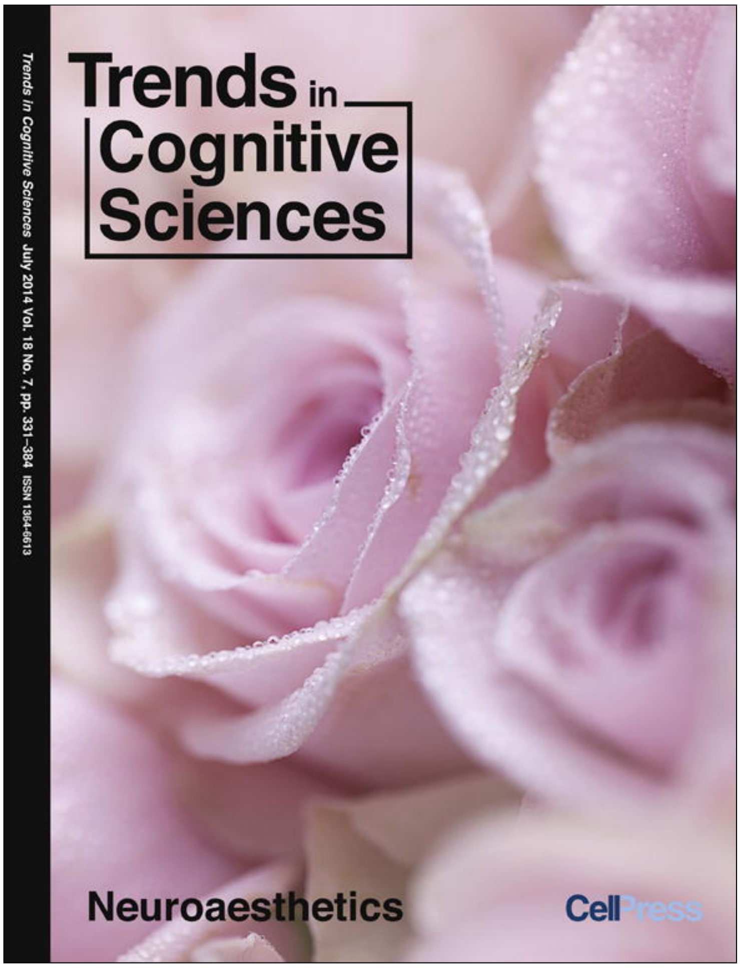
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Training brain networks and states

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Brain training refers to practices that alter the brain in a way that improves cognition, and performance in domains beyond those involved in the training. We argue that brain training includes network training through repetitive practice that exercises specific brain networks and state training, which changes the brain state in a way that influences many networks. This opinion article considers two widely used methods – working memory training (WMT) and meditation training (MT) – to demonstrate the similarities and differences between network and state training. These two forms of training involve different areas of the brain and different forms of generalization. We propose a distinction between network and state training methods to improve understanding of the most effective brain training.

Introduction

In the context of work on attention, we propose two methods of training [1]. One is attention training by repeated practice in exercises designed to engage the attention network [2]. The second general approach to training is attention state training that involves, for example, physical exercise or MT that might alter the brain state through changes in the autonomic and central nervous system [1]. Brain state refers to reliable patterns of brain activity that involves the activation and/or connectivity of multiple large-scale brain networks [3]. Two ways to use functional imaging are: (i) imaging the network for a specific task; and (ii) examining correlated activity at the resting state [4]. We feel that the two types of training fit well with two ways of functional imaging.

In this opinion article, we apply our idea of training to cognitive domains beyond attention. We propose two brain training strategies to improve cognitive performance [3,5,6]. Network training involves practice of a specific task (e.g., attention, working memory, visual discrimination) and thus exercises its specific brain network (e.g., the one involved in recognizing a specific object at a specific location). If the function of the network is general, such as attention or working memory, it may influence many tasks that use all or parts of that network. State training uses practice to develop a brain state that may influence the operations of many networks [3]. State training involves networks, but it is not designed to train networks using a cognitive task. For example, consider cognitive and performance difference between the waking and sleeping state. In addition, aerobic exercise and MT can establish a state that improves cognition, attention, and mood [7–10].

