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Review

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

Emmanuelle Rivest-Gadbois[a,b], Marie-Hélène Boudrias[a,b,c,*]

[a] School of Physical and Occupational Therapy, McGill University, Montreal, Quebec, Canada
[b] Montreal Center for Interdisciplinary Research in Rehabilitation (CRIR), Montreal, Quebec, Canada
[c] Feil and Oberfeld Research Centre, BRAIN Lab, Jewish Rehabilitation Hospital, Laval, Quebec, Canada

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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 performance, 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 (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.

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%).[1] The most common conditions present in those practicing yoga include back pain (20%), arthritis (6%) and stress (6%).[2] Consequently, yoga is increasingly considered as an affordable and promising modality for the management and the alleviation of the cost associated with these conditions.[3]

Exercise therapy has been traditionally used as the modality of choice for the treatment of chronic musculoskeletal pain.[4] However, persistent pain has been associated with fear of movement, anxiety, pain catastrophizing and nervous system sensitization.[4] 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[5] and to

* Corresponding author at: McGill University, School of Physical and Occupational Therapy, Hosmer House, Room 206, 3630 Promenade Sir-William-Osler, Montreal, Quebec H3G 1Y5, Canada.
E-mail address: mh.boudrias@mcgill.ca (M.-H. Boudrias).

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be a safe and effective way to alleviate pain.[6] 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.[60] 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 clienteles' needs, it can prove to be a highly cost-effective tool. In addition, in clinical settings, yoga could easily be tailored to diverse clienteles because of its accessibility, its cost-effectiveness and the fact that it promotes self-efficacy. Within these clienteles, 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.

2. 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 publication that could have been overlooked using traditional database.[61] For this reason, we also consulted an expert group called *Bridgebuilders to awareness in healthcare group*,[41] 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.

In respect to the yogic tradition, we included articles that used a form of practice within the eight limbs of yoga of Pantajali.[8] 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).[3] 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.[9] 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 regiment 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.

Table 1
Literature search tracking sheet.

Date of search	Database	Years searched	Search terms	# hits
02/11/2017	PubMed	1975–2017	yoga brain motor	12
02/11/2017	PubMed	1975–2017	yoga brain pain	21
02/11/2017	PubMed	1975–2017	effects yoga brain	77
02/11/2017	Science direct	Journal only	effects yoga brain motor performance	339
02/11/2017	PeDro	Full database (1929–2017)	effects yoga brain	3
02/23/2017	PubMed	1975–2017	Yoga AND brain (Pain OR body awareness OR motor performance)	33
02/12/2017	Expert group *Bridgebuilders to awareness in healthcare*	NA	effects of yoga on the brain in relation to pain, body awareness and pain	7
01/21/2019	PubMed	1975–2019	Yoga + Cortical activity	20
01/21/2019	PubMed	1975–2019	Yoga + cortex + sensory	10
01/21/2019	PubMed	1975–2019	Yoga + cortex + sensorimotor	1
01/21/2019	PubMed	1975–2019	Yoga + cortex + somatosensory	5
01/21/2019	PubMed	1975–2019	Yoga + cortex	70

Table 2
Results from the effects of yoga on the brain in relation to motor learning/performance.

