicting targets.	Anterior cingulate cortex Prefrontal cortex Basal ganglia Anterior insula	Dopamine

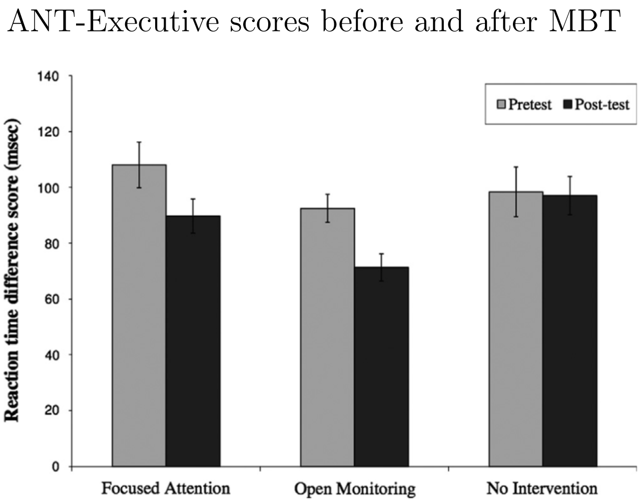

Figure 4: MBT on either FAM or OOM significantly improved reaction time on ANT-Executive (p=.002 and p=.001 respectively). No difference was seen in control group-time interaction. *Figure from Ainsworth et al. [1].*

3. Influence of Meditation on Attention

A paper by Ainsworth et al. [1] examined effects of MBT on the ANT. Participants were naive to meditation, and practiced either FAM or OOM in group session and at home for eight days, with a negative control present. Both the FAM and OOM groups performed better on ANT-Executive, with no difference for the control group (Figure 4). Beneficial effects were exclusive to Executive, and not seen in Orienting or Alerting. Finally, a self-reported measurement of mindfulness correlated with the pre-test scores in ANT-Executive.

Using the Stroop test, a paper by Allen et al. [2] reported on the effects of FAM and OMM in naive participants, compared to a cognitively active control group. The latter group consisted of shared reading and listening sessions, thought to train working memory recruitment and attentional control. Here, the MBT group showed substantial improvements in the Stroop conflict score, both when compared to the control group (group-group interaction), and when comparing pre- and post-treatment (group-time). This score is thought to represent top-down control over conflicting stimuli. Next, both groups were tested on the error-awareness task. Both improved scores on stop accuracy in this task, but importantly scores for the MBT group correlated with amount of total practice during the training. An improvement here reflects better inhibiting cognitive control.

Finally, a recent study by Ziegler et al. [55] with young adults found beneficial effects on sustained attention and working memory via use of a mobile app. The type of meditation taught therein was akin to FAM, and consisted of daily home treatment over 6 weeks. A placebo group was added consisting of other app use such as language learning apps. App use consisted of short training trials, starting at 20 seconds. Participants were to monitor whether their mind wandered during this time. If a lapse of attention was reported, trial time went down, otherwise duration increased. Over the course of six weeks, average trial time gradually increased to 47.5s at the end of the first week, and to 346s at the end. This indicates a self-reported decrease in frequency of lapses of attention.

To test sustained attention, a vigilance task was used. It requires attention over an extended period, with distractability and mind-wandering events resulting in worse scores. Lower variability in reaction time (RTvar) here indicates a decreases in number of lapses in attention. Deficiencies in RTvar are seen in those with dementia, ADHD and mild cognitive impairments. A significant decrease in average RTvar was seen in the meditation group, meaning improved sustained attention. The finding significantly differed in comparison to the placebo group, which showed no improvements. A regression analysis on trial duration versus RTvar revealed that those who advanced the most time also scored better on sustained attention.

Next, a cognitively demanding task was given to test working memory. The test consists of visual discrimination with distracting stimuli present. Again, RTvar is taken as a measure. And again, improvements were found for meditation in a group-time and group-

group analysis. As a second measure, the number of items held in memory across a delay was tested. Similar results were found here, with more items remembered by the meditation group. These findings again suggests better top-down control over attention, namely via improved working memory.

Combining the above results suggests meditation improves cognitive and executive control over attention. This subsequently leads to fewer lapses, and benefits sustained attention.

4. Three Network Model

This section will explore alterations in brain activity underlying the mentioned benefits on attention. Several widespread networks are discussed. Resulting is a conceptual view on the different modes a brain can be set in to achieve a goal behavior. Once in one of these states, several distinct brain areas will coincide in activity. The networks are orchestrators of behavioral complexes, and regulate processing and passing of information between areas. With this, attentional lapses can be viewed as faulty setting and switching of modes.