Given the widespread interest and dramatically increasing numbers of publications in WMT and MT, we use WMT as an example of network training and MT as an example of state training. We first discuss how WMT improves cognitive performance with practice and alters areas of the lateral cortex including frontal and parietal areas. We then consider how MT reduces stress and improves attention and mood through changes along the frontal midline brain in the anterior cingulate cortex (ACC) and its connections to the striatum and parasympathetic nervous system. Next we compare and contrast the two forms of training. Finally, we indicate new directions that can advance efforts to relate training to changes in brain activity and performance.

Training networks

WMT relates to storing temporarily a small number of items either recently presented or retrieved from memory (e.g., familiar phone numbers) [11]. One typical task presents participants with a stream of items such as words or letters; after each item, the participants press one key to

Glossary

Brain state: the reliable pattern of brain activity that involves the activation and/or connectivity of multiple large-scale brain networks.
Heart rate variability (HRV): a noninvasive technique that allows reliable and accurate measurement of sympathetic and parasympathetic functions. High-frequency HRV is related to parasympathetic function.
Integrative body–mind training (IBMT): this meditation technique originates from ancient Eastern contemplative traditions, including traditional Chinese medicine and Zen. IBMT stresses no effort or less effort to control thoughts and the achievement of a state of restful alertness that allows a high degree of awareness and balance of the body, mind, and environment. The meditation state is facilitated through training and trainer–group dynamics, harmony, and resonance. A number of randomized clinical trials indicate that IBMT improves attention and self-regulation and induces neuroplasticity through interaction between the CNS and ANS.
Network training: involves practice of a specific task (e.g., attention, working memory, visual discrimination) and thus exercises its specific brain network (e.g., the one involved in recognizing a specific object at a specific location).
Skin conductance response (SCR): a noninvasive method of measuring the electrical conductance of the skin. Lower SCR indicates more parasympathetic activity.
State training: uses practice to develop a brain state that may influence the operations of many networks. This state involves networks but is not designed to train networks using a cognitive task.
Working memory training (WMT): working memory involves the ability to maintain and manipulate information in one's mind while ignoring irrelevant distractions and intruding thoughts. WMT relates to training that exercises temporary storage of a small number of items either recently presented or retrieved from memory.

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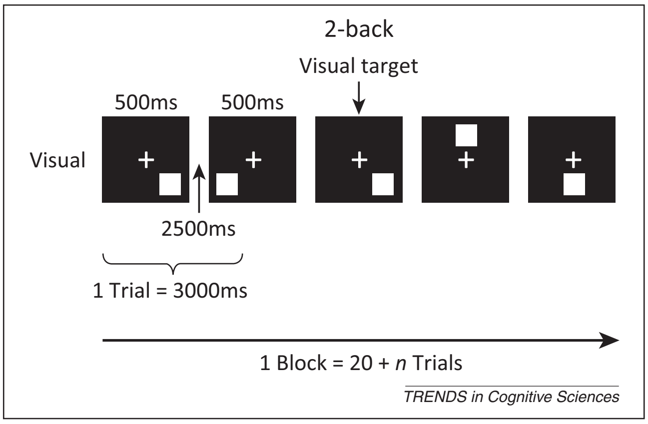

Figure 1. Visual *N*-back working memory task. The participant is presented with a sequence of stimuli. The task is to indicate when the current stimulus matches the one from *n* steps earlier in the sequence. The load factor *n* can be adjusted to make the task more or less difficult (here *n* = 2).

indicate whether the stimulus was presented *n* items before (where *n* is usually one to five items) and press another key if it was not presented at that position [12]. In adaptive training (increasing task difficulty as the training proceeds so that the task maintains a high level of effort), the value of *n* increases to ensure that the task continues to require a strong effort by the participants. Figure 1 shows the example of a visual *N*-back working memory task ($n = 2$).

