Neural Plasticity Induced by Working Memory Training: A Decremental Spatiotemporal Model of Brain Region Distribution Based on Serial fMRI Experiments

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Abstract

Working Memory Training (WMT) induces neuroplasticity, yet its specific mechanisms remain unclear. To investigate the spatiotemporal characteristics of brain functional changes induced by WMT in healthy populations, with the "extended parieto-frontal integration theory of intelligence" and "neural efficiency hypothesis" as theoretical foundations, this study employs a layer-by-layer progressive approach to review 37 fMRI studies on WMT in healthy populations from the past two decades. First, using narrative review, frequency analysis, and chi-square test methods to compare changes in brain activation patterns and functional connectivity before and after WMT, we find that five association areas, seven macro-areas, and three sub-regions of the brain are involved in WMT. Notably, the superior frontal gyrus, inferior parietal lobule, and cingulate gyrus each exhibit more decreased activation than increased activation, with these differences being statistically significant. Second, employing activation likelihood estimation (ALE) meta-analysis on 26 of these studies, we identify three subregions showing statistically significant differences in activation levels before and after WMT: the middle frontal gyrus (BA6 and 8), superior frontal gyrus (BA6), and anterior cingulate cortex (BA24 and 32). Third, integrating qualitative and quantitative analysis results, we propose a spatiotemporal model of decreasing brain region distribution for WMT, and based on this model generate five results and discussions. Then, using non-parametric tests to further analyze potential moderating factors of WMT effects, we find that WMT task type and duration each exert statistically significant influences on brain activation. Next, regarding the spatiotemporal characteristics of neuroplasticity induced by WMT in healthy populations, we draw four conclusions: First, WMT can alter neural activity in corresponding brain regions in healthy populations, manifested as either decreased or increased activation, but decreased activation is more prominent, and newer and shorter-duration WMT tends to induce more decreased activation; Second, these changes in neural activity primarily occur in frontoparietal association areas, but also include association areas dominated by the temporal lobe, occipital lobe, cingulate gyrus, and striatum, demonstrating whole-brain functional integration within a certain range; Third, the neural activity changes in the middle frontal gyrus, superior frontal gyrus, and anterior cingulate cortex primarily reflect the spatial characteristics of WMT-induced neuroplasticity, while the superior frontal gyrus, inferior parietal lobule, and cingulate gyrus primarily reflect its temporal characteristics; Fourth, the "extended parieto-frontal integration theory of intelligence" and "neural efficiency hypothesis"respectively support the spatial and temporal characteristics of brain region distribution in WMT. Finally, we point out that future research may need to differentiate the WMT effects reflected by these three sub-regions (superior frontal gyrus, inferior parietal lobule, and cingulate gyrus) and comprehensively examine the influencing factors that cause either decreased or increased brain activation following WMT.

Full Text

Preamble

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Neuroplasticity Induced by Working Memory Training: A Spatio-Temporal Model of Decreased Distribution in Brain Regions Based on fMRI Experiments

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Abstract

Working memory training (WMT) induces neuroplasticity, but its specific mechanisms remain unclear. To investigate the spatio-temporal characteristics of brain functional changes induced by WMT in healthy populations, this study employed a stepwise approach grounded in two theoretical frameworks: the Extended Parieto-Frontal Integration Theory (ExtPFIT) and the neural efficiency hypothesis. We systematically reviewed 37 fMRI studies on WMT in healthy populations published over the past two decades. First, using narrative review, frequency analysis, and chi-square tests, we compared changes in brain activation patterns and functional connectivity before and after WMT, revealing that five association networks, seven macro-regions, and three sub-regions participated in WMT. Notably, three sub-regions—the superior frontal gyrus, inferior parietal lobule, and cingulate gyrus—showed significantly more instances of decreased activation than increased activation.

Second, activation likelihood estimation meta-analysis of 26 studies identified three sub-regions with statistically significant differences in activation levels pre- and post-WMT: the middle frontal gyrus (BA6 and 8), superior frontal gyrus (BA6), and anterior cingulate cortex (BA24 and 32). Third, integrating qualitative and quantitative findings, we proposed a spatio-temporal model of decreased distribution in brain regions for WMT, which yielded five results and corresponding discussions. Fourth, non-parametric tests analyzing potential moderators of WMT effects revealed that both task type and training duration had statistically significant influences on brain activation.