Three entwined networks are often discussed in literature on attention processes: the Default Mode Network (DMN), Central Executive Network (CEN), and Salience Network (SN). Regions associated with each are laid out in Figure 5. This three network model (TNM) was first constructed in a landmark paper by Menon [37]. Dysregulation due to altered connectivity within or between the networks has been associated with a large variety of psychiatric disorders. They show obvious involvement in attention related processes, and are the subject of many articles concerning meditation. Brain regions of the CEN and SN in this model largely overlap with those of the ANT (Table 1).

The CEN is associated with goal-oriented behavior. As such, it plays a role in decision-making and problem-solving, and is the locus for working memory. Cognitive control over attention is ascribed to activity of this network. Next, the DMN is thought to be associated with mind-wandering [25, 51]. Activity is seen during internally directed thoughts and self-reflection [16]. For instance, the DMN is operating when a person is lamenting about the past, or imagining the future. This idea is directly relevant to meditation, which concerns itself with the temporal now, while viewing internal mentation as a lapse in awareness. Finally, the SN is crucial for detection and filtering of incoming stimuli, or bottom-up processing. With that, it plays a role in recruiting and updating other brain areas.

4.1. Anticorrelation of the DMN and CEN

The DMN and CEN are referred to as the task-negative and positive networks respectively. When a person is in rest the DMN shows persistent activity; ergo the name "default mode". When performing a task however, the CEN is switched on, while DMN activity diminishes. In other words, the DMN and CEN are

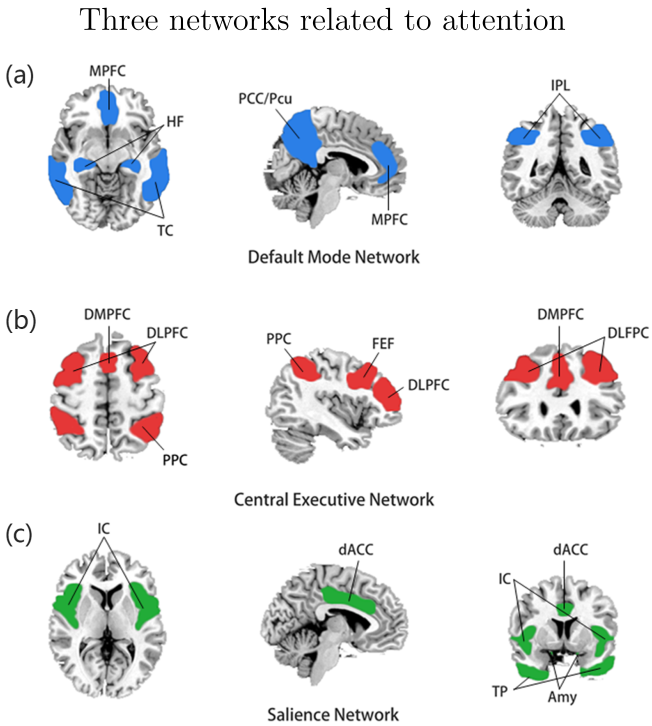

Figure 5: Presented are three brain wide networks as described by Menon [37]. Slices are presented in horizontal, sagittal and coronal planes respectively. (a) The network associated with mind-wandering. When this network is active, activity is seen in the medial prefrontal cortex (mPFC), posterior cingulate cortex (PCC) and percuneus (Pcu), hippocampal regions (HF), and parts of the temporal cortex (TC) and inferior perietal lobule (IPL). (b) Top-down control over attention is regulated via this network. It consists of parts of the prefrontal cortex, such as the dorsomedial (dmPFC) and dorsolateral (dlPFC), the frontal eye field (FEF), and the posterior parietal cortex (PCC). (c) The network responsible for salience determinance. Regions associated are the insular cortex (IC), dorsal anterior cingulate cortex (dACC), temporal pole (TP), and amygdala (Amy). *Figure from Dai et al. [16].*

associated with inward and outward focus of attention respectively.

In fMRI studies, the networks show a great level of anti-correlative firing between each other. In line with this, insufficient deactivation of the DMN and impaired CEN firing has been found to impair scores on attention tasks. An often cited article by Weissman et al. [51] looked at the interplay between these regions during lapses in attention. A conflicting stimuli task was given to participants, requiring cognitive control and selective attention. Sustained activity in DMN regions such as the precuneus is seen pre- and post stimuli. Only when a test stimulus is given does activity suddenly transiently drop. Coinciding with longer reaction times and a high RTvar were relatively high levels of activity in a number of DMN areas including the precuneus, IPL, PPC, and middle frontal gyrus. At the same time, reduced activity during lapses was found for the ACC, and inferior frontal gyrus, where the dlPFC is located.

The mentioned results lead to a conceptual view of diverting from default activity and reallocating attentional resources when a task is at hand. A clear task induced inactivation of the DMN is seen, with simultaneous activation of the CEN. During inattention, reallocation is insufficient, and DMN activity seeps through.

