What are the known effects of yoga on the brain in relation to motor performances, body awareness and pain? A narrative review

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Abstract

Objective

The current body of literature was reviewed to evaluate the effects of yoga on the brain in relation to motor performances, body awareness and pain.

Background

Yoga has been increasingly popular in the Western countries especially for its unique integration of the mind and body. Yoga has been studied more intensely in the last decade. Although it has been shown to improve cognitive functions, few studies have looked into the effects of yoga on improving motor performance, body awareness or pain and the possible underlying brain mechanisms associated with them.

Methods

A search of the current literature was made using keywords such as: "yoga brain motor", "yoga brain pain", "effects yoga brain" and "effects yoga brain motor performance”. The findings were then discussed in relation to motor performance, body awareness and pain and their reported mechanisms of action on the brain.

Results

A total of 61 articles were selected, out of which 29 were excluded because they did not meet our criteria. A total of thirty-two articles were included in this review, which we further subdivided by focus: motor performance (n = 10), body awareness (n = 14 and pain and n = 8).

Discussion

Our review shows that yoga has a positive effect on learning rate, speed and accuracy of a motor task by increasing attention and decreasing stress through a better control of sensorimotor rhythms. Yoga also seems to improve sensory awareness and interoception, regulate autonomic input, increase parasympathetic activity and promote self-regulation. Yoga was also shown to reduce the threat signal, increase pain tolerance, decrease pain unpleasantness and decrease the anxiety and distress associated with pain. Those changes are associated with the recruitment of specific brain areas such as the insula, the amygdala and the hippocampus.

Conclusion

Based on the studies reviewed in this report, we found that the practice of yoga seems to facilitate motor learning, to increase body awareness and to decrease pain. These are associated with a wide variety of changes in terms of brain activity and structure. Further studies are necessary to reveal its precise mechanism of action on the brain and to validate its wider application in clinical settings.

Keywords: Yoga; Pain; Brain; Motor performance; Body awareness; Narrative review; Neuroimaging

1 Introduction

Yoga is an ancient discipline that is becoming increasingly popular in Western countries. It is practiced by many people from different backgrounds, not only for its physical component but also for the mind–body connection it
promotes, in contrast to more regular fitness programs. In fact, according to a recent survey, yoga is now being practiced by over twenty million people in the USA.\(^1\) The main reported reasons by individuals for attending yoga classes are the increase of energy (66%), enhancement of immune function (50%) and health improvement and disease prevention (28%).\(^2\) The most common conditions present in those practicing yoga include back pain (20%), arthritis (6%) and stress (6%).\(^3\) Consequently, yoga is increasingly considered as an affordable and promising modality for the management and the alleviation of the cost associated with these conditions.\(^4\)

Exercise therapy has traditionally used as the modality of choice for the treatment of chronic musculoskeletal pain.\(^5\) However, persistent pain has been associated with fear of movement, anxiety, pain catastrophizing and nervous system sensitization.\(^6\) In this context, producing movement can become a very hard and anxiety-provoking task for people suffering from such condition. Through its mind–body connection, yoga has been reported to enhance body awareness\(^7\) and to be a safe and effective way to alleviate pain.\(^8\) It has been suggested that yoga practice could help to reduce allostatic load in stress response systems and to restore optimal homeostasis.\(^7\) Thus, yoga might be a unique modality to treat various conditions associated with chronic pain or neurological disorders by decreasing the fear of movement, alleviating pain, and normalizing the stress response, or by enhancing body awareness. Although yoga is known for its unique approach of mind–body connection, only a limited number of studies have looked into the underlying brain mechanisms associated with its reported beneficial effects on motor performance, body awareness and pain. So far, most of the studies using neuroimaging techniques have looked at its effects in a context of improving cognitive functions. For example, yoga has been shown to improve verbal memory performance in subjects with mild cognitive impairment (MCI) and this was associated with increased connectivity between the default mode networks (DMN) and the frontal medial cortex, posterior cingulate cortex and left lateral occipital cortex (Eyre, 2016). In this context, the purpose of this review was to identify the current existing literature on the effects of yoga on brain markers in relation to body awareness, motor performance and pain.

Yoga is a very promising approach to rehabilitation especially for the rapidly growing elderly population as it is low-cost and easy to implement a method in a clinical setting or in the community. Since yoga can be done on a group basis, depending on clientele’s needs, it can prove to be a highly cost-effective tool. In addition, in clinical settings, yoga could easily be tailored to diverse clientele because of its accessibility, its cost-effectiveness and the fact that it promotes self-efficacy. Within these clientele, people suffering from neurodegenerative conditions and chronic pain conditions could benefit from this therapeutic tool. A better understanding of the effects of yoga on the brain will help validate its use as a therapeutic tool in clinical settings, including its use on patients suffering from various neurodegenerative conditions.

# Method

A search was made using electronic databases, including PubMed, Science Direct Database and PeDro for publications between 1975 and 2017. Since we wanted to evaluate the effects of yoga on the brain, we used the search terms: “yoga brain motor”, “yoga brain pain”, “effects yoga brain” and “effects yoga brain motor performance”. During the review process, we conducted a subsequent search on January 21st 2019, adding a broader key words search. The key word “yoga + cortical activity”, “yoga + cortex”, “yoga + cortex + sensory”, “yoga + cortex + sensorimotor”, “yoga + cortex + somatosensory”, “yoga + cortex” were then added to the search.

The words were combined because when used as separate entities yielded too many results and were not specific enough for the sake of our goals. Table 1 in the annexed section summarizes the methodology of the search performed. When performing a narrative review for peer-reviewed journals, Green and colleagues suggest consulting expert groups to include relevant publications that could have been overlooked using traditional database (Green, 2006). For this reason, we also consulted an expert group called Bridgebuilders to awareness in healthcare group,\(^5\) which is a group of healthcare rehabilitation professionals interested in sharing ideas on how to foster awareness of creating the relationship and healing with patients and clients through yoga. The literature identified based on this consultation is included in the summary in Table 1. There were seven supplemental articles of relevance to our review. Our main inclusion criteria were that the articles had to associate the effect of yoga with the brain (with validated measures i.e. neuroimaging, electrophysiological) in relation to either motor performance, body awareness or pain. Hormonal markers, such as salivary cortisol level, were also considered as brain markers since they are used as indicators of plasma-free cortisol to assess hypothalamic–pituitary–adrenal axis secretory activity and rhythm, which involve the stimulation of the adrenal cortex to produce cortisol.

