Neuropsychological Trends

31
April 2022

Manipulating interoception for intervention purposes: some applications in the clinical, social and sports field

Laura Angioletti[1]

[1] *International Research Center for Cognitive Applied Neuroscience (IrcCAN), Catholic University of the Sacred Heart, Milan, Italy*

[2] *Research Unit in Affective and Social Neuroscience, Department of Psychology, Catholic University of the Sacred Heart, Milan, Italy*

DOI: https://dx.doi.org/10.7358/neur-2022-031-angi

laura.angioletti1@unicatt.it

ABSTRACT

Notwithstanding breakthroughs in our knowledge of interoception's various dimensions and implications, along with research demonstrating interoceptive impairments in clinical groups, there is limited data on the successful ways for enhancing this capacity. Here special attention will be given to the interventions that commonly directs attention to the body and to the respiratory rhythms, such as slow breathing technique and MBIs, and how these interventions can promote interoception modulation. Without claiming to be exhaustive and with the intention of soliciting research in this field, in this contribution some potentially interesting and relatively novel applications of the manipulation of interoception will be described, focusing in particular on the clinical, social and sports field.

Keywords: interoception; social interoception; synchronization; sport; physical exercise

1. A brief introduction to interoception

Although the concept of interoception has been hypothesized centuries ago by Sherrington (1906), as a type of perception distinguished from exteroception, only recently it has gained increased attention in the panorama of the neuroscientific literature.

Conventionally, it refers to the mechanism by which the nervous system detects, interprets, and integrates the signals that come from inside the body, providing a punctual and complete mapping, moment by moment, of the internal body condition, through the conscious and unconscious levels (Tsakiris & De Preester, 2018).

Despite, it has been widely considered as a stable index that reflects a fixed individual trait, recent works started to conceive it as a multidimensional construct along a continuum from the bottom-up to top-down systems that can be manipulated by different types of interventions (Weng et al., 2021). In fact, previous research conceived the first interoception dimensions (i.e., interoceptive sensitivity, accuracy, and awareness) as relatively stable traits which can modulate the subjective experience of emotion; however, recent research showed that the different dimensions of interoception can be instead modulated by specific training (Farb et al., 2013b), such as awareness-based approaches like Mindfulness-Based Interventions (MBIs), slow breathing (Weng et al., 2021), and the degree to which a person focuses the attention on bodily changes (Farb et al., 2013b, 2013a).

Notwithstanding breakthroughs in our knowledge of interoception's various dimensions and implications, along with research demonstrating interoceptive impairments in clinical groups, there is limited data on the successful ways for enhancing this capacity (Farb et al., 2015). There are still some open points that would deserve further deepening in this field, such as i) the full cortical basis of interoception, ii) the higher-level dimension of the construct related to awareness, attention and executive attribution, that suggests the link between the attention to the bodily signals, and executive functioning, and iii) the possibility to manipulate interoception through specific training.

With reference to this last point, in the next section, some of the possible interventions that can be implemented to manipulate the interoceptive capacity will be described.

2. Interventions and manipulations of interoception

At the basis of interventions involving interoception, there is the concept and evidence that interoception is not a static perceptual ability but is a multi-faced construct that can be modulated by different methods and approaches. Indeed, according to recent evidence, interoceptive pathways may be manipulated at various levels to develop interventions to improve symptoms in a range of clinical disorders (Weng et al., 2021).

Interventions of a given interoceptive system can be understood through four main domains: the intervention type, the target(s), the potential mechanisms underlying the intervention, and the clinical and psychological outcomes derived from the intervention.

Primarily via the respiratory system, various pathways can be manipulated at neural, behavioural, and psychological levels to change the representation of and attention to interoceptive signals, which can alter interconnected physiological systems and improve functioning and adaptive behaviour. Also, interventions can alter interoception via neuromodulation of the vagus nerve, slow breathing techniques to change respiratory rate and depth, or awareness processes such as MBIs. It is worth noticing that all these interventions act on the person's executive control directly or indirectly and at a conscious or unconscious level.