Reference	Sample	Method	Mesures	Results	Comments
Cassady et al.[10]	*N* = 36 healthy subjects (22–35 y.o.) - MBAT: 12 (min 1 yr exp, 2 × 1 h/wk) - CON: 24 subjects with little or no exp. (< 10 sessions) - All BCI naive	- Investigate the role of prior experience with MBAT, in learning to use a 1-D sensorimotor rhythm based BCI	- EEG (Autoregressive spectral amplitudes at 12 Hz) - 3 BCI sessions of 10 min for 80% accuracy over Left-right & up-down cursor task - PVC, # of hits/run, ITR in bits/min	- 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	- 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
Chandra et al.[11]	*N* = 25 healthy subjects (30–50 y.o.) SKY = 15 CON = 10 (both naive to yoga) SKY underwent 7 days training in SKY CON continued normal activities	- Effects of SKY on brain signals during Working memory task - Working memory task = 20–25 min AOSPAN	- 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	- SKY improved working memory capacity by changing brain rhythms = energy utilized more efficiently while performing the task - SKY = efficient use of energy + PSD for the gamma (F8 channel), alpha, theta 2 (F7 and FC5) bands - gamma PSD ↓ both phases of memory in SKY - Alpha energy ↑ in retrieval phase after SKY - Theta rhythm associated with memory consolidation	- Small sample - No subjective measures
Engström et al.[12]	*N* = 8 healthy subjects less than 2 years of meditation (5 Kundalini & 3 ACEM) practice (min 2×/wk for 6–24 months)	- Investigate whether moderately experienced meditators activate HIP and PFC during silent mantra meditation	- fMRI obtained during silent mantra meditation in prone position, on–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)	- Significant activation in the bilateral HIP/paraHIP formations, bilateral middle cingulate cortex and the bilateral precentral cortex - No activation in ACC, and only small activation clusters in PFC	- Very small sample - No control
Field et al.[37]	*N* = 38 adults did 20-min Tai chi/yoga class *Cross sectional study*	- Determine the immediate effects of a combined form of Tai chi/yoga	- Pre- and post-Tai chi/yoga effects were assessed using STAI, EKG, EEG and math computations	- Heartrate increased during exercise - ↑ relaxation, ↓ anxiety, trend ↑ EEG theta activity -↑ relaxation may have↑speed + accuracy on math computations post class	- No control - 2 forms of exe - No long-term effects studied - Description of exe protocol
Froeliger et al.[13]	*N* = 14 healthy subjects (18–55 y.o.) YMP = 7 (Hatha yoga > 45 min/day; 3–4 ×/wk, > 3 yrs & mindfulness 7 days/wk over last 5.6 yrs CON = 7 subjects matched naive meditation/yoga	- Investigate GMV differences between YMP and matched CON	- CES-D scale (depression) BAI (anxiety). PANAS (State-dependent mood) - Anatomical MRI	- YMP group exhibited greater GMV in frontal, limbic, temporal, occipital, and cerebellar regions; - CON no greater GMV - YMP significantly fewer cognitive failures on the CFQ *(positively correlated with greater GMV areas listed above)* - GMV was positively correlated with the duration of yoga practice	- *Preliminary study cross-sectional* - Same population as other study by Froeliger et al.[42] *(see body awareness section)*
Gard et al.[14]	*N* = 47 healthy subjects YOGA = 16 (Kripalu yoga) MED = 16 (Vipassana) CON = 15 (less than 4 yoga or med class in last year/10 in lifetime) *Cross sectional* *And replication study*	- Explore differences in whole brain resting-state FC between experienced yoga practitioners, experienced meditators, and matched controls	- Resting-state fMRI based measures	- YOGA & MED had significantly greater degree centrality in the caudate than CON - Not 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	- Subjects were told not to meditate during resting-state scan - Data from of subset of individuals previously investigated (Lazar et al.[22]: *see body awareness table*)
Gothe et al.[15]	*N* = 118 (55–79 y.o.) healthy sedentary subjects randomized in: 8wk Hatha yoga	- Determine if yoga practice moderated the stress response and resulted in improved executive function	- Baseline & post 8 weeks; *executive function*; - Running memory span & n-back task	- YOGA ↑ accuracy executive function measures, ↓ cortisol response vs CON (↑ cortisol levels & poor cognitive performance)	- *RCT* - No neuroimaging technique but use of salivary cortisol level

(*continued on next page*)

Table 2 (*continued*)