<table>
<thead>
<tr>
<th>Date of search</th>
<th>Database</th>
<th>years searched</th>
<th>Search terms</th>
<th># hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>02/11/2017</td>
<td>PubMed</td>
<td>1975–2017</td>
<td>yoga brain pain</td>
<td>21</td>
</tr>
<tr>
<td>02/11/2017</td>
<td>PubMed</td>
<td>1975–2017</td>
<td>effects yoga brain</td>
<td>77</td>
</tr>
<tr>
<td>02/11/2017</td>
<td>Science direct</td>
<td>Journal only</td>
<td>effects yoga brain motor performance</td>
<td>339</td>
</tr>
<tr>
<td>02/11/2017</td>
<td>PeDro</td>
<td>Full database (1929–2017)</td>
<td>effects yoga brain</td>
<td>3</td>
</tr>
<tr>
<td>02/23/2017</td>
<td>PubMed</td>
<td>1975–2017</td>
<td>Yoga AND brain (Pain OR body awareness OR motor performance)</td>
<td>33</td>
</tr>
</tbody>
</table>
In respect to the yogic tradition, we included articles that used a form of practice within the eight limbs of yoga of Pantajali. These limbs consist of Yama (5 limbs of moral conduct), Niyama (5 limbs of individual discipline), Asana (Physical Postures), Pranayama (breath and vital energy), Pratyahara (Withdrawal and freedom from attachment), Dharana (Focus), Dhyana (Meditation), Samadhi (Oneness). Yoga also had to be performed either by adult populations of healthy subjects or by those suffering from a form of musculoskeletal pain. Our exclusion criteria included the lack of use of validated brain-related measures (i.e. neuroimaging, electrophysiological measure or hormonal marker). We also excluded studies that specifically used a mindfulness-based stress reduction program (MBSR), as it is considered to be a mental form of training. Qi-Gong studies, which are not specific to yogic practices, were excluded for the same reason. We also omitted studies involving yoga experts such as Tibetan or Buddhist monks or yoga masters as they are known to live a very different life regimen than the common Westerner. Studies involving protocols aiming at acting specifically on anxiety/psychological disorders and loving-kindness meditation were considered to be outside of the scope of this review since the meditation component of these studies is related to the management of emotions or mood. We also excluded meditation techniques that are taught in specific schools like transcendental meditation because they do not specifically relate to yoga in the context of the eight limbs of Pantajali described earlier. However, certain studies in which the main program was meditation but deemed to be within the eight limbs of Pantajali were included such as mindfulness or mind-body training. Studies looking at the effects of yoga on cognitive declines or impairments were also considered to be outside the scope of this review.

3 Results

Based on the criteria described above, a total of 61 articles were identified. After carefully reading the articles, we excluded 29 articles because they did not meet our inclusion criteria. A total of thirty-two articles were included in this review, which we further subdivided by focus: motor performance, body awareness and pain. However, we did not find articles that specially assessed the effect of yoga on the brain in relation to motor performances. Therefore, ten articles on the effects of yoga in relation to motor learning were identified. Fourteen articles on the neural correlation associated with the effects of yoga on body awareness and eight in relation to pain were also identified. A synthesis of the articles included in this review is provided in Table 2.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Method</th>
<th>Measures</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassady et al 10</td>
<td>Investigate the role of prior experience with MBAT, in learning to use a 1-D sensorimotor rhythm based BCI</td>
<td>EEG (Autoregressive spectral amplitudes at 12 Hz) - 3 BCI sessions of 10 min for 80% accuracy over Left-right &amp; up-down cursor task - PVC, # of hits/run, ITR in bits/min</td>
<td>Left vs. right cursor task: MBAT faster than CON - MBAT higher accuracies of control vs CON - MBAT more hits/run vs CON - MBAT higher ITRs vs CON - Both left vs. right and overall 1D control, the group-weighted average neural power greater for MBAT vs CON - MBAT ability to learn at greater rate than CON</td>
<td>- Applied learning process to a new task using an SMR-based BCI (controlled by user's intention without external stimuli) a motor imagery based BCI system</td>
</tr>
<tr>
<td>Chandra et al 11</td>
<td>Effects of SKY on brain signals during Working memory task - Working memory task = 20 min AOSPAN +25 min AOSPAN</td>
<td>EEG (only gamma (30–45 Hz), alpha (8–13 Hz), and theta (4–8 Hz) bands were considered based on their active roles in working memory capacity) AOSPAN AOSPAN</td>
<td>SKY improved working memory capacity by changing brain rhythms = energy utilized more efficiently while performing the task - SKY = efficient use of energy + PSD</td>
<td>Small sample - No subjective measures</td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Design</td>
<td>Measurements</td>
<td>Findings</td>
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<tr>
<td>Empson et al. (2010)</td>
<td>8 healthy subjects</td>
<td>N = 8 healthy subjects less than 2 years of meditation (5 Kundalini &amp; 3 ACEM) practice (min 2 wk for 24 months; X/Wk for 6-24 months)</td>
<td>Investigate whether moderately experienced meditators activate HIP and PFC during silent mantra meditation</td>
<td>FMRI obtained during silent mantra meditation in prone position, off-block design. Whole-brain + ROI analyses performed. Each block = 2 min (total of 8 blocks), alternating meditate and word, (4 meditate and 4 word)</td>
</tr>
<tr>
<td>Field et al. (2012)</td>
<td>38 adults</td>
<td>N = 38 adults did 20-min Tai chi/yoga class</td>
<td>Cross sectional study</td>
<td>Pre- and post-</td>
</tr>
<tr>
<td>Froeliger et al. (2013)</td>
<td>14 healthy subjects</td>
<td>N = 14 healthy subjects (18-55 y.o.)</td>
<td>YMP = 7 (Hatha yoga &gt;45 min/day, 3-4 X/wk, &gt;3 yrs &amp; mindfulness 7 days/wk over last 5.6 yrs)</td>
<td>CON = 7 subjects matched naive meditation/yoga</td>
</tr>
<tr>
<td>Gard et al. (2014)</td>
<td>47 healthy subjects</td>
<td>N = 47 healthy subjects</td>
<td>YOGA = 16 (Kripalu yoga) MED = 16 (Vipassana)</td>
<td>CON = 15 (less than 4 yoga or med class in last year/10 in lifetime)</td>
</tr>
<tr>
<td>Gath et al. (2015)</td>
<td>118 healthy sedentary subjects</td>
<td>N = 118 (55-79 y.o.) healthy sedentary subjects randomized in: 8wk Hatha yoga YOGA= 61 or a stretching control group CON= 57</td>
<td>3X/wk for 1 h for 8-wk period</td>
<td></td>
</tr>
<tr>
<td>Hözel et al. (2016)</td>
<td>30 healthy subjects</td>
<td>N = 30 healthy subjects</td>
<td>MED = 15 Vipassana (7.9 years 2/h/day)</td>
<td>CON = 15 meditation naive matched</td>
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<tr>
<td></td>
<td></td>
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</tbody>
</table>

**Pre- and post-**

- YOGA & MED had significantly greater degree centrality in the caudate than CON.
- No driven by single connections but by greater connectivity between the caudate and numerous brain regions.
- YOGA & MED = stronger FC within basal ganglia cortico-thalamic feedback loops vs CON.

**Yoga & Meditation (YOGA & MED)**

- YOGA & MED had significantly greater degree centrality in the caudate than CON. No driven by single connections but by greater connectivity between the caudate and numerous brain regions. YOGA & MED = stronger FC within basal ganglia cortico-thalamic feedback loops vs CON.
4 Discussion

This narrative review discusses the effects of yoga on the brain in relation to three main topics: motor performance, body awareness and pain. Although the topics do overlap in certain studies, the discussion is divided by theme and a summary of the three themes is presented at the end of the section.

4.1 The Effects of Yoga on the Brain in relation to Motor Performance

Motor performance can be defined as a change in movement behavior observed during a practice session. It involves measures that indicate the outcome of performing a motor skill such as reaction time, error measures, duration of time to complete a task or the number of successful attempts or trials needed to complete a task. Motor performance and motor skills are essential for various daily activities. Based on this description, studies that encompass any sort of motor learning, the outcome of performing a motor skill were included in this review. The details of the studies discussed in this section are highlighted in Table 2.