The neural entry points that can affect upstream sensory or psychological functioning (e.g., the vagus nerve) or behavioural or psychological entry points that can affect downstream functioning (e.g., respiration rate and depth, interoceptive awareness, and interpretation of respiratory sensations) may be the target(s) of an interoceptive intervention. These targets can be reached through different intervention types. Here special attention will be given to the interventions that commonly direct attention to the body and to the respiratory rhythms, such as slow breathing techniques and MBIs, and how these interventions can promote interoception modulation.

2.1. Breathing techniques for modulating interoception and improving sympathetic function

Breathing processes are usually unconscious. However, breathing can become conscious when there is a shift in intensity (e.g., exercise) or an airway blockage, or through interoceptive awareness training previously mentioned. The mind-body link relies heavily on respiratory function and individuals can become active participants in their own health and homeostasis, by engaging in interventions that consciously regulate their respiratory rate or increase their interoceptive awareness capacity, for example, through different types of training such as slow breathing techniques and mindfulness approaches.

Slow breathing (or the decreasing of respiratory rate) is considered to lower blood pressure and causes a reflex reduction in autonomic nervous system (ANS) activation (Seals et al., 1990). Device-guided slow breathing, in which a biofeedback device uses musical tones to direct breathing rates to sub-physiological levels of ~5 breaths/min, can be used to alter respiratory rate (Sharma et al., 2011).

Various emotional states might raise the respiratory rate to boost oxygen intake in order to support the energy cost of escaping or resisting dangers. The respiratory challenge, on the other hand, causes panic-like feelings (Nardi et al., 2009).

Therefore, conscious processes can be utilized to affect respiratory functioning, just as respiratory processes can impact mental states; for example, by adjusting the respiratory rate or interoceptive awareness of breathing sensations (Grossman, 2010). Respiration differs from other peripheral systems in that conscious management may have an instantaneous influence on respiratory processes, and respiratory processes can affect emotion and cognition, as seen above. For example, in a core practice of focused attention to the breath, interoceptive attention is consciously focused on sensations of the breath until distracted by other internal or external stimuli, and then nonjudgmentally returned to the breath (a procedure very similar to the mindfulness approach).

Exteroceptive information like as visual and auditory stimuli has traditionally been used to study alerting, orienting, and executive control attention networks (Corbetta & Shulman, 2002; Petersen & Posner, 2012). Less is known about whether these attention networks can be similarly applied to interoceptive information, which is internal and difficult to measure.

2.2. Mindfulness-Based Interventions (MBIs)

As previously anticipated, psychological interventions such as MBI can alter the representation of interoceptive information by training awareness to i) internal respiratory signals from bodily areas associated with breathing, ii) internal and external sensations, iii) cognitive and affective qualities of attention, such as sustained focus with a non-judgmental attitude.

For instance, in terms of interventions, Mindful Awareness in Body-oriented Therapy (MABT) from Price and colleagues' (Price et al., 2012, 2019) combines manual and brain-and-body approaches to develop interoception and self-care tools for emotion regulation. MABT is unique among MBI in its use of touch to promote and develop the capacity for Interoceptive Awareness. As a therapeutic approach delivered individually, regulatory responses to sensory experience are assessed, and any difficulty with interoceptive processing is explicitly addressed through a combination of mindfulness instruction and psychoeducation (Price & Hooven, 2018). Previous findings highlighted the acquisition of interoceptive awareness skills, improved emotion regulation (self-report and physiological), reduced depression, and perceived benefits of this approach among women benefiting from this intervention (Price & Hooven, 2018).

Also, MBIs engage neural networks involved in interoception (anterior and posterior insula), Executive Function (EF), and emotion regulation (mPFC/ACC).

MBI appears to boost the activation of interoception and salience networks, which share a critical hub in the anterior insula, via using executive control networks. According to neuroimaging studies, breath-focused meditation enhances activity in networks involved in focused attention and cognitive regulation (i.e., EF network including the PFC, the ACC, and the premotor cortex) as well as interoception (the insula) (Fox et al., 2016).

Findings from EEG studies of breath-focused meditation suggest increased alpha in posterior areas and theta in frontal areas (Tang et al., 2019). Increased frontal theta may indicate a need for cognitive control and may also influence the white matter (Balconi & Vanutelli, 2017; Piscopo et al., 2018). During an interoceptive breath-focused activity, mindfulness meditation training resulted in increased activation in the posterior insula, a region sensitive to respiratory rate and putatively regarded primary interoceptive cortex, as well as a posterior limbic and medial parietal network (Farb et al., 2013b).