Behavioral measures

There are disputes about how widely WMT transfers to other tasks. The data from adaptive training suggest that close transfer between forms of the *N*-back task certainly occurs. It is likely that WMT does transfer to other, near forms of working memory such as memory-span tasks [13]. There is some evidence that WMT improves intelligence, as measured by standardized tests of intelligence quotient (IQ) [12], and the ability to solve problems [5].These tests usually contain some forms of memory span or other working memory components, but differ from the training task in format. Because WMT involves attention, the potential range of tasks that overlap is enlarged [1,14,15]. However, others have failed to replicate transfer to tasks that are remote from the training [16,17]. A recent meta-analysis concluded that WMT appears to produce short-term and specific training effects that do not generalize [18].

Brain measures

There has been agreement on the general areas of brain activation as measured by MRI following WMT. In one study of normal adults given 5 weeks of adaptive WMT, areas of the lateral frontal and parietal cortex were more strongly activated following the training than before such training [19,20]. Several recent imaging papers with normal adults using adaptive WMT have confirmed the brain areas involved in training [21–24]. Two studies also found that the caudate nucleus, a structure frequently involved in learning and memory, is activated more strongly following WMT [19,25,26].

However, there is less agreement on the nature and amount of the changes. One study of WMT showed that brain activation first increased and then decreased with learning [21]. Other studies showed increased stability of activation in the same areas [27]. A paper reported that intensive and adaptive WMT was also associated with reduced regional gray matter volume [28]. These results suggest that the time course of training may be one source of variation in the nature of plasticity.

Moreover, the direction of these changes in activation, their relation to improved performance, and what aspects of training foster them all remain unclear. A recent paper summarizes the different patterns of brain activation that have been reported with WMT [29]: increased activation of a brain area involved in the task; decreased activation; increases in some areas and decreases in others; and a changed pattern of involved brain areas. It appears that the direction of the effects of network training depends heavily on how the training is conducted. Training may use a task where performance shows improvement over trials or adaptive training in which task difficulty adjusts as learning occurs. The difference between fixed and adaptive training methods may be related to whether training increases or reduces brain activation.

Changes in activation in the frontoparietal regions may reflect the need for increased effort as more difficult tasks are used during adaptive training [30]. However, in one study the extent of the increase of brain activity was correlated with improved WM performance [19], indicating that increased activity can be related to learning and not merely to the increased effort needed for the more difficult tasks [5]. It remains elusive why both increased and decreased brain activations have been reported even when adaptive WMT is used. One possibility is that studies may obtain different results because they measure brain activation patterns during different stages of learning. In support of this idea, a study showed that WMT changes brain activation in an inverse U-shaped function, in which 2 weeks of training increased activation with improved performance but 4 weeks of training decreased activation [21]. Another possibility is that individual differences in WM capacity or sensitivity to WMT may result in large variability of brain activation, leading to inconsistencies [31,32]. Several moderators, such as training length, task difficulty, motivation, effort, and learning strategies, could all be involved in increasing variability and producing inconsistent results [5,16,17,29]. Thus, providing details of the training regimens may help explain why WMT sometimes increases and sometimes decreases activation.

Functional MRI cannot observe brain structural connectivity directly, in contrast to diffusion tensor imaging (DTI), which uses fractional anisotropy (FA) to measure the directionality of water molecules that are thought to follow axonal pathways [33]. Two months of WMT have been shown to increase FA and thus the efficiency of white matter connections between brain areas [34]. To examine the mechanisms of white matter change following WMT, researchers have distinguished between axial and radial diffusivity. Based on animal models, axial diffusivity involves changes related to axonal density within pathways, whereas radial diffusivity primarily involves