The first study looked at participants' previous experience in mind-body awareness training (MBAT) for at least one year. It was demonstrated that MBAT had a positive impact on the ability to learn how to use a Brain-computer interface (BCI), a new skill for the participants. Participants who practiced yoga and meditation at least 2 times per week for more than one hour over the year before the study were included in the experimental group. In this study, the authors used a motor imagery paradigm to decode the user's intent originating from the somatosensory cortices using EEG signals. Learning a BCI paradigm usually requires a long learning process. The MBAT group was found to learn at a greater rate, and to achieve the task faster and with better accuracy than the matched control groups. This was associated with better control of sensorimotor rhythms by the MBAT group in terms of greater magnitude of the spectral power in this band.

In relation to memory consolidation, participants who learned Sudarshan Kriya yoga (SKY) as part of a 7-day workshop were found to have improved their working memory capacity when compared to a control group who continued with their existing lifestyles. Prior to the training, the subjects underwent a baseline EEG recording at rest, followed by a 20 to 25-minute 25-min working memory (WM) test. The test involved an automated computer-based task, which consisted of remembering and retrieving letters and solving mathematical problems. After the SKY workshop, the experimental group kept practicing SKY daily. EEG measures were repeated 90 days later. The practice of SKY was shown to promote the power spectral density (PSD) in the gamma, alpha, and theta bands. Gamma PSD decreased in both the encoding and retrieval phases of working memory and the alpha band increased in the retrieval phase following SKY, while theta rhythms were associated with memory consolidation.

<table>
<thead>
<tr>
<th>Study</th>
<th>No.</th>
<th>Group</th>
<th>Procedure</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKY</td>
<td>60</td>
<td>MED: 30 CON: 30 matched non-meditators (obtained from the ICBM database of normal adults)</td>
<td>- Establish the presence and direction of callosal differences between long-term meditators and well-matched controls</td>
<td>- % of time kept attention on the task</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rate difficulties with task, on a Likert scale: 0 to 10–10</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>Healthy male police trainees divided in: Group 1: Asana Group 2: Pranayama Group 3: Asana + pranayama Group 4: Control</td>
<td>- EEG, NC, EMG, VEP, ART were recorded before and after the training period</td>
<td>- Callosal measures were larger in MED in anterior callosal sections</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Increased FA within Fminor but not Fmajor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Differences between MED &amp; CON in rostral body and posteriorly, involving large parts of anterior midbody and posterior midbody</td>
</tr>
</tbody>
</table>

Discussion

4.2 Evaluating the effect of asana + pranayama on neurological and neuromuscular functions in healthy human

2. Determine - Determine differential effects between training in asana, pranayama + combination

- Alpha, theta, & total power EEG ↑ asana training
- ↑ visual reaction time + ↓ in red-green discriminatory reaction time + ↓ in processing of visual input.
- ↓ resting EMG voltage: ↓ muscular relax after pranayama
- Beta, theta, and total power of EEG ↑; ART and red-green discriminatory reaction times ↓ = more alert state & ↓ central neural processing
- Asana + pranayama
- Asana + pranayama: ↑ motor & sensory nerve conduction
- Total power of EEG, alpha, and theta power, delta % ↓ while reaction time ↓
Using functional magnetic resonance imaging (fMRI), another study looked at the pattern of brain activation in meditators with less than 2 years of practice according to the Kundalini yoga. An increased activation was found in the bilateral hippocampus (HIP) and parahippocampal (paraHIP) formations while participants underwent silent mantra meditation, areas known to be involved in memory consolidation. The authors argued that hippocampus-dependent consolidation benefits could be linked with the modulation of slow waves sleep, which has been shown to increase in those practicing meditation. Brain areas involved in motor control and movement execution such as the bilateral middle cingulate cortex and the bilateral precentral cortex also showed significantly greater activation during meditation.

Another study investigated the effects of yoga and meditation practices (YMP) on the brain, especially using Hatha yoga (a common yoga practice of asana and pranayama practiced in the Western world). The YMP group was reported to maintain an active practice of hatha yoga meaning more than 45 minutes per day, three or four times per week for more than three years. This group exhibited greater grey matter volume (GMV) in frontal, limbic, temporal, occipital, and cerebellar regions, whereas the control group did not show any regional changes. The YMP group also had significantly fewer cognitive failures based on the Cognitive Failures Questionnaire (CFQ), which assesses memory functions, attention, and motor coordination. The scores obtained by the YMP participants on this test correlated with the changes in GM volume in frontal, limbic, temporal, occipital, and cerebellar regions. Interestingly, GMV changes were also correlated with the duration of yoga practice. The authors suggested that practicing hatha yoga might stimulate neuroplasticity events in the frontocerebellar network because of the intense, multimodal, cognitive, and motor skill learning involved in such practice.

In another study, whole brain resting-state functional connectivity of experienced yoga practitioners, meditators, and matched control was also assessed using fMRI. Yoga practitioners and meditators showed stronger connectivity between a large number of brain regions compared to controls, and more particularly with a greater degree of centrality in the caudate nuclei. The authors suggested that the increased functional connectivity (FC) within the caudate basal ganglia cortico-thalamic feedback loops might be related to the positive effect meditation and yoga have been reported to have on cognition, emotion, action, and perception. These findings suggest that a positive correlation exists between mindfulness and cognitive/behavioral flexibility. The authors also proposed that yoga could help recruit basal ganglia cortico-thalamic circuits to unlearn old, maladaptive behavioral patterns and to establish new adaptive ones, which could lead to an optimized self-regulation.

In a different study, it was demonstrated that participants who underwent an 8-week hatha yoga program showed increased accuracy on executive function and decreased cortisol response when compared to a control group who underwent a stretching program. The practice of yoga improved working memory performance on the running span task, n-back working memory and a task-switching paradigm. The attenuated stress levels, as well as self-reported stress and anxiety levels, predicted the performance on these tests.

Lastly, a study reported the positive neurophysiological effects of asana training, pranayama or their combination on neurological and neuromuscular functions in healthy male police volunteers, in contrast to a control group with no experience in such practice. It was reported that the combination of asana and pranayama training, on top of regular police training, produced an alert yet relaxed state of the neuromuscular system measured using electromyography (EMG) at rest. This relaxed state was associated with an increase in EEG alpha, delta, and theta power. These increases were associated with better reaction time using auditory and discriminatory tests. The authors also reported a decrease in resting EMG activity associated with muscular relaxation following pranayama and an increased motor and sensory nerve conduction following asana combined with pranayama practice.

In summary, the results discussed in this section show the effects of yoga on task efficiency, speed and reaction time as well as increased working memory capacity and memory consolidation. There was also some evidence for a greater activation of the caudate and precentral cortex associated with better motor control and movement execution. It was also demonstrated that cognitive performances were improved by the practice of yoga, which was associated with increased memory, attention, and motor coordination. Although limited, these findings suggest that the practice of yoga could lead to better motor performance although no study has specifically assessed this aspect.