In addition, breath-focused meditation practice decreases activation in regions associated with mind-wandering and self-referential processing (Fox et al., 2016). Results show that meditators can focus on the breath by activating brain networks associated with cognitive control and interoception and disengage from mind wandering and self-referential processing by decreasing decision-making activation (Fox et al., 2016).

Because it cultivates cognitive and emotional flexibility, disengaging from self-related cognition is very important in healthy and clinical contexts (Dahl et al., 2015). Nowadays new wearable devices have been developed to track these fluctuating neural states of attention to interoceptive signals during meditation, which provides empirical evidence of the neural differentiation between inner states of interoception, mind wandering, and self-referential processing. These neural patterns are then utilized to measure attention concentration during breath-focused meditation, which may be used to calculate the proportion of time spent interoceptively focusing on the breath (Weng et al., 2021).

To conclude, MBI may improve concentration, interoceptive focus, and stability (Khalsa et al., 2018), cognitive processes aimed towards interoceptive stimuli (such as sustained attention, cognitive monitoring, and meta-awareness (Dahl et al., 2015), and emotion regulation (more acceptance and less reaction to interior sensory experiences; Desbordes et al., 2015).

In addition, to connect MBI to empathic behaviour, meditation techniques can help people develop compassion (Weng et al., 2013) and kindness in the face of pain and suffering (Kirschner et al., 2019). These abilities may contribute to enhanced health-promoting decision-making and behaviours, by allowing for better monitoring and regulation of physical, emotional, and social processes (Quigley et al., 2021).

Without claiming to be exhaustive and with the intention of soliciting research in this field, in the next section, some potentially interesting and relatively novel applications of the manipulation of interoception will be described, focusing on the clinical, social, and sports fields.

3. Some applications

3.1 Manipulation of interoception for clinical purposes: the example of chronic diseases

One of the very first reasons why there is a specific interest in the manipulation of interoception concerns the positive clinical and psychological outcomes derived from such an intervention.

In fact, the manipulation of interoception acted by augmenting the awareness of the breath rhythms can be a free of side effects alternative or complementary treatment (non-pharmacological way) to improve sympathetic control. This opens avenues for patients to take control of their health by participating in programs that deliberately regulate their breathing rate or develop their interoceptive awareness capacity through mindfulness techniques.

Manipulation of breathing interoception may aid in the treatment of disorders involving dysregulation of the sympathetic nervous system (SNS), which is responsible for both acute and long-term blood pressure regulation. Several chronic conditions, such as chronic kidney disease (CKD) (Grassi et al., 2011) and post-traumatic stress disorder (PTSD) (Park et al., 2017), are featured by a persistent hyperactivation of SNS, which in turn increases the risk of developing chronic diseases. Treatments for SNS overactivation, on the other hand, are restricted, owing to the fact that existing pharmaceutical alternatives might produce side effects such as hypotension, orthostasis, and weariness, as well as metabolic implications (Carella et al., 2010). So, the nonpharmacological therapeutic techniques for SNS overactivity and dysregulation may provide an alternative treatment option.

Recently, we have deepened the construct of interoception in relation to two main chronic clinical conditions. First, a single case of a patient with fibromyalgia has been confronted with a control group of healthy participants, to explore the relationship between this well-known "amplification syndrome", emotional distress, and interoception (Balconi & Angioletti, 2020). Secondly, the link between impaired interoception and addiction has been discussed proposing interoceptive manipulation as a root for intervention (Balconi & Campanella, 2021). In both these two clinical conditions interventions involving interoception could be considered a potentially valuable alternative treatment for promoting a positive restoration of the brain-and-body system.

3.2. Manipulation of interoception for social purposes: interpersonal synchronization and dyadic performance

As briefly discussed above, due to its importance in physical and emotional well-being, interoception has been more investigated in recent years. However, recent contributions focused on the function of interoception in social connection, which is a relatively young and rapidly expanding field of study.