Based on these findings, we drew four conclusions regarding the spatio-temporal characteristics of neuroplasticity induced by WMT in healthy populations: (1) WMT can alter neural activity in corresponding brain regions, manifesting as either decreases or increases, with decreases being more prominent, and newer, shorter-duration WMT tends to induce more decreases; (2) These neural changes primarily occur in the frontoparietal association network, but also involve temporal, occipital, cingulate, and striatal networks, demonstrating whole-brain functional integration within a certain scope; (3) The middle frontal gyrus, superior frontal gyrus, and anterior cingulate cortex highlight the spatial characteristics of WMT-induced neuroplasticity, while the superior frontal gyrus, inferior parietal lobule, and cingulate gyrus reflect its temporal characteristics; (4) ExtPFIT and the neural efficiency hypothesis respectively support the spatial and temporal characteristics of the WMT brain distribution model. Finally, we suggest that future research should differentiate the WMT effects reflected in these three sub-regions and investigate the comprehensive factors influencing whether WMT leads to decreased or increased brain activation.

Keywords: working memory training, neuroplasticity, spatio-temporal model of decreased distribution in brain regions, middle frontal gyrus, superior frontal gyrus, anterior cingulate gyrus

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Increasingly high-pressure social environments and population aging have heightened interest in enhancing cognitive performance. Working memory (WM), a capacity-limited system for temporary information storage and processing, represents a core component of human higher-order cognitive functions and has become a key target for interventions aimed at improving executive functions (Constantinidis & Klingberg, 2016). Working memory training (WMT), emerging in the early 21st century, employs programmed WM tasks to progressively enhance WM capacity and related cognitive functions. Short-term WMT can induce neuroplasticity even after individual developmental maturity, though these changes exhibit diversity and even contradictions (Jolles et al., 2010; Schneiders et al., 2012). Consequently, the neural mechanisms underlying WMT remain insufficiently clear (Salmi et al., 2019). What, then, are the specific spatio-temporal characteristics of neuroplasticity accompanying WMT experience?

Given the close relationship between WM and intelligence, the spatial characteristics of WMT-induced neuroplasticity can be traced to the Parieto-Frontal Integration Theory (P-FIT) of intelligence (Jung & Haier, 2007). P-FIT has been tested and refined through series of experiments, evolving into the "Extended Parieto-Frontal Integration Theory" (ExtPFIT) (Gur et al., 2020). ExtPFIT extends intelligence to higher cognitive activities such as WM, focusing on relationships between advanced cognition and multimodal brain structural and functional parameters. In addition to confirming brain regions identified by P-FIT as related to intelligence—namely the dorsolateral prefrontal cortex, inferior and superior parietal lobules, anterior cingulate, temporal lobes, occipital lobes, and white matter regions including the arcuate fasciculus (Jung & Haier, 2007)—ExtPFIT newly incorporates striatal, limbic, and cerebellar regions (Gur et al., 2020). Do the brain regions altered by WMT also fall within ExtPFIT? Based on ExtPFIT and P-FIT, we hypothesized that WMT-altered brain regions would exhibit three characteristics: (1) changes occur across a series of brain regions rather than in a single localized area; (2) these regions differentially reflect WMT effects, showing either incremental or decremental distributions; and (3) among these regions, the frontal-parietal network (FPN) effects may be most prominent.

ExtPFIT further demonstrates that better WM performance is associated with greater brain volume, larger gray matter density, and increased activation within P-FIT brain regions (Gur et al., 2020). However, the "neural efficiency hypothesis" has repeatedly explained that "smarter brains are lazier." For instance, individuals with high IQ show minimal cortical activation during reasoning, with neuronal activity organized in a sparse yet efficient manner (Genç et al., 2018). Based on these two theories, we hypothesized that WMT-induced neuroplasticity would exhibit temporal characteristics where training both enhances and diminishes brain activation, with both phenomena coexisting in existing research.

We employed four stepwise methods—narrative review, frequency analysis, coordinate-based meta-analysis, and modeling—to systematically review 37 fMRI studies (42 experimental reports) on WMT in healthy populations over the past 20 years. By comparing brain activity during WM task performance before and after WMT, we aimed to detect and summarize the spatio-temporal changes in functional plasticity induced by WMT and further trace potential moderating factors influencing these changes.

1. Narrative Review of Brain Activation Changes Induced by WMT

1.1 WMT Induces Changes in Brain Activation Patterns

A review of 32 studies (36 experimental reports) revealed that WMT primarily alters activation patterns in five association networks: frontal, frontoparietal, frontoparietal-temporal, frontoparietal-occipital, and striatal regions, which exhibit decreased, increased, or redistributed activation after training.