### 4.2 The Effects of Yoga on the Brain in relation to Body Awareness

The results from the fourteen studies included in this section are described in Table 3. As body awareness is a wider term and its definition varies from one field to the next, we decided to use the definition by Mehling et al. who describe body awareness as “the sensory awareness that originates from the body’s physiological states, processes (including pain and emotion), and actions (including movement), and functions as an interactive process that includes a person’s appraisal and is shaped by attitudes, beliefs, and experience in their social and cultural context.”

<table>
<thead>
<tr>
<th>Reference</th>
<th>Sample</th>
<th>Method</th>
<th>Measures</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bajaj et al., 2010</td>
<td>20 healthy individuals: MED: 10 experienced</td>
<td>Investigate the temporal dynamics of oscillatory changes during Sahaj meditation</td>
<td>EEG measure at baseline and during intervention session</td>
<td>Distinct meditative states = distinct changes in spectral powers</td>
<td>Short term effects, cross sectional</td>
</tr>
</tbody>
</table>

Table 3 Effects of yoga on the brain in relation to body awareness.
<table>
<thead>
<tr>
<th>Study</th>
<th>Group Details</th>
<th>Methods</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Srinivasan et al., 2018</td>
<td>N = 14 healthy &gt;18-55 yrs. imaging in the right AMY, dorsal medial cortex, sensorimotor areas</td>
<td>- Significant decrease between pre and post % activation in the right dorsal medial frontal lobe, prefrontal cortex, and right sensorimotor cortex</td>
<td>- Small sample size, no control group;</td>
</tr>
<tr>
<td>Berkovich-Ohana et al., 2011</td>
<td>MED = 36 mindfulness meditators divided in 3 groups (short, medium &amp; long term)</td>
<td>- EEG: 2 × 20 min (MED-1/MED-2/IMW-1/IMW-2), (1/2) vs (1/2) vs (1/2) vs (1/2)</td>
<td>- MED had higher parieto-occipital gamma amplitude vs CON during MEDIT and IMW</td>
</tr>
<tr>
<td>Cohen et al., 2011</td>
<td>4 naive subjects: 2 men/2 women mean age of 45</td>
<td>- Pre-post training measures of SPECT ROI: the inferior frontal, superior frontal, dLPPC, OFC, dorsal medial cortex, inferior &amp; superior temporal, inferior &amp; superior parietal, occipital, sensorimotor areas, AMY, caudate, thalamus, midbrain, cerebellum, cingulate gyrus</td>
<td></td>
</tr>
<tr>
<td>Froeliger et al., 2011</td>
<td>N = 23 healthy &gt;18 yrs. meditation &gt;45 min/day, 7 days/week, &gt;3 yrs. mindfulness meditation 7 days/week, &gt;5.6 yrs CON = 7 matched yoga &amp; meditation-naive</td>
<td>- Investigate the effects of meditation experience and on multiple RSNs</td>
<td>- No other measures than GMV in medial prefrontal cortex were positively correlated with the subjective perception of the depth of mental silence inside the scanner</td>
</tr>
<tr>
<td>Hernandez et al., 2018</td>
<td>N = 40 MED = 20 mindfulness (Vipassana) meditators</td>
<td>- Assess which brain regions were structurally and functionally associated with the state of mental silence in long-term meditators of SYM</td>
<td>- GMV in medial prefrontal cortex was positively correlated with the subjective perception of the depth of mental silence inside the scanner</td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Methods</td>
<td>Findings</td>
</tr>
<tr>
<td>------------------------------</td>
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</tr>
</tbody>
</table>
| **Mazer et al.**             | 8 highly experienced (7–26 years on a daily basis) healthy male (age 31±50) | Evaluate whether endogenous dopamine release increases during loss of executive control in Yoga Nidra meditation | MRI brain scan: 5 ROI: right caudate, left caudate, right corticostriatal, putamen, left putamen and ventral striatum  
Two C-raclopride PET scans: 1) attending to speech with eyes closed, 2) during active meditation.  
- 5 of 8 participants underwent EEG data collection  
- Questionnaire to assess pleasure, relaxation, awareness & awareness  
- GM medial OFC positively correlated with cumulated hours meditation training  
- GM in the OFC **not** found to be greater in MED vs CON  

**Lazar et al.**         | N = 35 MED= 20 western practitioners CON = 15 matched healthy subject no experience in meditation or yoga | Investigate differences in cortical thickness in brain regions (attention and sensory processing) in meditators to evaluate cortical plasticity | **MR-based technique**  
- MRI: Heart rates  
- Heart rate  
- Respiration rate  
- End-tidal CO₂  
- O₂ saturation levels  
- ECG measures  
- MED: Thicker right middle and superior frontal sali (BA9±10), PFC and right anterior insula  
- 1 PFC thickness in older participants,  
- Mean thickness across the entire cortex did not differ significantly between the groups for either hemisphere  

**Lazar et al.**         | N = 5 Kundalini meditators of min. 4 yrs experience | Identify brain foci of activity that are modulated by a very simple form of meditation | **MR-based technique**  
- MRI: Heart rate  
- Heart rate  
- Respiration rate  
- End-tidal CO₂  
- O₂ saturation levels  
- ECG measures  
- 1 in putamen, midbrain, pregenual ACC, HIP and parahIP formations, prefrontal, parietal and temporal cortices, precenetal and postcentral gyri  

**Tang et al.**         | N = 86 without training experience randomized undergraduates assigned to 2 experiments (IBMT) or control (relaxation) | Explore the effects of a 5 day IBMT training on brain and physiological measures; relationship between brain networks & ANS during training in subjects no experience | **MR-based technique**  
- Heart rate, SCR, belly respiratory amplitude, and chest respiratory rate  
- Power spectral analysis of HRV  
- SPECT scanner (2 scans before and after training)  
- EEG collected at baseline (eyes closed), before and after training  
- stronger subgenual and adjacent ventral ACC activity in IBMT  
- Frontal midline ACC theta was correlated with high frequency HRV  
- Frequency HRV  
- After training: 1 HR, 1 belly respiratory amplitude, 1 chest respiratory rate, 1 high frequency HRV, 1 SCR in IBMT vs relaxation  
- Relaxation: more frontal, temporal, and parietal cortex activations (including Wernick’s area) than IBMT  

**Tang et al.**         | N = 45 randomized undergraduates to IBMT or relaxation 11 h of training, 30 min/session over 1-mo period. | Investigate if 11 h of training with IBMT over 1 mo would 1 FA in anterior corona radiata | - Structural MR-based techniques including DTI  
- Data acquired before and after training  
- IBMT increases FA, in left anterior corona radiate, adjacent left & right superior corona radiate  
- FA ↑ in body and genu of corpus callosum, superior corona radiata, and superior longitudinal fasciculus  
- No change GM both groups  

**Westergard Poulsen et al.** | N = 20 MED = 10 (in the Dzogchen tradition of Tibetan Buddhism) CON= 10 healthy matched non-meditators | Observe GM density in lower brain stem regions of experienced meditators compared with age-matched non-meditators | - Structural MR-based technique  
- 1 GM density but no volume differences in MED in lower brain stem–medulla oblongata  
- Separation of GM densities between groups in brain stem  
- 1 GM densities in left superior frontal gyrus BA 10 and left inferior frontal gyrus–pars triangularis (BA 45A) anterior lobe of cerebellum bilaterally & left fusiform gyrus  
- No difference in GM density as a function of total practice hours in any region  