4.2. Temporal network states during meditation

Interplay between the three networks during a meditation session was elucidated by Hasenkamp et al. [25]. Again, the idea of DMN activity during lapses in attention is explored. Meditators experienced in FAM were invited for an fMRI study. Whenever they noticed their mind-wandered, a button was to be pressed. Then they returned to the practice by again focussing on the breath. This way the authors hypothesised four distinct phases within a cognitive cycle. A graphical representation of this is shown in Figure 6.

Brain activity was mapped onto these subjective phases. Analysis revealed that the mind-wandering phase was indeed associated with DMN activity. Then, during awareness, regions involved in salience activated. Finally, during shifting and sustained attention, the CEN was seen firing.

The authors describe the AWARE state as a conflict between current state (MW), and cherished state (FOCUS). Indeed, activity of the ACC and insula was seen during this state, involved in the SN, representing updating of information to the present state of awareness.

Activity seen in the SHIFT phase overlaps with regions associated with the CEN, including the lPFC and PPC. As is the function of the CEN, during this phase attention was reoriented and directed back to the goal at hand [51]. VmPFC activity was still seen here, as during MW, suggesting a gradual shift from DMN to CEN.

Finally, activity of the dlPFC was observed during the FOCUS phase. This area is core to the CEN, and activity has been associated with maintaining sustained attention. Together with SHIFT this phase represents executive action.

Using the button press as an indication of mind-wandering provides a convincing subjective layer to DMN research. Lapses in attention during a meditation session are visualized, elucidating the cognitive control performed to again focus attention. As will be discussed, the cycle of repreatedly reallocating and sustaining attention seems integral to the observed benefits of meditation.

4.3. Changes in functional connectivity

A variety of studies explore the influence of meditation on brain activity and functional connectivity (FC) within the TNM. Many cite the DMN-CEN anticorrelation.

During the Stroop task in the previously mentioned paper by Allen et al. [2], fMRI scans were performed. Coinciding with task processing, higher levels of dlPFC activity were seen in the MBT group. Indeed, this was true for group-group and group-time interactions.

Similar results were found in a recent article by Kwak et al. [33]. Participants naive to meditation performed the ANT before and after a 4-day retreat. The relaxation control group also spent these days at a temple, but time was treated as a vacation and no meditation was performed. Backing up earlier results, the authors found increased performance in the meditation group for the ANT-Executive, but not for Alerting and Orienting. In fMRI scans during the tests increased activity in the dlPFC and ACC was found comparing pre- to post retreat. Similar results were not found for the relaxation group, which even showed statistically significant decreases in activity of the regions. Following a regression analysis, right ACC activity was found to be a significant predictor of Executive test score.

Next, in a recent article by Bauer et al. [4], the DMN-CEN anticorrelation was explored. Here, MBT was given to children at school. A positive control consisted of computer programming classes. Before and after the training, a Sustained Attention to Response Task (SART) was given, measuring both sustained attention and response inhibition. Accuracy scores improved only in the mindfulness group in a group-time analysis. Concurrent with the task the authors performed an ICA to measure FC. Before training, accuracy for all participants already correlated with greater anticorrelation between the CEN and DMN. Moreover, the mindfulness group increased anticorrelation after training, with again no difference for control. This relationship was reduced specifically to an interaction between the DMN and the right dlPFC. Indeed, for the meditation group, a stronger change in anticorrelation between these areas was associated with a larger change in accuracy scores following a regression analysis. This means that children that saw the greatest improvements in the attention task also showed higher levels of anticorrelation.

Functional connectivity

Information shared between linked brain areas can be determined via functional connectivity (FC). FC is defined as temporal dependent activity from one region to an anatomically separated other. As such, areas that share FC can be in correlation, or anti-correlation, firing with or against one another. Using this technique, the brain can be divided into networks, with numerous areas coinciding in activity to achieve the goal at hand.

Two correlation based statistical analyses can be performed on fMRI data to determine FC: Seed-based Correlation Analysis (SCA). Here, predetermined regions of interest, or seeds, are taken and correlative activity is calculated; Independent Component Analysis (ICA). Conversely, all data is decomposed here into independent components, with synchronisation between components representing FC.