Reference	Sample	Method	Mesures	Results	Comments
	YOGA = 61 or a stretching control group CON = 57 3×/wk for 1 h for 8-wk period		- Task switching paradigm *self-reported stress and anxiety;* - 14-Item Perceived Stress Scale - State sub-scale of STAI - *salivary cortisol samples* pre & post cognitive test	at follow up - Change in cortisol levels & self-reported stress and anxiety levels predicted performance on the running span task, n-back working memory and task switching paradigm	
Hölzel et al.[47]	*N* = 30 healthy subjects MED = 15 Vipassana (7.9 years 2 h/day) CON = 15 meditation naive matched *Cross sectional*	- Investigate differences in brain activation during meditation between meditators and non-meditators	Block-design fMRI study that included 6× (1) mindfulness breathing (1 min eyes closed) (2) mental arithmetic (on screen in front of them) Subjective measure: - % of time kept attention on the task. - Rate difficulties with task, on a Likert scale: 0–10	- In meditation vs arithmetic, MED stronger activations in the rostral ACC and the dorsal medial PFC bilaterally vs CON	- Arithmetic, differs from the meditative state, also the external (vs internal) focus, open (vs closed) eyes, preparation for response (vs quiet)
Luders et al.[57]	*N* = 60 MED: 30 CON: 30 matched non-meditators (obtained from the ICBM database of normal adults)	- Establish the presence and direction of callosal differences between long-term meditators and well-matched controls	- DTI in combination with structural MRI - Callosal measures of tract-specific FA	- Callosal measures were larger in MED in anterior callosal sections - Increased FA within Fminor but not Fmajor - differences between MED & CON in rostral body and posteriorly, involving large parts of anterior midbody and posterior midbody	- Neuroimaging only - *Cross sectional study* - Control from ICBM database
Trakoo et al.[16]	*N* = 80 healthy male police trainees divided in: Group 1: Asana Group 2: Pranayama Group 3: Asana + pranayama Group 4: Control All received a training of 4 days a week for 6 months during their police training	1 – Evaluate the effect of asana + pranayama on neurological and neuromuscular functions in healthy human 2 – Determine differential effects between training in asana, pranayama + combination	- EEG, NC, EMG, VEP, ART were recorded before and after the training period - NC, EMG, and VEP data were obtained from 28 subjects; EEG data from 48 subjects; and RT from 67 subjects	- Alpha, theta, & total power EEG ↑ asana training - ↓ visual reaction time + ↓ in red-green discriminatory reaction time: ↑ 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 ↑ motor & sensory nerve conduction - Total power of EEG, alpha, and theta power, delta % ↑ while reaction time ↓	- Inability to complete all the electrophysiological tests in all the participants - All participants continued their police trainee to the same extent during the study (control group included)

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.

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.[10] 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.[10] 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.[11] Prior to the training, the subjects underwent a baseline EEG recording at rest, followed by a 20–25-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.

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.[12] The authors argued that hippocampus-dependent consolidation benefits could be linked with the modulation of slow waves sleep, which have been shown to increase in those practicing meditation.[52] 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).[13] The YMP group was reported to maintain an active practice of hatha yoga meaning more than 45 min per day, three or four times per week for more than three years. This group exhibited greater gray 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.[14] 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.[14] 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.[9]

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.[15] 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.[15]

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.[16] 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[10,16] as well as increased working memory capacity and memory consolidation.[11,12]

Table 3
Effects of yoga on the brain in relation to body awareness.