**Wallwork et al.** | N = 86 participants (practicing yoga at least) | Determine if people who do regular yoga practice performed | **RECOGNISE app**, evaluating accuracy and speed of laterality task for 1. 40 basic images of  
- No difference between Groups (yoga and no yoga) for either response time or accuracy  
- Online study, no controlled environment
In the first study, brain activity was measured during meditation using EEG. Subjects were asked not to meditate during the first part of the scanning and following this, they underwent one session of Sahaj Samadhi meditation (a concentrative form of meditation that is part of Sudarshan Kriya yoga). The authors reported increased theta activity in frontal areas while subjects were meditating. They argued that this might be related to the ability of the experimental group to separate one's self from the environment. An emergence of slow frequency in the attention-related increased theta activity in the frontal regions was also associated with deactivation of the parietal-occipital areas, which may signify the reduction in processing associated with self, space and time. The authors also speculated that the changes observed could demonstrate a more "task-focused state", which is related to the reduced awareness of the surroundings or the Prathyahara and Dharana limbs of yoga (withdrawal of the senses and focus). Thus, these results suggest that meditation, as part of this Kriya yoga, could be an effective way of training attentional brain networks as they were shown to benefit cognitive processing in humans.

In a different study, EEG signals recorded from three experiential levels of mindfulness meditators, who practice a typical form of meditation within the eight limbs of yoga, were compared to a non-meditator control group. Spontaneous EEG was recorded during resting-state for 5 min prior to a battery of tasks designed to measure temporal and spatial perception, as well as attentional skills. Afterwards, EEG signals were recorded during a meditation session of 15 min, while the control participants were given the instruction to relax without falling asleep. Then, resting-state EEG was repeated and the tasks were administered once more. The study showed that gamma power was increased in the temporal and the parietal-occipital areas during meditation when compared to resting-state in the mindfulness meditators group. This was interpreted as a momentary enhancement of sensory awareness following the practice or an increased attention. The authors suggested that this attentional process could be attributed to the "bottom-up" system of attention, which is largely lateralized to the right hemisphere. The authors also reported a large reduction of gamma waves in the default mode network during the transition from resting-state to a time production task in the right prefrontal cortex suggesting "a trait transition from self-reference processing which is narrative in nature, towards experiential self-reference mode". This self-reference mode could be related to a sense of embodiment or to body-awareness. Interestingly, there was no correlation between gamma power and the experience of the practitioners, even if the range of training experience was very wide in this study. Therefore, mindfulness meditation as described within the eight limbs of yoga seems to induce neural activity changes within networks associated with self-referential and attention networks during the early stage of the practice.

In a case-study derived from a larger clinical trial on Iyengar yoga (IY) to treat mild hypertension, four subjects underwent twelve weeks of IY training, which included the practice of asana, pranayama, and guided relaxation with awareness described as meditation. IY is a form of yoga that uses various props such as pillows and chairs to facilitate the ability of individuals to attain the necessary asanas (postures) involved in yoga. An important part of this type of yoga is the use of meditation and breathing exercises. The study involved pre-post training measures using single photon emission computed tomography scan (SPECT), in which part of the scan was done at rest and the other in a meditation state. The authors found a significant decrease in activity in the right amygdala, dorsal medial cortex, and sensorimotor area after training. They also demonstrated a significantly increased activation in the right dorsal medial frontal lobe, prefrontal cortex, and right sensorimotor cortex. They also reported that the left hemisphere was primarily recruited during the resting-state scan performed after training. The right hemisphere was the most active during meditation after the training. The frontal lobes were also more active after training and were associated with an enhanced attention state during meditation, which might be attributable to the dharana aspect of yoga.

In another study, MR-based gray matter (GM) concentration was quantified in mindfulness meditators of the Vipassana yoga tradition and compared to that of non-meditators. Mindfulness meditators were found to have greater GM concentrations in the right insula, an area known to be involved in interoception and visceral awareness. This suggests that meditation induces structural changes at the brain level in areas that are typically reported as being activated during meditation.

Another study that used structural MRI to assess cortical thickness provided evidence of experience-dependent cortical plasticity in relation to meditation practice. Brain regions associated with attention, interoception and sensory processing such as PFC and right anterior insula (AI) were found to be thicker in those meditating an average of forty minutes a day than matched control with no meditation or yoga experience. Consequently, Lazar and colleagues argued that the regular practice of meditation might delay the onset of age-related cortical thinning in the frontal cortex.

In a previous fMRI study completed by the same authors, the frontal and parietal cortex, the pregenual anterior cingulate cortex (ACC), AMY, midbrain and HIP were found to be activated during a simple form of meditation in Kundalini Yoga meditators. Kundalini is a common form of yoga, which involves a wide variety of breathing techniques, meditation and asana. These brain structures are thought to be involved in attention and arousal or autonomic control and may contribute to the meditative state. The authors suggested that the activation observed in limbic regions were most likely modulating the output of the autonomic system.

Several studies from the same group have looked at the effects of integrative body-mind training (IBMT), a technique very similar to yoga involving relaxation, mental imagery and mindfulness on brain structures and...
physiological processes, especially on the autonomic nervous system (ANS).\textsuperscript{24-26} Tang et al.\textsuperscript{25} showed improved physiological reactions after a five-day training such as lower heart rate (HR) and skin conductance response (SCR), higher belly respiratory amplitude, and lower chest respiratory rate than the control who underwent relaxation only. This indicates that IBMT trainees attained ANS regulation with less effort. They reached a relaxed state of the body and a calmer state of mind after the training. Tang et al.\textsuperscript{25} also suggested that the increase in high-frequency heart rate variance (HRV) in the IBMT group during training could be indicative of successful inhibition of the sympathetic tone and activation of the parasympathetic system more so than classical relaxation. This short-form of training was also shown to improve attention and self-regulation and to be associated with an increased theta power in the ACC and high-frequency HRV.\textsuperscript{25} In turn, the increased activity in frontal midline theta rhythm, the lowered heart rate and skin conduction, the increased belly and decreased chest amplitude and the high-frequency HRV reported by the authors were thought to provide strong evidence for the central and autonomic nervous system to be modulated by such a practice.

A study evaluated how yoga practitioners performed on a task of left/right body discrimination.\textsuperscript{27} Using a timed imagery task, yoga practitioners did not show better response time or accuracy than non-practitioners for this task, suggesting that yoga might not improve acuity of cortical proprioceptive maps. There were many confounding factors in this study such as its online nature, the lack of controlled environment, and the absence of a protocol detailing frequency, type or length of yoga practice. Although not conclusive, the authors suggested that yoga might still have an effect on body awareness. They argued that yoga practice would rely on an integrative sensory system while the task used in their study relied on a visuo-proprioceptive mechanism. Therefore, the task they used might not be the best to evaluate body awareness. This aspect remains to be further clarified.