1.1.1 WMT Induces Decreased or Increased Activation in Frontal Association Networks Short-term updating, inhibition, and verbal WMT can decrease or increase activation in frontal lobe-dominant association networks. Visual updating training decreased activation in the dorsolateral prefrontal cortex of adults (Miró-Padilla et al., 2020); auditory updating training decreased activation in the right inferior frontal gyrus of young adults (Schneiders et al., 2012) and in the right middle frontal gyrus and caudal superior frontal sulcus of older adults (Heinzel et al., 2016); inhibition training produced gradual decreases in dorsolateral prefrontal cortex activation and rapid declines in anterior cingulate activation (Milham et al., 2003); while verbal WMT both decreased activation in bilateral dorsolateral prefrontal cortex, right superior frontal gyrus, right frontal pole, and supplementary motor area of young adults (Jansma et al., 2001) and increased medial prefrontal cortex activation (Jolles et al., 2010, Experiment 1). These findings suggest that WMT may enhance neural efficiency across visual, auditory, and verbal WM modalities.

1.1.2 WMT Induces Decreased, Increased, or Redistributed Activation in Frontoparietal Networks The parietal lobe participates in WMT jointly with the frontal lobe, and short-term visual-auditory updating, spatial, and verbal WMT can decrease or increase frontoparietal network activation. Visual updating training decreased activation in the right middle frontal gyrus and right posterior parietal lobule of adults (Schneiders et al., 2011, Experiment 1), bilateral superior frontal gyrus and right supramarginal and angular gyri (Clark et al., 2017), and the frontoparietal WM network in older adults (Heinzel et al., 2014). Auditory updating training also decreased activation in the right middle frontal gyrus and right posterior parietal lobule of college students (Schneiders et al., 2011, Experiment 2). Verbal WMT decreased activation in frontoparietal-cerebellar circuits and subcortical regions of middle-aged adults (Emch et al., 2019), while comprehensive WMT decreased activation in left frontoparietal regions and left posterior insula of college students (Takeuchi et al., 2014).

Conversely, visuospatial and verbal WMT increased activation in frontal and parietal regions of young adults (Olesen et al., 2004, Experiment 1) and in middle frontal gyrus, inferior frontal gyrus, and superior, inferior, and medial parietal regions (Westerberg & Klingberg, 2007). Visual inhibition training enhanced activation in core frontoparietal inhibition regions of young adults (Kelly et al., 2006), and verbal updating training increased activation in left inferior frontal gyrus and right posterior parietal cortex of adults (Beatty et al., 2015).

Furthermore, some visuospatial WMT induced both decreased and increased activation simultaneously, producing activation redistribution. First, abacus-based mental calculation (AMC) training enhanced sustained activation while decreasing transient activation in frontoparietal regions of college students. During memory maintenance, middle frontal gyrus and superior parietal lobule activation increased, while sustained activation decreased in right inferior parietal lobule, medial prefrontal cortex, right prefrontal and right orbital frontal cortex, and posterior cingulate cortex. During manipulation, transient activation decreased in bilateral inferior frontal gyrus and presupplementary motor area, while medial prefrontal cortex activation increased (Zhou et al., 2019). Second, spatial updating training induced an inverted U-shaped change, initially increasing then decreasing activation in right inferior frontal gyrus and right intraparietal sulcus after four weeks (Hempel et al., 2004). Visuospatial WMT increased activation in middle frontal gyrus and medial, superior, and inferior parietal cortex while decreasing activation in right inferior frontal sulcus, cingulate sulcus, and left postcentral gyrus (Olesen et al., 2004, Experiment 2). Visual updating training decreased superior frontal gyrus activation while increasing left superior parietal activation (Nęcka et al., 2021). Third, longer-duration visuospatial WMT decreased activation in frontal (middle frontal gyrus, precentral gyrus), parietal (inferior parietal lobule, precuneus), anterior cingulate, and occipital regions (Garavan et al., 2000, Experiment 2), whereas shorter training additionally decreased activation in inferior frontal gyrus, superior frontal sulcus, intraparietal sulcus, and posterior cingulate (Garavan et al., 2000, Experiment 1). These two experiments by Garavan reflect reorganization of activation locations before and after training, indirectly supporting activation redistribution. Comparing them suggests that decreased activation more likely reflects improved neural efficiency, while practice may interfere with training effects (Garavan et al., 2000). Whether decreased or increased activation is regulated by WMT duration requires further verification.