Reference	Sample	Method	Measures	Results	Comments
Baijal and Srinivasan[18]	20 healthy individuals MED: 10 experienced meditators Sudarshan Kriya yoga (3–7 years) CON: 10 non-meditators	- Investigate the temporal dynamics of oscillatory changes during Sahaj Samadhi meditation	- EEG measure at baseline and during intervention session: MED: 8 min meditation CON: 8 min relaxation - Questionnaire of subjective experience before and after session	- Distinct meditative states = distinct changes in spectral powers: - Enhanced Theta band activity during MED in frontal areas - Emergence of slow frequency waves in attention-related frontal regions - Increased frontal theta activity = deactivation of parietal-occipital areas	- Short term effects, cross sectional - Meditation experience of 3–7 years
Berkovich-Ohana et al., 2011[63]	$N = 48$ MED = 36 midfulness meditators divided in 3 groups (short, medium & long term) CON = 12 meditation naive	- Investigate whether MED affects self-referential processing and is associated with DMN, either as short (state) – or long-term (trait) effects	- Resting-state EEG recorded pre- and post-task - Time production task - ROI: left and right frontal, central, temporal, parietal–occipital and midline and the mean log spectral power was calculated separately for each ROI	- EEG gamma power over frontal and midline areas reflect DMN - MED a trait lower frontal gamma activity & longer time durations negatively correlated with front gamma activity - State and trait increase in posterior gamma power without a link to proficiency	
Braboszcz et al.[58]	20 meditators from the Vipassana tradition, 27 meditators from Himalayan Yoga Tradition, 20 meditators from Isha Shoonya Yoga tradition and 32 controls	- Examine the differences in brain activity between meditation practitioners and non-practitioners	- EEG -2 × 20 min (1-MED 2-IMW). (1/2 = 1 then 2; other 1/2 = 2 then 1)	- MED had higher parieto-occipital gamma amplitude vs CON during MEDIT and IMW - Positively correlated with meditation experience - Higher 7–11 Hz alpha activity in the Vipassana group compared to all the others in MEDIT and IMW - Lower 10–11 Hz activity in the Himalayan yoga group during MEDIT - MED practice correlated to changes in the EEG gamma frequency range commonly	- Independent component analysis was used to show that gamma activity did not originate in eye or muscle artifacts
Cohen et al.[20]	4 naive subjects: 2 men/2 women mean age of 45	−12 wk IY training including (1) asanas, (2) pranayama, (3) a guided relaxation with awareness, (meditation)	- Pre-post training measures of SPECT ROI: the inferior frontal, superior frontal, dLPFC, OFC, dorsal medial cortex, inferior & superior temporal, inferior & superior parietal, occipital, sensorimotor areas, AMY, caudate, thalamus, midbrain, cerebellum, cingulate gyrus	- Significant ↓ between pre and post program baseline scans in the right AMY, dorsal medial cortex, sensorimotor area. - Significant difference between pre and post % activation in the right dorsal medial frontal lobe, prefrontal cortex, and right sensorimotor cortex	- Small sample - No control - *Case study part of larger study* - Changes may relate to any or all the components IY program
Froeliger et al.[42]	$N = 14$ healthy 18–55 y.o. MED = 7 (Hatha yoga > 45 min/day; 3–4×/wk, > 3 years & mindfulness meditation 7 days/wk over last 5.6 yrs CON = 7 matched yoga & meditation-naive	- Investigate the effects of meditation experience and on multiple RSNs MED: two 5 min scans, 1 – rest eyes closed, 2 – meditating CON: one scan resting-state eyes closed	- fMRI - Regression analyses of the relations between years of meditation practice and RSNs-FC and MED-FC were conducted	- MED exhibited greater RSN-FC within the DAN - MED, in meditation vs rest = strengthened FC between the DAN and DMN and Salience network; ↓ FC between the DAN, dmPFC, insula. - Positive correlations between years of experience and MED-FC between DAN, thalamus, and anterior parietal sulcus; negative correlations between DAN, lateral and superior parietal, and insula	- Small sample - Liberal significance threshold, - Short duration of meditation in the scan - Meditation practitioners were scanned twice, controls were only scanned once - *Cross-sectional study*
Hernández et al.[46]	$N = 46$ MED = 23 long-term Sahaja Yoga Meditation (SYM) practitioners CON = 23 healthy matched participants	- Assess which brain regions were structurally and functionally associated with the state of mental silence in long-term meditators of SYM	- MR-based techniques (VBM & FC): MED: measured in 3 phases: 1 – RS. 2 – structural morphometry data collected, and MED instructed to start meditating. 3 – Measure of MS CON: measured in 2 phases. 1 – RS identical to MED. 2 – Subjects watched entertainment video when structural morphometry data was collected using identical acquisition parameters as MED.	- GMV in medial prefrontal cortex were positively correlated with the subjective perception of the depth of mental silence inside the scanner - Significantly increased FC between this area and bilateral anterior insula/putamen during a meditation-state specifically -decreased connectivity with the right thalamus/ parahippocampal gyrus during the meditation-state and the RS - Capacity of MED to establish a durable state of mental silence inside an MRI scanner associated with larger GMV in a medial frontal region	- Subjective measure of depth of meditation known as mental silence was used
Holzel et al.[21]	$N = 40$ MED = 20 mindfulness	Compare the regional GM concentration of mindfulness meditators in the whole	- MR-based VBM (ROI: bilateral DLPFC, ACC, HIP, left inferior	- MED: ↑ GM right anterior insula, left inferior temporal gyrus and right HIP	- No other measures than neuroimaging