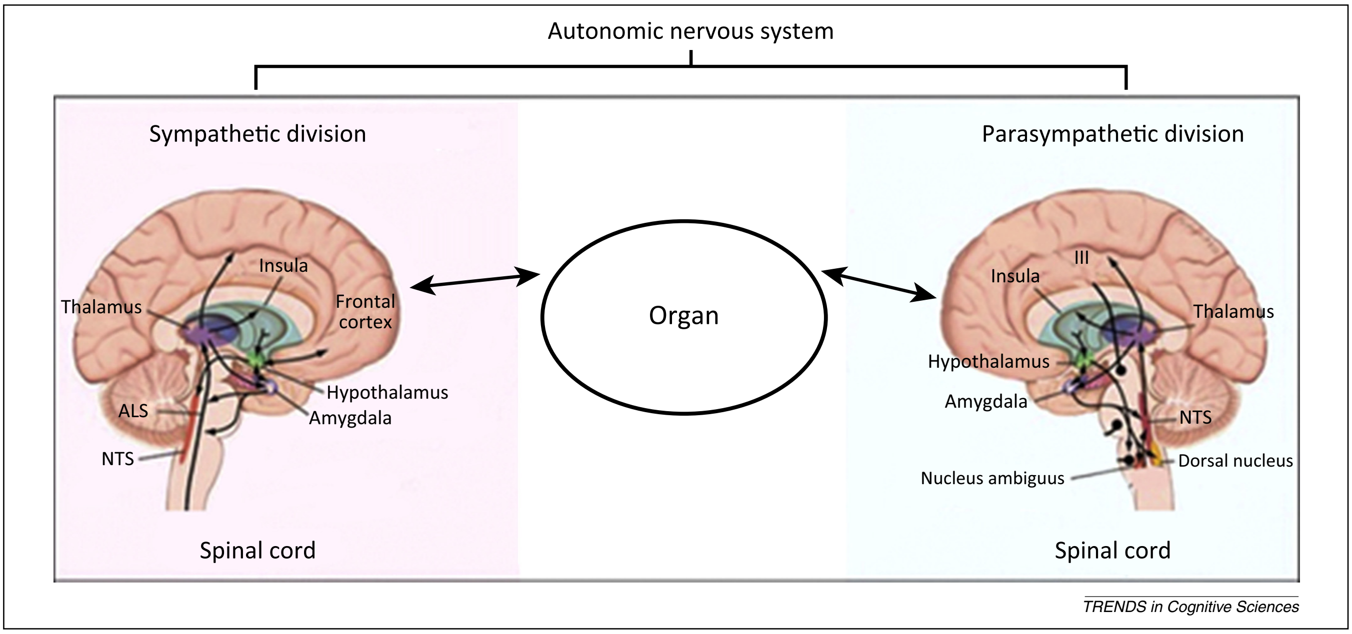

Figure 2. Autonomic nervous system (ANS). The sympathetic and parasympathetic divisions of the ANS are depicted on the left and right, respectively. All brain pathways are schematically depicted. On the left (sympathetic) side, depicted brain pathways include those to the thalamus from the anterolateral system (ALS) of the spinal cord, output from the thalamus to the neocortex, insula, and amygdala, bidirectional pathways between the hypothalamus and both the amygdala and frontal cortex, output from the hypothalamus to the nucleus tractus solitarius (NTS), and output from the amygdala to the ALS and brainstem. On the right (parasympathetic) side, depicted pathways include those to the thalamus from the NTS, output from the thalamus to the neocortex, insula, and amygdala, and bidirectional pathways between the hypothalamus and amygdala. Three vagal nuclei in the brainstem, including the NTS, nucleus ambiguus, and dorsal vagal nucleus, are also depicted. Modified from [50].

changes in myelination. Normal development involves both axial and radial diffusivity [35]. Practice on particular networks has generally shown changes in myelination but not axonal density [36].

State training

Styles of MT differ, but training methods share several key components, such as body relaxation, mental imagery, and mindfulness (nonjudgmental attention to the present moment), which can help to accelerate the practitioner's access to meditative states [3,7–9]. One example is integrative body–mind training (IBMT) [7,37–44]. Because IBMT shares key components with other forms of meditation and has been investigated with rigorous designs and randomized controlled trials, in contrast to other meditation methods [8,45,46], here we take IBMT as an example of MT [3,7].