1.1.3 WMT Induces Decreased Activation in Frontoparietal-Temporal Networks The temporal lobe, together with frontoparietal regions, participates in top-down adaptive processing and demonstrates good plasticity (Landau et al., 2007). Short-term item recognition and updating WMT can decrease activation across these three regions. For instance, delayed face recognition training decreased activation in frontal, parietal, and temporal subcortical regions of young adults (Landau et al., 2004); delayed object or spatial location recognition training decreased activation in lateral and medial frontal, parietal, and temporal regions (Landau et al., 2007) and in left middle frontal gyrus, right inferior parietal lobule, lateral temporal, and superior temporal cortex (Sayala et al., 2006). Visual n-back training decreased activation in superior/middle frontal cortex, inferior parietal cortex, anterior cingulate cortex, and middle temporal cortex, with WMT effects remaining stable five weeks post-training (Miró-Padilla et al., 2019). Visual emotional dual n-back training decreased activation in ventrolateral and dorsolateral prefrontal cortex, inferior parietal lobule, temporal cortex, and cingulate gyrus (Schweizer et al., 2013). These changes reflect broad improvements in neural processing efficiency following WMT.

1.1.4 WMT Induces Increased Activation in Frontoparietal-Occipital Networks As a visual processing center, the occipital lobe participates extensively in visuospatial WMT and is activated jointly with frontal or parietal regions. Relatively long-term abacus training increased activation in right supplementary motor area, right posterior superior parietal lobule, and superior occipital gyrus during digital WM tasks in elementary school students (Li et al., 2013a), and enhanced frontoparietal-occipital activation during visuospatial updating tasks, suggesting that the middle frontal gyrus serves as the neural basis for transfer from abacus training to visuospatial WM (Wang et al., 2019). Thus, WMT produces relatively fewer changes in the occipital lobe.

1.1.5 WMT Induces Decreased, Increased, or Redistributed Activation in Striatal Networks The striatum, as part of the basal ganglia, participates in updating activities, and striatal-dominant networks are similarly affected by WMT. Switching training decreased striatal activation in older adults (Dörrenbächer et al., 2020), while visuospatial and verbal updating training decreased striatal and hippocampal activation in young adults (Flegal et al., 2019).

However, visuospatial, updating, and verbal WMT can also increase activation in striatal-dominant frontoparietal-temporal-occipital networks. Both visual-auditory dual n-back training (Salminen et al., 2016) and visuospatial WM span training (Song et al., 2020) enhanced striatal activation. Visual updating training increased activation in left striatum and left frontal, bilateral parietal, right temporal, and left cerebellar regions of older adults (Dahlin et al., 2008, Experiment 1). Verbal WMT increased striatal activation in young adults and, to a lesser extent, enhanced left lateral prefrontal, bilateral dorsolateral prefrontal, and left superior parietal cortex activation (Jolles et al., 2010, Experiment 2).

Moreover, WMT simultaneously induced activation redistribution in striatal and frontoparietal-temporal-occipital networks. Digital and spatial updating training initially increased bilateral striatal activation (specifically in the putamen) before subsequently decreasing right striatal activation (Kühn et al., 2013). Visual updating training increased activation in left and right striatum, right occipital, and right temporal regions while decreasing right frontal and right parietal activation (Dahlin et al., 2008, Experiment 2).

1.1.6 Summary of WMT-Induced Changes in Brain Association Networks In summary, WMT primarily induces activation changes in five association networks: frontal, frontoparietal, frontoparietal-temporal, frontoparietal-occipital, and striatal. The involvement of numerous brain regions strongly supports WM training effects and demonstrates whole-brain functional integration within a certain scope. Furthermore, both decreased and increased activation coexist in existing experimental reports. As individuals gradually learn new memory strategies during training, the brain may undergo activation redistribution or functional reorganization, potentially reflecting general versus specific processing in brain regions (Buschkuehl et al., 2012). What, then, are the typical brain regions and changes induced by WMT in both temporal and spatial dimensions?

1.2 WMT Induces Changes in Brain Network Functional Connectivity

WMT alters the temporal correlation of spontaneously generated high-amplitude, low-frequency BOLD signals between brain regions—namely, functional connectivity (FC)—primarily within two networks during resting-state or task-state conditions (see Table 2).

1.2.1 WMT Enhances FC in the Frontoparietal Network The frontoparietal network (FPN) comprises two networks closely linked to WM: the executive control network (ECN) and dorsal attention network (DAN) (Thompson et al., 2016). Updating, verbal, visual memory, mathematical calculation, and abacus WMT can enhance FC in these networks. For example, visual-auditory dual updating training strengthened FC among frontoparietal regions of interest activated during 2-back tasks in young adults, including between ECN nodes, between DAN nodes, and across the two networks, with connectivity enhancement correlating positively with WM performance improvement (Thompson et al., 2016). Verbal WMT enhanced FC within the FPN, default mode network, and WM network in older adults (Iordan et al., 2020). Mathematical calculation and visual WMT enhanced attention network FC, specifically between right middle frontal gyrus and right temporal nodes, with this FC closely related to inhibition performance improvement (Sánchez-Pérez et al., 2019). Abacus training enhanced FC between right inferior frontal gyrus and right supplementary motor area in children (Li et al., 2013a).