(*continued on next page*)

Table 3 (*continued*)

Reference	Sample	Method	Measures	Results	Comments
	(Vipassana) meditators (exp 8yrs 2 h/day) CON = 20 healthy matched subjects	brain to that of people without meditation experience	temporal gyrus and left postcentral gyrus right anterior insula, (the standard mask for the right insula was restricted to those voxels anterior to MNI coordinate y¼0)	- GM left inferior temporal gyrus predictable by amount of meditation training - GM medial OFC positively correlated with cumulated hours meditation training - GM in the OFC **not** found to be greater in MED vs CON	
Kjaer et al.[48]	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 cortico-striatal, 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, awakeness & awareness	- In MED, C-raclopride binding in ventral striatum decreased by 7.9% = to a 65% increase in endogenous dopamine release - Reduced raclopride binding correlated significantly with increase in EEG theta activity - All participants reported a decreased desire for action during meditation, along with heightened sensory imagery	- Small sample of highly experienced yogis - Male only
Lazar et al.[22]	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	- MED: Thicker right middle and superior frontal sulci (BA9–10), PFC and right anterior insula - ↑ PFC thickness in older participants, - Mean thickness across the entire cortex did not differ significantly between the groups for either hemisphere	- Not monks, typical Western meditation practitioners
Lazar et al.[23]	N = 5 Kundalini meditators of min. 4 yrs experience	Identify brain foci of activity that are modulated by a very simple form of meditation	- fMRI - Heart rate - Respiration rate - End-tidal CO_2 - O_2 saturation levels - ECG measures	- ↑ in putamen, midbrain, pregenual ACC, HIP and paraHIP formations, prefrontal, parietal and temporal cortices, precentral and postcentral gyri	- Small sample - No control - Cardiorespira-tory measures taken on 2 subjects only
Tang et al.[25]	N = 86 without training experience randomized undergraduates assigned to 2 experiments (IBMT) or control (relaxation) N = 46 (I: brain imaging & physiological) N = 40 (II: EEG & physiological)	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	- 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 - After training: ↓ HR, ↑ belly respiratory amplitude, ↓ chest respiratory rate, ↑ high frequency HRV, ↓ SCR in IBMT vs relaxation - Relaxation: more frontal, temporal, and parietal cortex activations (including Wernicke's area) than IBMT	- *RCT* control for variations of physiological indexes over the circadian rhythm; measurements performed from 2 to 6 p.m.
Tang et al.[24]	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 ↑ 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	
Vestergaard-Poulsen et al.[59]	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	- ↑ GM density but no volume differences in MED in lower brain stem–medulla oblongata - Separation of GM densities between groups in brain stem - ↑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	- Neuroimaging measures only - *Cross-sectional study*

(*continued on next page*)

Table 3 (*continued*)

Reference	Sample	Method	Measures	Results	Comments
				- No difference in GM density as a function of total practice hours in any region	
Wallwork et al.[27]	N = 86 participants (practicing yoga at least 30 min/week) N = 86 control (taken from a large online cross-sectional study of 1737 participants, which include people in pain)	- Determine if people who do regular yoga practice performed better at a left/right judgement task than people who did not - *Case–control comparison design*	RECOGNISE app*, evaluating accuracy and speed of laterality task for 1. 40 basic images of neck 2. 40 Context images of neck 3. 40 Basic images of hands	- No difference between Groups (yoga and no yoga) for either response time or accuracy Difference between Tasks; people were faster and more accurate at making left/right neck rotation judgements than they were at making left/right-hand judgements, regardless of group	- Online study, no controlled environment - No detailed information on frequency, length, type of yoga practice - Mixed sample of people in pain and healthy participants