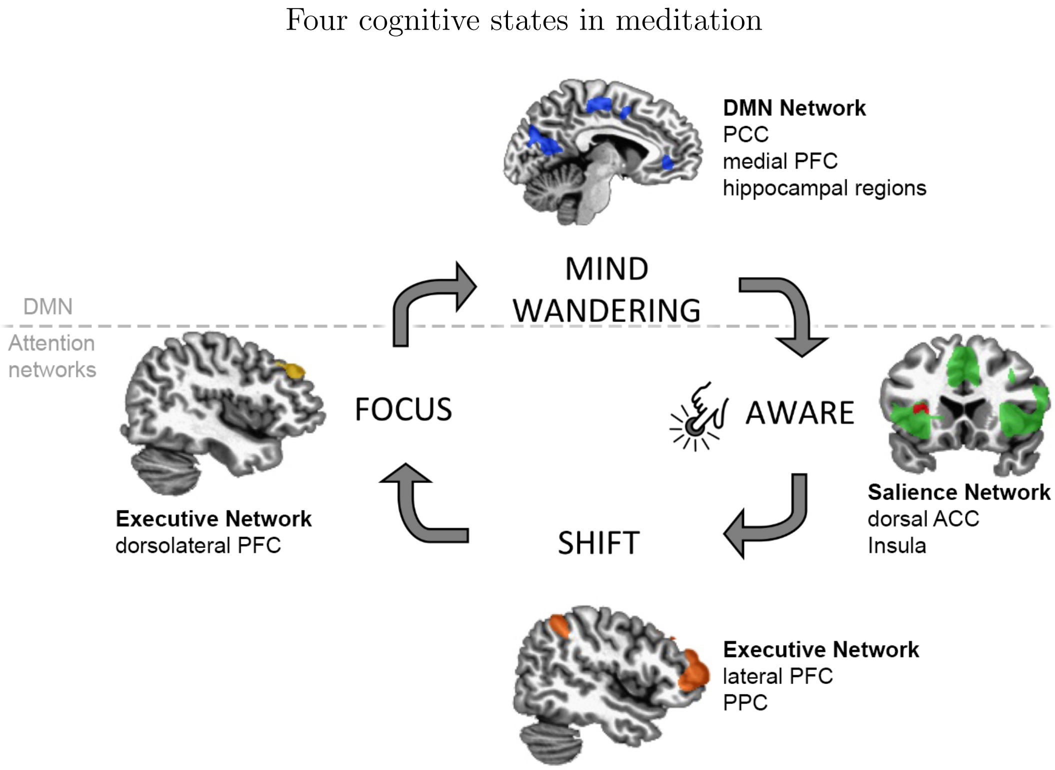

Figure 6: Hasenkamp et al. hypothesises four distinct phases present during FAM. A button press was made by participants whenever becoming aware of having a wandering mind. Each phase is presented with the corresponding active brain regions, and the network they belong to. Mind-wandering is associated with DMN activity, whereas the other states represent various attention networks (grey dotted line). The part colored red in AWARE represents part of the motor cortex active due to the button press. *Figure adapted from Hasenkamp [24].*

Finally, Brewer et al. [9] reported on the impact of meditation on the TMN both during practice, and at baseline representing a resting state. The article viewed fMRI scans during three forms of meditation, including two resembling FAM and OMM, and a third called Loving-Kindness. The control group was naive to meditation, while the experienced group had an average of 10 000h total practice time. During practice, the experienced group showed a larger decrease in overall activity in a multitude of DMN regions. Reductions were seen in DMN related PCC for all forms of meditation, and mPFC was lower for those performing FAM and Loving-Kindness. Then, an SCA was performed to view FC. Both at rest and during practice the experienced group showed remarkable differences. With the PCC (DMN) taken as the seed, increased connectivity was found both towards the dACC (SN) and dlPFC (CEN). Using the mPFC (DMN) as seed revealed stronger FC with the insula (SN).

Concluding, meditation decreases DMN activity, and results in increased DMN-SN and DMN-CEN FC. With that, a decrease in DMN activity during attention tasks results in improved scores. Increased activity of top-down CEN occurs simultaneously, attributing to more DMN-CEN anticorrelation. Furthermore, changes were seen during meditation, but persisted in a resting state. Combining the results suggests a shift in balance within the TNM, such that attention becomes stronger, and lapses occur less frequently. Indeed, the changes in functional connectivity observed in meditators maps onto the four phases by Hasenkamp et al. [25] (Figure 6). By repeatedly reallocating cognitive resources from a mind-wandering state to a focused state, the mind seems able to be trained to shift network balance. Wandering is more often noticed by the SN, and attention is sustained longer by the CEN.

4.4. Top-down dlPFC control, and a mediating role of the SN

Key players in results on the TNM seem to be the dlPFC and ACC. As mentioned, the dlPFC is integral to the CEN. The area is implicated in cognitive control, the type of cognition that is tested by the Stroop, SART, and ANT-Executive tasks. Altered activity in meditators explains why benefits with regard to attention are seen for top-down control especially. With that, the area aids in maintaining attention on a wanted set of stimuli. Specifically, robust firing was found during rehearsing, or repeatedly reciting pieces of information [17]. This perfectly aligns with FAM, where repetitive attention to one object is central.

With regard to the ACC, apparent conflicting involvement is seen. In the ANT model, the region is ascribed to the Executive network (Table 1). However, in the TNM it is deemed part of the SN (Figure 5). As mentioned, the SN is generally attributed to external stimuli and bottom-up processing. The article by

Hasenkamp et al. [25] however suggests the regions to be involved in internal salience determinance, as it is involved in becoming aware of mind-wandering. Function of the regions during meditation might therefore be more akin to sensitivity control as seen in Figure 3.