1.2.2 WMT Alters FC in the Default Mode Network Some brain regions exhibit stronger spontaneous activity during resting state than task state, constituting the default mode network (DMN) that supports brain functional baseline activity. WMT can alter DMN FC. First, verbal WMT decreased FC between DMN and temporal regions in young adults, specifically between medial prefrontal cortex and right posterior middle temporal gyrus, with DMN FC reduction correlating negatively with WM behavioral performance improvement (Jolles et al., 2013, Experiment 1). Second, WMT both decreased FC between DMN and frontoparietal regions and increased intra-network DMN FC. Visual-auditory WMT decreased resting-state FC between key nodes of the peripheral attention system (medial prefrontal cortex and right posterior parietal/right lateral prefrontal cortex) while increasing resting-state FC between important DMN nodes (medial prefrontal cortex and precuneus) (Takeuchi et al., 2013). Third, WMT did not alter DMN FC in children (Jolles et al., 2013, Experiment 2), indicating age-dependent changes in DMN FC following WMT.

1.2.3 Summary of WMT-Induced Changes in Brain Network Functional Connectivity WMT not only alters activation in multiple brain regions but also changes the connectivity status of neural networks within the frontoparietal and default mode networks. This demonstrates the plasticity of brain network FC following WMT and provides potential neural-level signals for WM improvement. Moreover, FC enhancement or reduction generally corresponds to activation pattern changes, with the frontoparietal network representing the primary brain region affected by WMT. The opposing phenomena of decrease and increase coexist across studies, possibly reflecting differential sensitivity of specific brain regions to WMT. However, what are the statistical effects of these differences? This awaits future investigation.

3. Frequency Analysis and Chi-Square Tests of Brain Activation Changes Induced by WMT

We re-summarized 37 studies (42 experimental reports) based on the dimensions of decreased versus increased neural activity induced by WMT and conducted frequency analysis and chi-square tests.

First, frequency analysis (see Appendix Table 8) revealed that WMT altered activation (including redistribution) in seven macro brain regions: frontal, parietal, temporal, occipital, limbic system, basal ganglia, and other regions, encompassing 44 sub-regions. Specifically, WMT altered 15 frontal sub-regions: frontal and prefrontal cortex, dorsolateral prefrontal cortex, ventrolateral prefrontal cortex, medial prefrontal cortex, lateral prefrontal cortex, superior frontal gyrus (including medial frontal gyrus), middle frontal gyrus, inferior frontal gyrus, precentral gyrus, supplementary motor area (including premotor cortex), frontal pole, inferior frontal sulcus, superior frontal sulcus, frontal eye field, and orbital frontal cortex. It altered six parietal sub-regions: parietal lobe, intraparietal sulcus, superior parietal lobule, inferior parietal lobule (including supramarginal and angular gyri), postcentral gyrus, and precuneus. It altered six temporal sub-regions: temporal lobe, lateral temporal cortex, superior temporal gyrus, middle temporal gyrus, inferior temporal gyrus, and fusiform gyrus. It altered six occipital sub-regions: occipital lobe (including lateral occipital cortex), superior occipital gyrus, middle occipital gyrus, inferior occipital gyrus, cuneus, and calcarine gyrus. It altered four limbic sub-regions: cingulate sulcus, cingulate gyrus (including anterior, posterior, and paracingulate), hippocampal region, and temporal pole. It altered five basal ganglia sub-regions: striatum (including caudate nucleus), amygdala, substantia nigra, anterior thalamus, and pulvinar. Finally, it altered two other regions: insula and cerebellum.

Eight sub-regions with $ 9*occurrences*(*from*28*studies*)*wereselected* : *middlefrontalgyrus*(17), *superiorfrontalgyrus*(10), *inferiorfrontalgyrus*(11), *inferiorparietallobule*(17), *su*
seeoriginalpaper]).*Thedifferenceindecreaseversusincreaseratiosacrosstheseeightsub*−*regionswasstatisticallysignificant*(χ^{2}$ = 18.35, df = 7, p = 0.010).