The ability of IBMT to produce a meditation state within 5 days (20–30 min per session) has made it possible to use randomized trials in which individuals participating in IBMT are compared with active controls undergoing relaxation training [3,7,9,41].

In a comparison between IBMT and relaxation training, IBMT produced significantly more improvement in attention, mood, and stress regulation and increased activity and connectivity in the ACC, striatum, and anterior insula [7,38–42]. Electroencephalography (EEG) studies revealed increased frontal midline ACC activity in the theta band [38,47]. The measures of connectivity were taken under standard resting conditions before and after training. A recent study, using a different form of concentration-based mindfulness meditation, has shown similar increases in the ability of the meditation group to resolve conflict and increased activation in the cingulate cortex [45]. However, unlike the IBMT work, this study also found increased dorsolateral prefrontal activity even after 6 weeks of training. This difference may suggest that the meditation method continued to demand effort to maintain the state [3,45,48,49].

Training the autonomic nervous system (ANS)

As shown in Figure 2, the central nervous system (CNS) and ANS work together to maintain brain states [50]. Physiological measures of ANS activity include heart rate, skin conductance response (SCR), and respiratory amplitude and rate [38]. MT is often accompanied by changes in these measures and ANS activity is used as a biomarker for monitoring meditative states [38,51,52].

During and after 5 days of training, both IBMT and relaxation groups showed positive changes in physiological indices of ANS activity, indicating training effects. However, the IBMT group showed significantly lower heart rates and SCR, increased belly respiratory amplitude, and decreased chest respiratory rate than the relaxation controls [38]. These results reflect improved ANS regulation during and after IBMT practice compared with relaxation training. High-frequency heart rate variability (HRV) is related to parasympathetic function [38,53]. The significant increase of high-frequency HRV in the IBMT group during training indicates successful inhibition of sympathetic tone and activation of parasympathetic tone compared with relaxation training. This result is consistent with previous findings of decreased sympathetic activity and increased parasympathetic activity during MT [38,51,52].

In summary, MT often changes the frontal midline, including the ACC and its connections to the striatum and parasympathetic nervous system associated with self-regulation [3,8,9,39,45].

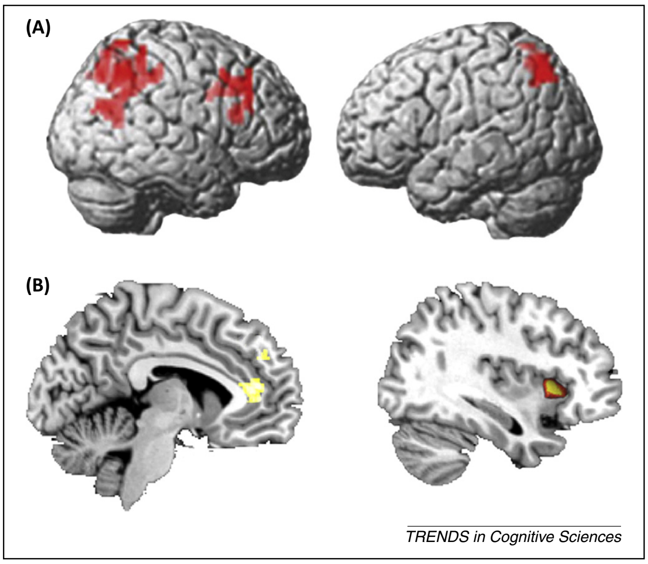

Figure 3. Differences between the core brain areas induced by working memory training (WMT) and by meditation training (MT). **(A)** WMT-related core brain areas including the frontoparietal cortex [19]. **(B)** MT-related core brain areas including the anterior cingulate cortex (left) and insula (right). Modified from [60,61].