Using MR-based techniques, Hernández et al.\textsuperscript{28} investigated the association between brain volume and FC with the depth of mental silence achieved in the scanner in long-term practitioners of Sahaja Yoga Meditation. GMV in the medial prefrontal cortex was found to be positively correlated with subject's perception of mental silence depth. Larger gray matter volume in this region was also found to be associated with the capacity of long-term meditators to achieve a durable state of mental silence in the scanner. Additionally, an increased in FC within the medial prefrontal cortex and bilateral anterior insula/putamen was observed during meditation, a phenomenon that was not present while subjects were asked to rest in the scanner. This recent study aligns well with the growing evidence supporting the benefit of the meditation aspect of yoga to increase body awareness, interoception and attentional control.

Lastly, Kjaer et al.\textsuperscript{29} found a large increase of endogenous dopamine release in the ventral striatum in highly experienced male yogis who underwent PET scan while performing Yoga Nidra meditation. In comparison to attending speech with eyes closed, the eight tested yogis were found to have a 65% increase in dopamine release during the meditation stage. The concentration of dopamine correlated with an increase in EEG theta activity, which is a common feature of meditation. Subjects also reported a decreased desire for action during meditation. Based on these results, the authors suggested that being in the conscious state of meditation might cause a suppression of corticostriatal glutamatergic transmission. This in turn would contribute to heightening the attentional control reported by those practicing the meditation aspect of yoga.

Overall, these studies suggest that yoga and meditation have effects on brain networks associated with attention, focus and interoception, as well as on the parasympathetic nervous system. These findings are believed to be associated with the relaxed state, increased focus and withdrawal of external stimuli described in yoga practice, which is known as body awareness by its practitioners.

### 4.3 The Effects of Yoga on the Brain in relation to Pain

The results from the eight studies included in this section are described in Table 4. The first study evaluated how meditators, who practice a form of yoga practice within the eight limbs of yoga, perceived pain unpleasantness induced by a laser compared to controls.\textsuperscript{28} The authors reported that the meditators perceived pain as less unpleasant than their matched control and that pain unpleasantness rating was correlated to the number of years of subjects' experience in meditation practices. Using EEG, they also found an increased activity in the mPFC and pACC. The authors claimed that since meditation showed an association with an improved cognitive function, this was an indication for meditators to better modulate the pain anticipation and appraisal. As such, these brain regions could accentuate cognitive control over perceived threat and be related to the meditators' attitude of acceptance linked to the attentional network.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Sample</th>
<th>Method</th>
<th>Measures</th>
<th>Results</th>
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<tbody>
<tr>
<td>\textsuperscript{27} Jones et al.</td>
<td>27 MEDITATORS: 12 of various practice types</td>
<td>- Test whether any differences in the affective appraisal of pain could be explained by lower anticipatory neural processing in relation to meditation experience</td>
<td>- Questionnaire for meditation experience; - Anticipatory and EEG pain-evoked ERPs and reported pain unpleasantness (VAS) in response to laser stimuli of matched subjective intensity</td>
<td>- MED: pain as less unpleasant vs controls, with experience correlating inversely with unpleasantness ratings - ERP source data for anticipation in MED = lower activity in MCC vs CON related to lower unpleasantness ratings, (experience predicted) - MED reversed the normal positive correlation between mPFC activity and pain unpleasantness in</td>
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<tr>
<td>\textsuperscript{26} Brown et al.</td>
<td>15 without meditation experience</td>
<td>- Radiation with 5/10 every 10s, preceded by visual anticipation cue</td>
<td>- ERP data after source estimation</td>
<td></td>
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</table>

| Table 4 Effects of yoga on the brain in relation to pain. |
Ceko et al. 2014

YOGA: 14 long term yoga practitioners
CON: matched control, 14 matched control

- Evaluate WM connectivity in long-term yoga practitioners and its relation to pain tolerance
- MRI session including a DTI scan after completing a cold pain tolerance test
- Correlation between FA in significant brain map clusters and pain tolerance
- YOGA: enhanced WM connectivity in pain-related regions, (CC, insula, S2)
- Effects are related to higher tolerance of pain

Grant et al. 2014

MEDITATORS: 17 mindfulness practitioners (trained in Vipassana meditation)
CON: 17 matched healthy control without meditation experience

- Investigate the underlying brain mechanisms by which the state of mindfulness reduces pain
- MED and CON received unpleasant transcutaneous electric stimuli of moderate intensity during a mindfulness and a control condition (no specific strategy)
- MED: P300, PMRI
- Respiratory rate during scanner Subjective reports:
- Stimulus intensity, Unpleasantness and anticipatory anxiety VAS after stimulation
- Mood, task difficulty and self-perceived success 7-point Likert scale pre-post scanning
- Freiburg Mindfulness Inventory
- German Fear of pain questionnaire
- MED ↓ pain unpleasantness by 22% & anticipatory anxiety by 29% during a mindful state.
- Reduction = ↓ activation the lateral PFC and increased activation in right posterior insula during stimulation and increased rostral ACC activation during anticipation of pain

Grant et al. 2014

N = 35
17 meditators and 18 controls
Cross-sectional study

- Investigate whether differences in brain morphometry are associated with the low pain sensitivity observed in Zen practitioners

- Structural MRI scans (ROI: dACC, PFC, SI, SII, HIP)
- Thermal Pain sensitivity with VAS
- Five Factor Meditation questionnaire
- MED: lower pain sensitivity than CON associated with thicker cortex in affective, pain-related brain regions (ACC, bilateral para-HIP gyrus and anterior insula)
- MED = thicker cortex dorsal ACC and bilaterally SII
- More experience = thicker GM in ACC, bilaterally in the lower leg area SI + hand area right hemisphere

Grant et al. 2014

N = 26
MEDITATORS: 13 healthy Zen meditators
CONTROL: 13 matched non-meditators

- Investigate how Zen reduce practitioners’ activity in executive, evaluative and emotion areas during pain (PFC, AMY, HIP)
- Moderate-pain level assessed and used for trials on six locations on left calf
- fMRI collected during single-block stimulation along with Pain VAS scale
- MED: higher stimulus intensities than CON
- More experienced MED showed the largest activation reductions
- MED more robustly activated primary pain processing regions (ACC, thalamus, insula) vs CON showed stronger activation in bilateral DLPFC and AMY, left MFG and right HIP and med PFC/OFC
- ↓ Lower pain sensitivity in MED predicted by reductions in FC between executive and pain-related cortices

Orme-Johnson et al. 2012

N = 24
MEDITATORS: 12 long-term TM (average of 31.3 ± 2.3 years)
CONTROL: 12 matched healthy control interested learning TM

- Identify if TM has a long-term effect on pain
  1. Pretest, MED compared CON
  2. TM taught 4-day course, 20 min/day 5 months
  3. Both groups post-test same protocol
- fMRI collected during single-block stimulation along with Pain VAS scale
- MED does not significantly differ from CON on Pain VAS, either at pretest, at posttest, or collapsed across trials.
- Both groups, ↓ pain ratings 25% from pre to post-testing
- MED showed 40–50% ↓ voxels to pain in the thalamus and total brain than CON.
- After CON did TM training ↓ 40–50% in thalamus, PFC, total brain, and ACC

North American Villemure et al. 2013

N = 28
YOGA: 14 North American yoga practitioners (of all types of yoga)
CONTROL: matched control, 14 matched control