In line with this, ACC activity was seen following a stimulus in the cognitive task of the Weissman et al. [51] article. Indeed, lapses in attention were associated with reduced activity in the area. Similarly, as mentioned, ACC activity correlates with ANT-Executive performance [33]. Central to this task is determinance of conflicting congruent and incongruent stimuli. As has repeatedly been reported, the ACC monitors cognitive conflict [33, 51]. As such it works together with executive brain regions by updating them with information to aid in resolving conflicting stimuli. Conflict resolution is seen as core to cognitive control.

These findings could explain the apparent disparity seen between the TNM and Posner's networks. Nodes core to the SN appear to closely cooperate with those of the CEN. Implicated is a mediating role of the SN between the other two networks, aiding in the shift from decreased DMN presence to increased CEN activity in meditators.

4.5. Network stability in DMN-CEN interplay

Continuing on resolving of conflict, results from EEG studies suggest an interesting change in network stability. These go hand in hand with altered connectivity, so that meditation might result in increased information transfer effectiveness and efficiency.

During the previously cited article by Ziegler et al. [55], EEG measurements were performed concurrently with the sustained attention task. An independent control group was added especially for this part. Here, two often used measurements of EEG were analysed: P3b event-related potential (ERP) latency, and theta wave power and inter trial coherence (ITC). P3b activity is found in the parietal cortex, whereas theta oscillations are collected in the frontal midline.

ERP represents measurable brain activity following a sensory or cognitive event. Of this activity, P3b is a distinct segment, and latency represents the time between event and potential. In the article, lower RTvar correlated with lower P3b latency in the independent control group. Significantly lower latency levels were found for the meditation group both in group-time and group-group interactions.

Another article combining fMRI and EEG finds P3b activity to stem predominantly from an interplay between the IPL (DMN), precuneus (DMN), and PPC (CEN) [6]. Activity of P3b has been implicated in allocation of attentional resources, and updating and retrieving of working memory [23, 55]. The start of the segment represents a solve of uncertainty, so latency is a function of the time it takes to successfully evaluate stimuli [23]. Latency increases with task related cognitive difficulty, and correlates with cognitive decline. Furthermore, those with ADHD have higher latency measures for P300 measures, of which P3b is a component, on a go/no-go attention task [29]. Evidence implicates P3b to be associated with executive function [23, 49, 29]. Indeed, using a choice-response task, one often cited article links perception of stimuli to decision-making reaction thereto as a role of P3b [49]. This idea is congruent with one of the main themes of meditation: noticing of lapses in attention followed by redirecting awareness. A decrease in P3b latency due to meditation suggests a more stable interplay between networks, leading to more efficient attentional resource allocation.

For the second EEG measure, ITC represents how consistent in frequency and latency a network or area is activated across different trials of a task. Thereby, it is a measure for network stability. Both stability and power are used as markers for improved attentional control of networks. In the article, both measures for theta activity correlated negatively with RTvar in the independent control group, suggesting a beneficial association with attention. Indeed, improved ITC was seen in the meditation group comparing pre- and post-training, and post compared to placebo. Findings could be specifically localised to increased ITC levels both in the medial (DMN) and lateral (CEN) PFC for the meditating participants.

The mentioned results suggest an interplay between elements of the CEN and DMN in maintaining attention. In this interplay, reduced P3b latency and increased ITC both point toward increased network stability. This stability is then beneficial to attentional processes.

5. A Gym for the Mind: Experience in Meditation

The results mentioned in section 4 indicate lasting changes in firing in the brains of meditators. Results are found for increased network stability, and altered FC between the three networks. This leads to a view of meditation practice induced neuroplasticity, with repeated cognitive training leading to gradual rewiring. Neuroplasticity here describes changes in brain activity over time that occur in response to experiences.

Indeed, a commonplace theme in mindfulness is that it is a skill which can improve with amount of practice. Parallels are often drawn to workouts in the gym, but for the mind instead of the body. Experienced meditators in FAM or OMM have a higher degree of conscious awareness over inner mental states [35]. This backs up buddhist texts and claims by meditation apps that practice gets better with time, and that less effortful concentration is required; something that is sometimes facetiously described as an increase in "the number of notices per minute": you increase the frequency of conscious awareness of thoughts and stimuli. A variety of articles focus on experience in meditation, with results indeed reflecting the idea of neuroplasticity.

5.1. *Gradual changes in firing in the three network model*

The amount of practice time correlated with multiple findings in the Hasenkamp et al. article. During SHIFT, more cumulative hours was indicative of less activity in the vmPFC. The authors discuss that this might be due to less effort required in this group to exit MW. Then, the shift from DMN to CEN goes faster, and less overall activity is seen.