Second, separate chi-square tests for each brain region's decrease versus increase ratio (see Table 4) revealed a statistically significant difference for the inferior parietal lobule (^{2} = 4.77, df = 1, p = 0.049), with more instances of decreased activation (13) than increased activation (4). Combined with superior frontal gyrus and cingulate gyrus, which showed only decreased activation (>10 occurrences) and no increases, we conclude that WMT induced significantly more activation decreases than increases in these three brain regions.

These analyses strongly support the brain regions mentioned in ExtPFIT. Moreover, decreased and increased activation respectively verify the neural efficiency hypothesis and ExtPFIT, with the neural efficiency hypothesis receiving greater support.

3.1.1 Literature Search and Inclusion Criteria

The search period was limited to January 1, 2000, to March 20, 2021, for articles containing both "fMRI" and "working memory training" or "training working memory" in titles or abstracts. PubMed searches yielded 73 articles, with an additional 16 identified from other review articles (Buschkuehl et al., 2012; Constantinidis & Klingberg, 2016), totaling 89 articles.

Inclusion criteria were: (1) empirical studies; (2) WMT training effects as research content; (3) healthy populations; (4) fMRI technology; (5) whole-brain analysis of peak activation coordinates pre- and post-WMT; (6) MNI or Talairach coordinate systems. This yielded 26 studies for meta-analysis: 10 from 2000–2010, 7 from 2011–2015, and 9 from 2016–2021, with 614 total participants and 294 coordinates (25 in MNI, 6 in Talairach). Figure 2 [Figure 2: see original paper] shows excluded studies and criteria; Table 5 details included studies.

3.1.2 Meta-Analysis Algorithm

Activation Likelihood Estimation (ALE) (Turkeltaub et al., 2012) was used to examine brain activation differences pre- and post-WMT reflected in fMRI data. The algorithm automatically calculates brain spatial coordinates using specific optimization algorithms, followed by permutation testing or multiple comparison correction for inferential statistics.

3.1.3 Tools and Data Processing

Data were processed using GingerALE 2.3.6 (http://www.brainmap.org/ale/) and results were visualized using Mango 4.1 (http://ric.uth-scsa.edu/mango). Talairach coordinates were converted to MNI using the icbm2tal function (Lancaster et al., 2007). All meta-analyses were conducted in MNI space. Following GingerALE manual recommendations, the FDR pID algorithm was used with a threshold of $p < 0.05$ and minimum volume of 300 mm^3 (Eickhoff et al., 2009).

3.2 Results

As shown in Table 6 and Figure 3 [Figure 3: see original paper], meta-analysis of 26 studies (31 reports) revealed two activation clusters with decreased activation post-WMT. One cluster centered at coordinates ($x = 36$, $y = 20$, $z = 40$) in the middle frontal gyrus (MFG) (100%), volume = 352 mm^3. The other cluster centered at ($x = -2$, $y = 12$, $z = 52$) encompassing the superior frontal gyrus (SFG) (93.3%, BA6, with medial frontal gyrus comprising 39.2% of this activation) and ventral anterior cingulate cortex (ACC) (6.8%), volume = 1024 mm^3. Meta-analysis of studies reporting increased activation post-WMT revealed no significant clusters. Thus, brain regions showing statistically significant differences were the middle frontal gyrus, superior frontal gyrus, and anterior cingulate cortex.

4. Results and Discussion of the Spatio-Temporal Model of Decreased Distribution in Brain Regions for WMT

Integrating qualitative and quantitative findings, we modeled the frequency analysis and meta-analysis results to propose a spatio-temporal model of decreased distribution in brain regions for WMT (see Figure 4 [Figure 4: see original paper]). This model yielded five results and corresponding discussions regarding spatio-temporal brain changes. The first three results derive from descriptive statistics; the fourth and fifth from inferential statistics that complement the descriptive results and explain WMT-sensitive sub-regions.

First, WMT effects primarily manifest as decreased or increased neural activity, with decreased effects being more prominent. Decreased neural activity is considered indicative of improved neural processing or circuit efficiency (Brooks et al., 2020; Constantinidis & Klingberg, 2016). Sustained training may facilitate a transition from controlled to more automatic processing, reducing attentional control demands, optimizing cognitive resources, and producing more efficient general neural processing (Schneiders et al., 2011). Increased activation reflects greater involvement of neural tissue, enhanced neuronal activity (Buschkuehl et al., 2012), or stronger regional brain responses (Kelly et al., 2006). WMT-induced increases in dendrites, axons, and other cellular components may constitute the neural basis for enhanced cortical activity, leading to stronger neuronal responses, increased neuron numbers, and elevated local BOLD signals. The coexistence of decreased and increased phenomena may result from WMT-induced adoption of different cognitive strategies or from different training intensities/content triggering distinct neural mechanisms.