- Investigate possible neuroanatomical underpinnings of the beneficial effects of yoga
- Surprise-2X: YOGA > 2X LONG AS CON & 1 GM multiple brain regions
- Insular GM correlated pain tolerance.
- Insular GM volume in yogis positively correlated with yoga experience
- Yogis have greater left intra-insular WM connectivity
- Yogis- cognitive strategies involving parasympathetic activation and interoceptive
Zeidan et al.\textsuperscript{35} 15 healthy volunteers without MED experience (6 male/9 female) - Assess the neural mechanisms by which mindfulness meditation influences pain - 4 days of 20 minutes of mindfulness meditation training - Painful Thermal stimuli - MRI 1 performed before training and MRI 2 after 4 days of training (MRI: 1/2 eyes closed; 1/2 meditation) - ASL-fMRI-VAS-FMI - ↓ pain-unpleasantness 57% = ↓ activity ACC and anterior insula, - ↓ pain-intensity ratings 40% = OFC activation and thalamic deactivation, - MED ↓ pain-related activation contra lateral SI - Brief MED training ↓ mindfulness skills - MED post training activate SI bilat (nose and throat) + bilat activation posterior insula SII, AI and ACC

<table>
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<th>Table 5 Abbreviations used in this review.</th>
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<tbody>
<tr>
<td><strong>Abbreviation</strong></td>
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<tr>
<td>AI</td>
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<tr>
<td>ACC</td>
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<td>AMY</td>
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<td>ANS</td>
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<td>AOSPAN</td>
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<td>ART</td>
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<td>ASL</td>
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<td>BA</td>
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<td>BAI</td>
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<td>BCI</td>
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<tr>
<td>BOLD</td>
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<td>CC</td>
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<td>CES-D</td>
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<td>CFQ</td>
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<td>CNS</td>
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<td>CON</td>
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<tr>
<td>DAN</td>
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<td>DMN</td>
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<tr>
<td>DLPFC</td>
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<td>DTI</td>
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<td>EEG</td>
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<td>EKG</td>
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A second study, evaluated WM connectivity of long-term yoga practice using diffusion tensor imaging (DTI).\textsuperscript{29} The length of yoga practice was found to be linked with enhanced WM connectivity in pain-related regions such as CC, insula and SII. These brain changes were also related to higher tolerance of pain for yoga practitioners over the control group (Table 5).
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>EMG</td>
<td>electromyogram</td>
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<tr>
<td>FA</td>
<td>fractional anisotropy</td>
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<td>FC</td>
<td>functional connectivity</td>
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<tr>
<td>fMRI</td>
<td>functional magnetic resonance</td>
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<td>FMI</td>
<td>Freiburg Mindfulness Inventory</td>
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<tr>
<td>GM</td>
<td>Gray matter</td>
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<td>GMV</td>
<td>gray matter volume</td>
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<td>HIP</td>
<td>Hippocampus</td>
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<tr>
<td>HR</td>
<td>heart rate</td>
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<td>HRV</td>
<td>heart rate variance</td>
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<tr>
<td>IBMT</td>
<td>integrative body-mind training</td>
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<td>ICBM</td>
<td>International Consortium for Brain Mapping database</td>
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<td>IMW</td>
<td>Instructed Mind wandering task</td>
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<tr>
<td>IPC</td>
<td>right inferior parietal cortex</td>
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<td>ITR</td>
<td>information transfer rate (standard metric of BCI control)</td>
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<td>IY</td>
<td>Iyengar yoga</td>
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<td>LORETA</td>
<td>low-resolution electromagnetic tomography</td>
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<td>MBAT</td>
<td>mind-body awareness training</td>
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<td>MCC</td>
<td>midcingulate cortex</td>
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<td>MED</td>
<td>Meditation group</td>
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<td>MEDIT</td>
<td>Meditation task</td>
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<td>MFG</td>
<td>middle frontal gyrus</td>
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<tr>
<td>mPFC</td>
<td>medial Prefrontal cortex</td>
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<tr>
<td>MRI</td>
<td>magnetic resonance imaging</td>
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<tr>
<td>msFC</td>
<td>meditation-state FC</td>
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<tr>
<td>NC</td>
<td>nerve conduction</td>
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<tr>
<td>OFC</td>
<td>Orbitofrontal cortex</td>
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<tr>
<td>pACC</td>
<td>pregenual ACC</td>
</tr>
<tr>
<td>PANAS</td>
<td>20-item positive and negative affect schedule</td>
</tr>
<tr>
<td>PFC</td>
<td>Prefrontal cortex</td>
</tr>
<tr>
<td>PSD</td>
<td>power spectral density</td>
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<tr>
<td>PVC</td>
<td>percent valid correct</td>
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<tr>
<td>ROI</td>
<td>Region of interest</td>
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<tr>
<td>RSNs</td>
<td>resting-state networks</td>
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In a third study, meditation practice was found to decrease pain unpleasantness by 22% and anticipatory anxiety by 29% during a mindful state of yoga. Using fMRI, the painful electrical stimulation was linked to a decreased activation of the lateral PFC as well as an activation of the right posterior insula during the stimulation. There was also a greater activation in the rostral ACC during the anticipation period before pain induction in meditators compared to control. Consequently, the authors concluded that focusing attention on the sensory aspects of the stimulus was related to the increased activation observed in the posterior insula, an area known to be involved in interoceptive and sensory processing. Since there was a correlation between increased insula activity during mindfulness and reduction in pain unpleasantness, this further supports the role of the insula in attenuating the effects of mindfulness. In other words, the area could be involved in increasing the sensory processing of the sensation itself through a distinctive brain state of cognitive disengagement.

Another study looked at the link between pain sensitivity and changes in fMRI pattern of activation in meditators who practice Zen, a meditation linked to yoga practices. During pain, a reduced activity in executive, evaluative and emotional areas of the brain was found such as in PFC, AMY, HIP. The lower pain sensitivity expressed by these meditators was characterized by a reduction in FC between the executive and pain-related cortices. The authors suggested that this “decoupling” might enable the meditator to view pain more neutrally. Decreased activation of the DLPFC was found in meditators whereas the opposite was found in the same region in controls. Activity is typically increased in DLPFC during pain, which is thought to reflect higher cognitive processes such as working memory and stimulus evaluation. Additionally, meditators showed reduced activation in the orbitofrontal cortex (OFC), HIP and AMY, suggesting that their present moment awareness (potentially reflected in the dorsal ACC) might enable them to decrease the cognitive-emotional and evaluative process during the aversion type of stimuli received. These same authors reported that Zen meditators where found to have lower pain sensitivity than control. These findings were associated with thicker cortex in the affective and pain-related brain regions (ACC, bilateral para-HIP gyrus and anterior insula) for the meditators.

In line with this, using a different type of meditation, transcendental meditation (TM) was reported to reduce the affective/motivational dimension of the brain's response to pain. When first tested using fMRI, transcendental meditators with on average 30 years of experience showed 40% fewer voxels responding to pain in the thalamus and total brain compared to healthy matched control. After five months of TM, the same control subjects reduced their response by 40-50% in the thalamus, PFC, total brain and ACC and after the training, the brain responsible for the two groups did not vary. The authors suggested that such reduction in brain activation might represent a reduced general arousal and anticipatory anxiety that may attenuate the pain response and the decreased distress caused by pain. It is interesting to note that pain intensity rating was the same in both groups, but TM practitioners seem to be less distressed as shown by their reduced fMRI pattern of activation. This suggests that expectancy was modulated by the practice of TM, thus altering pain perception.
In a study by Villemure et al., North American yogis of various styles with an average 9 years of experience showed an insular volume that correlated with yoga experience. They also tolerated cold pain for more than twice as long as controls. Yogis are reported to use cognitive strategies involving parasympathetic activation and interoception awareness to tolerate pain better than controls. This is thought to be achieved via the use of strategies such as focusing on their breath and on the sensations without reacting to it, relaxing their mind and body and accepting the painful sensation.