Contrasting mechanisms in state and network training

Because our goal is to understand similarities and differences between network and state training, we contrast IBMT practiced for 4 weeks with WMT of roughly the same duration. In contrast to the lateral frontoparietal areas in WMT, the core areas of increased activity in IBMT appear to be the ACC, the anterior insula, and the striatum (putamen and caudate), with increased white matter connections among the ACC, striatum, and insula [7,8,38,39,42]. The differences are shown in Figure 3. During the early stages of IBMT and for other meditation methods, there is often activity in the lateral prefrontal cortex. There is also substantial evidence that IBMT can produce strong parasympathetic dominance through the ANS [3,38,52]. These ANS and CNS changes appear to differ from those in WMT, but no effort has been devoted to a direct comparison of the two training methods.

Attention and effort

Adaptive WMT requires maintenance of mental effort over the course of training. However, we do not know whether increased brain activity derives from greater overall task difficulty, more attention or effort needed to perform the task, or other factors. In the early stages of MT, achieving the meditation state appears to involve the use of attentional control and mental effort; thus, areas of the lateral prefrontal and parietal cortex could be more active than before training [3,54,55]. This may reflect the higher level of effort often found when participants struggle to obtain the meditation state in the early stages [3,30,48] and thus provides greater overlap with what happens during adaptive WMT [1,3,5,40]. However, in the advanced stages of MT, prefrontal–parietal activity is often reduced or eliminated, but ACC, striatum and insula activity remains [3,8,38,40,55–57] (Table 1).

Table 1. Training, effort, and system involved: relationships among IBMT and WMT, effort, and associated CNS–ANS involvement

State training	Network training
IBMT	*WMT*
Parasympathetic dominance	Sympathetic dominance
ACC, insula, striatum	Lateral frontoparietal areas, caudate
Less effort	More effort

Change in axon density and myelination

As discussed above, DTI provides measures of magnitude and direction of water diffusion in the brain tissue [33,42]. Eleven hours of IBMT over a 4 week-period increased FA and decreased both axial and radial diffusivity [42]. Two weeks of IBMT produced changes in axonal density only, but 4 weeks of training produced both axonal density and myelination changes [42]. These results indicate that both network and state training can influence white matter efficiency, but they may use different mechanisms [3].

In summary, WMT increases frontoparietal activation, whereas MT increases activation of the ACC, insula, and striatum. Connections between the ACC, insula, striatum, and ANS are also changed [1,3,58,59]. Efforts to obtain the meditation state may recruit frontoparietal areas, but this is reduced as effort is decreased during the advanced stages of training [3].

Concluding remarks

We believe that the distinction between state and network training helps understanding the neuronal correlates of training in general. Future studies may show unique characteristics of different methods within each training category, such as improvements in physical condition following aerobic exercise. We do not argue that the network and state distinction is the only one or that all methods within each category require identical mechanisms. Rather, we see this as a step toward a better understanding of the potential of each training method to lead to generalized improvements and further research that might combine these two training approaches. We also need to improve our understanding of the mechanism of training; for example, how meditation leads to such fast changes in white matter.

The issue of generalization of training has thus far been confined to the study of networks. We hope this opinion article will encourage further investigations of how transfer occurs, for example, through the overlap of brain networks and whether the concept of near and far transfer can be applied to meditation and, if so, what would be the best way do it.

We know little about how training might differ among individuals. It is likely that such differences will make it impossible to determine which methods would be most efficient. We are at the beginning of understanding the significance of how the brain changes with learning. The distinction between network and state training may be a small step along that road.

Previous studies have shown brain changes in WMT that involve lateral frontoparietal areas and lead to improvements in task performance and in some cases in transfer to remote tasks. MT mainly shows changes in the activation of the ACC and its connectivity to the striatum and parasympathetic nervous system. It is now understood that the brain changes with practice of many types. We are beginning to define the types of training and the specific changes that the brain undergoes with training. Further increases in our knowledge may lead to improvements in application that can make brain training an important tool in education, mental health, and development.

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