Second, WMT effects appear across multiple brain regions including frontoparietal association networks, limbic system, and basal ganglia, with frontoparietal networks being particularly prominent. Neuroimaging studies have revealed that WM neural substrates are distributed across complex cortical regions, especially prefrontal, posterior parietal, and anterior cingulate cortices (Alagapan et al., 2019). The frontoparietal network and its sub-regions can modify functional connectivity with other network nodes according to task goals, with connectivity patterns reflecting both specific task engagement and facilitation of new task learning (Zanto & Gazzaley, 2013). This network participates in numerous cognitive processes including WM, fluid intelligence (Assem et al., 2020), episodic and source memory (Eschmann et al., 2020), visuospatial attention (Lobier et al., 2018), abacus mental calculation (Li et al., 2013), and explicit emotion regulation (Pozzi et al., 2020). This indirectly supports the frontoparietal association network as the primary site of WMT effects, with decreased activation reflecting increased automatic processing. Notably, the inferior parietal lobule prominently reflects WMT effects, participating in attentional control processes within WM networks and representing a commonly activated region in updating training paradigms (Dahlin et al., 2008; Schneiders et al., 2011). The inferior parietal lobule may also belong to an important inhibition network, with enhanced activation during inhibition reflecting improved information maintenance capacity (Kelly et al., 2006).

Third, the striatum prominently reflects WMT effects. WM updating training promotes dopamine release in the striatum, enhancing striatal activation (Bäckman et al., 2017). Increased striatal activation reflects improved maintenance and updating efficiency of WM information (Dahlin et al., 2008; Kühn et al., 2013; Salminen et al., 2016), while decreased striatal activation also aligns with the neural efficiency hypothesis, reflecting enhanced automatic processing of updating (Kühn et al., 2013) and improved cross-modal (general control) neural processing efficiency (Brooks et al., 2020). How dopamine release and striatal activation specifically improve cognitive behavior requires further investigation.

Fourth, the middle frontal gyrus and superior frontal gyrus show statistically significant WMT effects. These gyri have long been considered important brain regions participating in WM and other mental activities, with their volumes correlating with clusters in the intraparietal sulcus (dorsal parietal cortex) activated during WM tasks (Harms et al., 2013). However, evidence for middle frontal gyrus involvement in WM is more extensive (Alagapan et al., 2019).

Middle frontal gyrus activation intensity and cortical thickness correlate positively and negatively, respectively, with WM performance (Owens et al., 2018). This region influences WM performance by participating in attentional processes during WM, with activation intensity closely related to attentional information regulation (Zhu et al., 2018; Japee et al., 2015). It plays important roles in regulating attention networks (Song et al., 2019), maintaining attention network integrity (Gogulski et al., 2017), and controlling sustained attention (Han et al., 2018; Song et al., 2019; Neale et al., 2015) and vigilance (Neale et al., 2015). The right middle frontal gyrus is considered a convergence point of dorsal and ventral attention networks, functioning as a "circuit-breaker" that interrupts endogenous attention and reorients exogenous attention (Japee et al., 2015). It is selectively activated during prediction processes for changing events in visual information storage, maintenance, and updating within WM (Heinzel et al., 2016). In summary, decreased middle frontal gyrus activation reflects reduced demands on attentional control processing and flexible switching of general control processing, while rare instances of increased activation reflect enhanced task-related neuronal activity or increased numbers of participating dendrites and axons (Westerberg & Klingberg, 2007).

The superior frontal gyrus comprises two parts: one closely connected with the anterior cingulate cortex (a key node of the cognitive control network) and another connected with the middle frontal gyrus (a key node of the executive control network) (Li et al., 2013b). It participates in motor, cognitive control, and WM activities (Briggs et al., 2020), representing an important node in WM networks (Alagapan et al., 2019). BA8 of the superior frontal gyrus is more closely related to object information maintenance in spatial WM (Briggs et al., 2020). Left superior frontal gyrus endogenous oscillations in theta and alpha bands match WM stimulus frequency (especially during encoding), shortening response times and supporting this region' s regulatory role in WM (Alagapan et al., 2019). Thus, decreased superior frontal gyrus activation reflects reduced top-down attentional control (Milham et al., 2003) and improved efficiency of WM processes (updating, focused attention, stimulus selection, and sequencing) (Miró-Padilla et al., 2019).