Lastly, after a four-day mindfulness meditation within the eight limbs of yoga for twenty minutes per day, fifteen healthy controls were able to use meditation to reduce pain unpleasantness by 57% and pain intensity by 40%. These measures were associated with reduced activation in the contralateral primary sensory cortex, increased activity in the ACC, anterior insula, and the orbitofrontal cortex and thalamic deactivation when measured at rest using fMRI. The authors claimed that this might indicate a cognitive regulation of nociceptive processing and a reframing of the contextual information, which may reflect a limbic gating mechanism. This, in turn, could modify the interaction between afferent input and executive functional brain areas through the thalamic reticular nucleus, a GABAergic structure that operates as a “gatekeeper” between the thalamus and cortex. The breath focus used in this study, a focused-attention type of meditation, may therefore influence pain intensity by altering the expansion of nociceptive input.

Based on these studies, yoga seems to affect the brain in a way that subjects practicing it become less affected by pain through cognitive disengagement, which leads to a decrease in the affective/motivational dimension of pain as well as to an increase in interoception. The insula seems to play a key role in this process in addition to an increase in parasympathetic activation via the hypothalamic-pituitary-adrenal (HPA) axis and vagus nerve regulation.

**4.4 Effects of yoga on the brain in relation to motor performance, body awareness and pain**

When taken together, the studies reported here revealed that yoga has a positive effect on learning rate, speed and accuracy of a motor task by increasing attention and decreasing stress through a better control of sensorimotor rhythms. Yoga also seems to improve sensory awareness and interoception, to increase the sense of embodiment and consequently to decrease fear. It was also found to regulate autonomic input, increase parasympathetic activity and promote associated self-regulation. These effects were associated with increased theta power in the ACC and high-frequency HRV. Yoga was also shown to reduce the threat signal, increase pain tolerance, decrease pain unpleasantness and decrease the anxiety and distress associated with pain. Those effects on pain signals were primarily associated with the recruitment of specific brain areas such as the insula, the amygdala and the hippocampus. The precise physiological mechanisms underlying these effects remain to be fully elucidated but it is proposed that yoga might promote a shift towards bottom-up interoceptive processing and the integration of a bottom-up and top-down self- regulatory system across the cardiovascular, musculoskeletal and neuroendocrine systems. It has also been proposed that yoga could improve physical and mental health through down-regulation of the HPA axis and the sympathetic nervous system.

A decrease in stress response was reported in many studies throughout this review. As cited earlier, although there is some evidence for yoga practice to reduce the allostatic load in stress response systems, further studies are needed to clarify the precise brain mechanisms associated with this effect. Throughout this review, there were also many inconsistent findings regarding the amount of experience or the dose of yoga practice required for structural or functional changes to take place in the brain. In one study, noted changes after a meditation session as short as twenty minutes. In their other studies, the same authors evaluated meditation sessions of six to eleven hours for such changes to take place. Therefore, no conclusions can be made as for the specific amount of training dose required for structural and functional brain changes to occur. Additionally, no research has been done so far to evaluate the effects of yoga on motor performance per se.

Yoga can be considered as a moderate aerobic exercise. An acute-bout of moderate-intensity aerobic exercise has been shown to facilitate the maintenance of motor performance during skill acquisition. It was also shown that a simple deep breathing technique, often used in yoga, facilitated the retention of a newly learned motor skill. Therefore, yoga could have tremendous potential for improving motor learning and performance. In line with this, a recent study by Yadav and Mutha reported the beneficial effects of alternate nostril breathing when subjects are learning a new motor skill. It is also noteworthy that a thirty-minute exercise of alternate breathing, a technique very often used in yoga practices, has been shown to facilitate complex functions such as motor memory when performed both immediately after the exercise session and 24 h after it. One mechanism suggested by Gard et al. is that through yoga, because of its resilience effects on basal ganglia cortico-thalamic circuits, one could unlearn old maladaptive behavioral patterns and to establish new adaptive ones. Consequently, yoga could have a significant impact on people suffering from chronic pain by helping them to unlearn maladaptive movements and behavior while helping them to decrease pain, which could ultimately impact motor learning or performance. This could have important implications in the field of neurorehabilitation and pain management since yoga could help patients to move in a more controlled manner as well as to unlearn old movement patterns, which are often associated with persistent pain.

**4.5 Limitations**

Being a narrative design, this review has the limitation of not being systematic. Being less structured systematically in its design, the narrative design could have led to overlooking relevant studies. For instance, studies evaluating the effects of yoga on motor performance without the concomitant use of brain measures were excluded from this study. Another important aspect to consider is that most of the studies involving yoga using neuroimaging techniques utilize cross-sectional design. Therefore, more longitudinal studies are needed to address the precise effects yoga has on the brain and the consequence its practice leads to over time. This type of study might help shed light on the innate physiological predisposition, which some people might have to gain from such practice. It was previously suggested that studies involving yoga practice should incorporate an active control group to better compare its effects to conventional exercise. A multidisciplinary approach across the domains of physiology, neuroscience and psychology should also be considered to properly understand the underlying brain mechanisms associated with its...
positive reported effects. Lastly, a thorough description of the protocols used in yoga research is crucial to translate knowledge and assure that they can easily be reproduced across studies.

5 Conclusion

The purpose of this review was to assess the body of existing literature on the effects of yoga in relation to motor performance, body awareness and pain and their associated brain mechanisms. It was shown that yoga practice improves learning rate, speed and accuracy. Yoga also increases attentional skills, decreases stress and seems to have a positive effect on memory. Its practice also increases a sense of embodiment, interoception, sensory and body awareness. Yoga is also shown to increase pain tolerance, decrease its unpleasantness and decrease the anxiety or distress associated with pain. These beneficial effects are associated with reduced activation of the contralateral primary sensory cortex, increased activity in the ACC, anterior insula, the orbitofrontal cortex and thalamic deactivation. However, no study has specifically looked at the effects of yoga on motor performance. Further studies are needed to address this gap in the literature. This review also highlights the importance of incorporating active control groups, of describing in greater details the intervention used and of favoring a multidisciplinary approach. In light of this review, the practice of yoga seems to have great potential for rehabilitation purposes and should be further investigated in order to reveal its precise effects on the brain. This will ultimately help promote its use and further validate its application in clinical settings.

Uncited references

References


Highlight

- Yoga has positive effect on learning rate, speed and accuracy of a motor task.
- Yoga improves sensory awareness and interoception, regulate autonomic input, increase parasympathetic activity and promote self-regulation.
- Yoga reduces the threat signal, increase pain tolerance, decrease pain unpleasantness and decrease the anxiety and distress associated with pain.
- A variety of brain areas are involved in these functions and specifically recruited during the practice of yoga.
- No study has yet specifically looked at the effects of yoga on motor performance on specific population.

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