There was also some evidence for a greater activation of the caudate and precentral cortex associated with better motor control and movement execution.[12] It was also demonstrated that cognitive performances were improved by the practice of yoga, which was associated with increased memory, attention and motor coordination.[14,13] 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.[5] 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”.[17]

In the first study, brain activity was measured during meditation using EEG.[18] 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.[18]

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.[19] 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 as 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, toward 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.[20] 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.[21] 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.[22] 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.[23] 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).[24–26] Tang et al.[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.[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.[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.[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.[46] 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 between 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.[48] 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 cortico-striatal 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.[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.

A second study, evaluated WM connectivity of long-term yoga

Table 4
Effects of yoga on the brain in relation to pain.

Reference	Sample	Method	Mesures	Results	Comments
Brown and Jones[28]	$N = 27$ MEDITATORS: 12 of various practice types CONTROL: 15 without meditation experience	- Test whether any differences in the affective appraisal of pain could be explained by lower anticipatory neural processing in relation to meditation experience - Two runs of 15 trials lasting 5 minutes, laser heat of 7/10 every 10s, preceded by visual anticipation cue	- Questionnaire for meditation experience; - Anticipatory and EEG pain-evoked ERPs and reported pain unpleasantness (VAS) in response to laser stimuli of matched subjective intensity - ERP data after source estimation with LORETA - VOIs were MCC, IPC, mPFC (the mPFC cluster included pACC)	- 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 anticipation. - MED: associated with lower activity in SII and insula during the pain-evoked response	- Meditation was not part of the experimental protocol, only meditation experience was investigated - Small sample size
Ceko et al.[29]	$N = 28$ YOGA: 14 long term yoga practitioners CON: 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 task - 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	- Short study description
Gard et al.[30]	$N = 34$ MED: 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)	- fMRI - 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	- Mindfulness meditation during task - Small sample size
Grant et al.[33]	$N = 35$ 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	- Thermal stimuli applied to calf influenced also by posture Zen meditation Half of participants had been in previous study by Grant et al.(2009)[62]
Grant et al.[32]	$N = 26$ 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 - Participants were instructed to attend to the stimuli as they normally would, with eyes closed - Mediators were specifically asked to not meditate - Pain perception assessed using electronic VAS measuring intensity and unpleasantness - Questionnaire of meditation history	- 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	- No behavioral data
Orme-Johnson et al.[34]	$N = 24$ 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 2×/day 5 months, 3. Both groups post-tested 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	- Pain same intensity but reduced response to acute pain after TM training - Small sample - One type of meditation studied - Partial crossover design
Villemure et al.[6]	$N = 28$ YOGA: 14 North-American yoga practitioners (of all	- Investigate possible neuroanatomical underpinnings of the beneficial effects of yoga	- Expectation measures (subjective question) - Thermal detection and pain threshold	- YOGA expected practice to ↓ reactivity to pain - Yogis > 2× long as CON & ↑ GM multiple brain regions	

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Table 4 (*continued*)

Reference	Sample	Method	Mesures	Results	Comments
	type of yoga) CONTROL: 14 matched control		- Cold pain tolerance - Mental strategies used during tolerance task (subjective question) - MR-based techniques (voxel-based morphometry, Cortical Thickness analysis, DTI Analysis and Tractography)	- 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 awareness to tolerate pain	
Zeidan et al.[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	- ASL - fMRI - VAS - FMI - Painful Thermal stimuli - MRI 1 performed before training and MRI 2 after 4 days of training (MRI: 1/2 eyes closed; 1/2 meditation)	- ↓ 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	- MED might activate cognitive regulation of nociceptive processing and in reframing the contextual evaluation of sensory events

Table 5
Abbreviations used in this review.