Fifth, the anterior cingulate cortex shows significant WMT effects. Together with prefrontal and posterior parietal cortices, it forms the "scaffolding" of cognitive activity (Schneiders et al., 2011), participating prominently in verbal WM (Emch et al., 2019), attention (Miró-Padilla et al., 2019), conflict processing (Kanske & Kotz, 2011), and monitoring competition, motivation, emotional conflict, error detection, and task switching (Zhu et al., 2018). Its decreased activation reflects improved WM capacity.

5. Moderating Factors of WMT Effects

The model shows diverse neural activity changes induced by WMT, with decreases and increases coexisting across reports. What might explain these opposing phenomena? We must examine potential moderating factors of WMT effects.

Frequency analysis of 33 studies (see Figure 5 [Figure 5: see original paper]) revealed: (1) Training group sizes varied widely (3–41 participants), most commonly 10–20 (15.2 ± 3.0); (2) Neural activity analysis primarily used BOLD signals (21 studies), supplemented by FC (12 studies); (3) Age ranges were broad, predominantly young adults (24 studies), with few children (3) and middle-aged/older adults (6); (4) Training tasks were diverse, predominantly updating (17 studies), plus short-term memory (9), inhibition (3), switching (1), calculation (1), and comprehensive multiple-psychology tasks (1); (5) Training duration varied widely (20 minutes–5 years), most commonly $ $4 weeks (19 studies), with some 4–6 weeks (11) and >6 weeks (3).

Non-parametric tests examining whether these moderating factors influenced decreased versus increased neural activity (see Table 7) revealed: (1) Task type significantly affected the decrease/increase ratio (^{2} = 10.56, df = 5, p = 0.023), with updating training inducing significantly more decreases than increases; (2) Training duration significantly affected the ratio (^{2} = 7.57, df = 2, p = 0.019), with training $ $4 weeks inducing significantly more decreases than increases. Thus, updating tasks and shorter training durations tend to decrease neural activity.

6. Conclusions and Outlook

Learning-induced plasticity is particularly evident in WMT. To clarify the spatio-temporal characteristics of brain activity changes induced by WMT, we proposed hypotheses and analyzed 37 fMRI studies on healthy populations over the past 20 years. Comparing activation and functional connectivity changes across specific brain regions before and after WMT, we established a spatio-temporal model of decreased distribution in brain regions for WMT. From this model, we derived four conclusions: (1) WMT can either decrease or increase neural activity in healthy populations, with decreased activity being more prominent, and updating and shorter-duration training tending to induce more decreases; (2) These neural changes primarily occur in frontoparietal association networks, but also involve temporal, occipital, cingulate, and striatal networks, demonstrating whole-brain functional integration within a certain scope; (3) The middle frontal gyrus, superior frontal gyrus, and anterior cingulate cortex highlight the spatial characteristics of WMT-induced neuroplasticity, while the superior frontal gyrus, inferior parietal lobule, and cingulate gyrus reflect its temporal characteristics; (4) ExtPFIT and the neural efficiency hypothesis respectively support the spatial and temporal characteristics of the WMT brain distribution model.

How WMT enhances WM capacity and other cognitive functions through increased or decreased neural activity represents both a challenging and valuable research question. Future studies should further investigate large-scale, general neural network mechanisms related to learning that are induced by WMT (Salmi et al., 2018) to identify more universal principles of WMT neural mechanisms. Notably, literature reviews show that WMT commonly decreases neural activity in the superior frontal gyrus and cingulate gyrus, with no reports of increased activity, and inferior parietal lobule decreases significantly outnumber increases. Therefore, two future research directions may be: (1) using these three brain regions to differentiate between "decrease" and "increase" mechanisms of WMT-induced neural activity, and (2) investigating comprehensive influencing factors that determine whether WMT leads to decreased or increased brain activation.

Appendix 1: The complete frequency analysis of all brain regions from the literature is presented in Table 8 below. Due to length constraints, this was condensed into Table 3 in the main text.

Table 8. Frequency Distribution of Brain Regions Showing Neural Activity Changes Induced by WMT (37 studies, 42 reports)

[The table content would be preserved here with proper formatting, maintaining all brain region classifications and study references as in the original]

References

[The references section would be preserved exactly as in the original, maintaining all citations and formatting]

Denotes studies included in meta-analysis

Song, J., Zhao, W., Zhang, Q., & Li, J. (2020). Behavioral and imaging studies on transfer effects of working memory span training in college students. *Chinese Journal of Behavioral Medicine and Brain Science*, 29(10), 909-914.

[All other references would be listed here in their original format]

Note: Figure translations are in progress. See original paper for figures.

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