Next, an fMRI study on FAM by Brefczynski-Lewis et al. [8] compared new meditators (NM) with no prior experience to experienced meditators (EM) with 10 000–54 000 practice hours. When comparing overall activity during a session, NM showed substantially higher mPFC, indicative of more DMN activity. For EM, more dlPFC activity was seen, along with various other attention related regions including the superior- and frontoparietal (CEN/Alerting and Orienting), frontal eye field (CEN/Orienting), and anterior insula (SN/Executive).

Interesting to note in this study are results for a subset of the EM group with the most practice hours; on average twice as much. Data for the whole group were divided into low EM and high EM. Mapping the activity levels in attention related regions from NM→EM→lEM→hEM now show inverted-U curves. Activity increases until lEM, but then sharply drops in hEM, back to NM levels. The authors discuss this citing their own work on P3b ERP after intensive 3-month long meditation retreats [47]. Participants in this study showed a substantial decrease in attention resource allocation, without impaired performance on the task, backing up earlier EEG results.

These results suggest that experience in meditation goes through a cycle: first more training results in a better ability to activate and aim attention networks toward staying focussed. Finally, a point is reached where less attention resources are needed to be able to maintain attention at all.

5.2. *Amygdala activity and salience of stimuli*

As a final measure, Brefczynski-Lewis et al. investigated the effect of a distracting sound cue. Following one, EM was found to have less activity in the PCC and precuneus, both associated with the DMN. This suggests attention is disturbed less by unexpected stimuli via reduced salience in those trained in meditation. Furthermore, the amount of practice hours correlated with less amygdala activation, especially for sounds that evoked negative emotions. Indeed, the amygdala is a powerful emotional hub, and is central to the SN (Figure 5) [32, 19].

In a follow-up study from the same lab, this finding was explored further [32]. Here, participants with differing experience levels were shown emotional pictures that were to elicit positive, neutral or negative feelings. EM were trained in OMM and FAM, while the short term group (ST) was naive to meditation, but completed an MBSR course for the experiment. Participants were not actively meditating, which backs up persisting cognitive changes. Compared to control, reduced amygdala activity was seen both in ST and EM for positive images. Furthermore, EM showed less activation difference in the region between neutral and affective (negative and positive combined) images. In this group the amount of retreat hours correlated with a reduction in amygdala response to negative images. In a questionnaire, EM reported higher non-reactivity towards the negative pictures. This finding correlated between participants when plotted against the amount of amygdala activity, so that those with more activity reported higher levels of distress.

The authors explain this through increased FC between vmPFC and amygdala. This was true for ST but interestingly not for the EM group. The PFC is known as a powerful inhibitor and modulator of other regions, and is highly interconnected with the rest of the brain. Specific to the vmPFC is an involvement in regulation of automatic emotional reaction. The authors explain the difference between ST and EM again via a possible inverted-U curve. Completing an MBSR course would have wired a vmPFC inhibition of emotional reactions towards affective images. Again however, the non-reactivity in EM might be explained as a more automatic reduction in salience of affective stimuli, without the need for vmPFC recruitment.

The findings back up the mediating role of the SN, now in the form of an inhibitory connectivity between the vmPFC and amygdala. In this framework, meditation as a practice of top-down supervision over the mind's reactivity leads to lasting changes in mental processes. Experience in meditation then leads to extinction of previous automatic connections, and rewiring of habitual responses. Combined, results on experience suggest activity-dependent plasticity such that the brain eventually reacts differently to stimuli, and during attention. The core meditative concept of repeatedly reallocating and sustaining attention again is likely fundamental in inducing these changes.

6. Using MBT for Psychiatric Disorders

6.1. *PTSD, anxiety and depression*

The results on the connection between the vmPFC and amygdala is of particular interest to PTSD. This disorder is characterised by overwhelming orienting behavior, with high stress levels and hyperfocus [19]. Associated is a strong attentional bias following and towards triggering stimuli. One study by El Khoury-Malhame et al. [19] explored the role of the amygdala in PTSD patients. Here a gross overactivation of the amygdala was found following a visual task eliciting emotional responses. Furthermore, amygdala activity correlated with anxiety levels. In a second task, patients were found to have an impaired disengagement of attention for words eliciting a negative emotional reaction. In line with this, a recent review article by Boyd et al. [7] cites reduced connectivity between the vmPFC and amygdala in those with PTSD, with hypo- and hyperactivity respectively.

Similar results are found in DMN research on depression. Sheline et al. [46] cites greater activity in the amygdala and hippocampus of depressed patients when looking at pictures eliciting negative emotions. Activity in these areas suggests more salience of negative self-referencing. In line with this, a variety of DMN nodes including the vmPFC and TC remain activated longer in these participants. Indeed, the authors cite deficits in cognitive task performance coinciding with an inability to inhibit DMN related regions like the mPFC. A recent meta-analysis back up these findings, and notes the DMN to be critically involved in ruminations seen in depression [53]. Similar patterns are visible in anxiety states [15]. These findings reiterate the idea that negative ideations linger longer in the brains of those with depression and anxiety. As such, the TNM shifts toward inward focussed activity, with an inability to suppress this emotional state when task-positive activity is required.