AI	anterior insula
ACC	anterior cingulate cortex
AMY	amygdala
ANS	autonomic nervous system
AOSPAN	Automated of operation span (15 trial remembering and retrieving letters and solving math problems)
ART	auditory reaction time
ASL	arterial spin labeling
BA	Brodmann areas
BAI	Beck Anxiety Inventory
BCI	brain–computer interface
BOLD	blood oxygen level-dependent
CC	Cingulate cortex
CES-D	Center for Epidemiological Studies-Depression
CFQ	Cognitive Failures Questionnaire
CNS	central nervous system
CON	Control group
DAN	Dorsal Attention Network
DMN	default mode network
DLPFC	Dorsolateral prefrontal cortex
DTI	diffusion tensor imaging
EEG	Electroencephalogram
EKG	electrocardiogram
EMG	electromyogram
FA	fractional anisotropy
FC	functional connectivity
fMRI	functional magnetic resonance
FMI	Freiburg Mindfulness Inventory
GM	Gray matter
GMV	gray matter volume
HIP	Hippocampus
HR	heartrate
HRV	heartrate variance
IBMT	integrative body–mind training
ICBM	International Consortium for Brain Mapping database
IMW	Instructed Mind wandering task
IPC	right inferior parietal cortex
ITR	information transfer rate (standard metric of BCI control)
IY	Iyengar yoga
LORETA	low-resolution electromagnetic tomography
MBAT	mind–body awareness training
MCC	midcingulate cortex
MED	Meditation group
MEDIT	Meditation task
MFG	middle frontal gyrus
mPFC	medial Prefrontal cortex
MRI	magnetic resonance imaging
msFC	meditation-state FC
NC	nerve conduction
OFC	Orbitofrontal cortex
pACC	pregenual ACC
PANAS	20-item positive and negative affect schedule
PFC	Prefrontal cortex
PSD	power spectral density
PVC	percent valid correct
ROI	Region of interest
RSNs	resting-state networks
RT	reaction time
SII	Secondary somatosensory cortex
SCR	skin conductance response
SKY	Sudarshan Kriya yoga
SMR	sensorimotor rhythms
SPD	spectral power difference
SPECT	single photon emission computed tomography scan
SYM	Sahaja Yoga Meditation
STAI	State Anxiety Inventory
TM	Transcendental meditation
VAS	Visual analog scale
VBM	voxel-based morphometry
VEP	visual evoked potentials
VOI	Volume of interest
WM	White matter

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Table 5 (*continued*)

YMP	yoga meditation practitioners
*RECOGNISE App (Neuro Orthopaedic Institute, Adelaide, Australia)	Online application that has been validated for the recognition of left/right judgements, which reflects the integrity of the cortical representation (Bray H, Moseley GL, 2011)[64] (Parsons LM, Fox, PT, 1998)[65]

practice using diffusion tensor imaging (DTI).[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).

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.[30] 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.[31] 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.[30] 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.[32] 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.[32] 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.[33] 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.[34] 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.[34] 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.,[6] North American yogis of various styles with on 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.[6] 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%.[35] 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.[35] 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.[10] 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 assonated 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 toward bottom-up interoceptive processing and the integration of a bottom-up and top-down self-regulatory system across the cardiovascular, musculoskeletal and neuroendocrine systems.[9] 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.[36] 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,[7] 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,[25] 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.[24,26] 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.[37] An acute-bout of moderate-intensity aerobic exercise has been shown to facilitate the maintenance of motor performance during skill acquisition.[38] It was also shown that a simple deep breathing technique, often used in yoga, facilitated the retention of a newly learned motor skill.[39] Therefore, yoga could have tremendous potential for improving motor learning and performance. In line with this, a recent study by Yadav and Mutha[39] reported the beneficial effects of alternate nostril breathing when subjects are learning a new motor skill. It is also noteworthy that a 30-min 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.[39] One mechanism suggested by Gard et al.[9] 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.[2] 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.[1] 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.[40]

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.

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