The results on altered brain activity due to meditation have implications for attentive emotional dysregulation. Indeed, the mentioned disorders show an important interplay between their emotional and attentional components. Less salience of negative emotions and ideations coinciding with increased cognitive control is likely to explain at least part of the emotional benefits of meditation.

6.2. Reported benefits of meditation on ADHD symptoms

An obvious disorder related to deficits in attention is ADHD. One of its core symptoms is low inhibition control coinciding with inattention. As such, those diagnosed score lower on a variety of attention tasks.

A recent meta-analysis by Cairncross and Miller [10] concludes multiple benefits of the use of MBTs in ADHD diagnoses. With regard to attention, they cite improvements both in solitary treatment, or combined with regular medication. Specifically, MBTs seem to reduce inattention, with mixed results on hyperactivity and impulsivity. Benefits are mainly found with regard to top-down control. Indeed, one mentioned study by Zylowska et al. [56] reports improvements in AND-Executive scores (Figure 7), as well as on Stroop tasks, and Trial Making Tests. The latter two require sustained and selective attention, and executive functioning. ANT-Executive post-treatment scores matched those of non-ADHD individuals in another article by the lead author. At a mean of 102ms these scores indeed match the pre-treatment of Figure 4. Again, no significant differences were detected for the ANT-Alerting and Orienting. Further, nearly 80% of participants self-reported a reduction of their total symptoms. Reported ratings for inattention dropped around 25% on average.

Again, a role of the DMN is found in those diagnosed with ADHD. An article by Liddle et al. [34] found an increase in activity of the network during a go/no-go

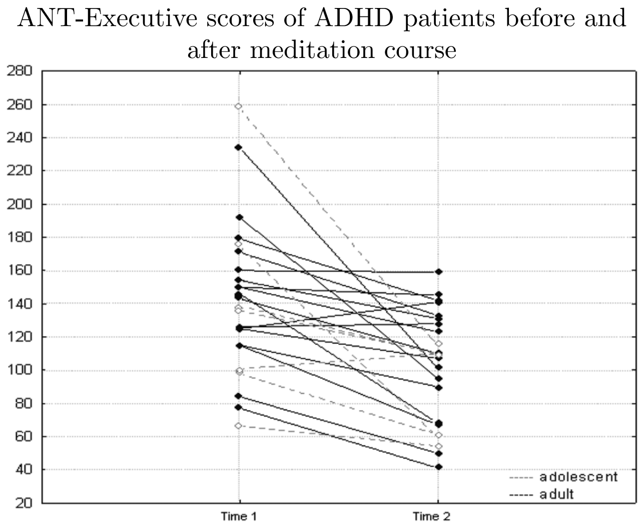

Figure 7: Participants were assessed on ANT before and after an 8 week meditation course. Adults and adolescents are plotted with solid and open dots respectively. Mean ANT-Executive reaction times (ms) dropped significantly ($p<.01$). *Figure from Zylowska et al. [56].*

task. As expected, insufficient deactivation correlated with number of task errors. Impairments of the DMN were not seen in the ADHD group on methylphenidate medication, coinciding with rescued task performance. Future experiments should elucidate on DMN activity in ADHD patients after MBTs.

Results on the benefits of meditation for the core symptoms of ADHD seem promising. However, multiple pitfalls of the current state of literature can be voiced. Cairncross and Miller mention high heterogeneity and variability between studies. The authors bring up a recurring lack of control groups, small sample sizes, and large use of subjective reports. Indeed, Zylowska et al. lacks a non-ADHD control, and a negative ADHD control, as noted by the authors. In proper follow-up clinical trials such control groups are a necessity.

6.3. Benefits of MBTs for ADHD patients over other therapies

First line treatment for adults with ADHD has consisted for many years out of stimulatory drugs [31]. Several reasons can be given why pharmacological treatment might be unwarranted. First, a substantial portion of patients are non-responsive to normal medication. Second, side effects associated with the drugs might outweigh the benefits.

Indeed, behavioral therapies are already used in cases where medication might be unwanted. Both mildly symptomatic patients and children are recommended to seek out these therapies as a first line treatment [31]. Institutions advice medication for youngsters only in severe cases where the disorder has substantial impact in daily life and school performance [12].

In line with this, (partial) remission of ADHD is often seen with age, and the diagnosis persists in around 50% of cases into adulthood [31]. Especially hyperactivity symptoms show a stark decline, with inattentiveness less so [21]. Remission is thereby often described as the development and management of coping skills [22]. This is where behavioral therapies based on meditation can shine, by providing increased cognitive control over attention.

Finally, ADHD is often seen with comorbidities including depression, chronic stress and anxiety [13]. MBTs can aid in, and were indeed popularised for these mood disorders.

Conventional behavioral therapies are known to amplify medication [10]. As an isolated treatment however, they often seem lacking in their efficacy to benefit core ADHD symptoms. MBTs in contrast show promising results, and reveal themselves as a possible aid or even replacement of normal pharmaceutical treatments.

6.4. Psychological impact of COVID-19

In the wake of the recent COVID-19 pandemic, worrying reports on mental health have emerged. Questionnaires repeatedly report high levels of stress coinciding with increased incidents of anxiety and depression [14, 27]. Indeed, a substantial percentage reports overall deteriorated mental health.

Special mention is often made of frontline healthcare professionals. Higher levels of anxiety, depression and even PTSD have been reported in these workers [43, 50]. Indeed, similar findings have repeatedly surfaced for other pandemics such as the SARS outbreak. Organisational guidelines have emerged with indicators of stress reactions including poor concentration, hypervigilance and ruminations [50].

Moreover, patients recovering from COVID-19 often report persisting subjective mental health issues including poor concentration, anxiety and depression [52]. Another article finds cognitive impairments on a variety of tasks including on working memory, divided attention and other tasks related to executive function [28]. The authors here speculate on alterations functioning of by now familiar brain regions including the PFC, and the parietal and cingulate cortex.

Research on pandemic-related distress (defined as stress responses directly related to the pandemic) found large improvements when comparing non-practitioners to those with low, medium or high levels of experience [54]. Furthermore, reduced distress was found after three weeks of autonomous practice in non-practitioners. Results were especially robust for younger participants between age 25–30. Finally, in this group self-reported measures of reduction of anxiety, depression and overall stress correlated with practice frequency. Another study reports similar findings in teachers after an 8-week MBT [36]. Benefits were found on a variety of measures including on depression, anxiety and burnout.

Meditation as a therapeutic practice seems to be able to aid in pandemic-related mental health issues. Findings seem of special interest to healthcare workers to cope with work-related emotional distress. Further, MBTs could benefit those recovering from the disease by improving cognition related to attention and executive functioning. Accessibility in the form of mobile apps is of great benefit due to lockdown restrictions.

7. Conclusion and Future Prospects

7.1. Conclusion

Meditation provides substantial benefits for attention. Underlying the salutary effects is a shift in TNM balance, such that dominance shifts from DMN towards CEN, with a mediating role for the SN. Associated is a better conflict resolution, along with improved network stability. Changes in brain activity are found both during tasks, and in a resting state. Similarly, alterations are already seen after brief MBTs, reflecting improved top-down cognitive control. Then, connectivity again changes in those with more experience, suggesting more automatic responses via altered salience determinance. Combining these results leads to the idea that repeatedly performing executive control over reallocation of attention instantiates persisting changes in the brain due to induction of neuroplasticity.

Overall, meditation provides a low cost, solitarily performable behavioral therapy. The technique is useful for anyone wishing to improve their attention, and shows to be of possible aid in a variety of psychiatric disorders. Furthermore, it could be of widespread benefit for the current COVID-19 pandemic. Salutary effects consist of improved cognitive control and reduced salience of unwanted stimuli. Finally, benefits have been found for all age ranges. The use case for children and young adults is of special interest with regard to ADHD.

7.2. Future prospects

As the field of research is still in its infancy, multiple pitfalls should be avoided in the future. First, clinical trials often lack the necessary control groups. In line with this, active controls are deemed important, but are not always adhered to. For clinical trials, these comparisons are crucial to test whether meditation has the ability to exceed other comparable behavioral therapies. The methods should aim to trigger cognitive activity in ways resembling aspects of meditation. For example, general relaxation therapy shows beneficial effects, but comes short in comparison to meditation for tinnitus [3], and anxiety [39]. Second, due to the inherent subjective nature of meditation, many clinical trials put an overreliance on self-reports. Finally, the experienced groups used in articles performed vast amounts of practice unattainable by the average practitioner. When comparing short-term to experienced meditators, confounding factors like readily existing personality types could reveal themselves.

Next, the use of apps in meditation is of growing impact. They provide guidance, and with that a lower entry barrier for those starting a practice. The use of apps is relatively cheap compared to MBT like the

MBSR course. Furthermore, they aid research as data can be collected for measurements of session time, total meditation time, latency to first lapse in attention, etc. Use is also beneficial for children, who are generally less interested in standard sessions.

Lastly, recent articles are exploring the idea of real-time self monitoring of brain activity [18]. Similar as in Hasenkamp et al. [25], shifts in brain network activity can be observed, but are now directly shown to participants. This way, a visual feedback over one's own brain activity is present, aiding in cognitive control over network states. For instance, participants can be notified of DMN activity, suggesting that they are lost in thought and should redirect awareness. Albeit still costly and difficult to perform, the concept has obvious benefits for psychiatric illness. Advances in this field should rely on finding similar assessments with more accessible imaging techniques.

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