According to research in the so-called field of "social interoception", interoception may be particularly important in the appraisal of physiological signals in social contexts (Arnold et al., 2019). It has been also suggested that interventions aimed to improve interoceptive abilities, such as mindfulness-based meditation practices, may be key for alleviating loneliness (as an extreme case of poor social connection, which is associated with physiological decline, increased mortality risk, and interoceptive dysregulation) and improving the social connection.

Interestingly, to date little is known about how deliberate attention to interoceptive correlates (Interoceptive Attentiveness, IA) affects the performance during a social interaction that requires or necessitates the synchronization with another partner of the dyad, such as a communication process, a teamwork dynamic, or a general interpersonal relation.

The ability to synchronize with another person comprises a set of social communication actions that encompasses joint attention, imitation, turn-taking, nonverbal social-communicative exchanges, time and content synchronization (Delaherche et al., 2012) and is extremely relevant in several real-life conditions requiring reciprocal cooperative interactions and interpersonal coordination, and just by way of example, dyadic sports such as synchronized diving or dancing competitions. Interpersonal synchronization can occur either consciously when there is an explicit objective or unconsciously when the goal is absent. The activation of neural correlates such as the PFC, supporting interpersonal synchronization can be enhanced by the focused attention to a particular interoceptive signal, such as the breath, for a specified time interval, a skill known as interoceptive attentiveness (Balconi & Angioletti, 2022).

Nowadays there is little understanding of how IA may affect brain responses during synchronized cognitive or motor tasks. To this aim, a new protocol was recently developed to explore the effect of explicit IA manipulation on hemodynamic brain correlates of simple cognitive tasks implying linguistic or motor synchronization (Balconi & Angioletti, 2022).

Eighteen healthy participants completed two linguistic and motor synchronization tasks during both explicit IA and control conditions while hemoglobin variations were recorded by functional Near-Infrared Spectroscopy (fNIRS) (Balconi & Molteni, 2016). During the explicit IA condition, participants were instructed to focus on their body (specifically on their breath) while executing the synchronization tasks. Instead, in the control condition no explicit request to concentrate on their interoceptive correlates was provided. In the meanwhile, fNIRS was used to record oxygenated (O2Hb) and deoxygenated hemoglobin (HHb) changes during the tasks.

Findings suggested that the brain regions associated with sustained attention, such as the right prefrontal cortex (PFC), were more involved when inducing the explicit focus on the breath during the cognitive linguistic task requiring synchronization with a partner, as indicated by increased O2Hb. Interestingly, this effect was not significant for the motor task.

In conclusion, for the first time, this pilot research found increased activity in neuroanatomical regions that promote sustained attention, attention reorientation, and synchronization when a joint task is carried out and the person is focusing on its physiological body reactions. Moreover, results suggested that the benefits of conscious concentration on physiological interoceptive correlate while executing a task demanding synchronization, particularly verbal alignment, may be related to the right PFC.

However, IA is also relevant for motor synchronization since interoceptive processes inform motor planning, making predictions of a partner's movements, and motor coordination with the social partner (Farmer & Tsakiris, 2012). Also, previous studies suggested a link between controlled breathing and motor synchronization stating the first plays a special role in mediating respiration-entrained brain synchrony, which could enhance motor activity (McKay et al., 2003) and synchrony in the motor cortex (Herrero et al., 2018).

In another recent pilot study, participants performed a task requiring interpersonal movement synchrony with and without a social framing in both explicit IA and control conditions. This study was developed to explore the effect of explicit IA manipulation on hemodynamic brain correlates during a task involving interpersonal motor coordination framed with a social goal (e.g., to synchronize to perform better in a sports team).

The IA manipulation conditions and the fNIRS recording procedure were equivalent to the previous study, while the tasks differed: the motor synchronization tasks consisted of a simple finger movement task, that in one case, was socially framed specifying that participants needed to synchronize in order to develop greater dyadic teamwork skills.

According to the results, the PFC, which is involved in high-order social cognition and interpersonal relations processing, was more responsive when inducing the explicit focus (IA) on breathing during the motor task requiring synchronization and socially framed, as indicated by increased O2Hb. Overall, the present study suggests that when a joint task is performed and the individual focuses on his/her physiological body reactions, the brain hemodynamic correlates are "boosted" in neuroanatomical regions that support sustained attention, reorientation of attention, social responsiveness, and synchronization. Furthermore, the PFC responds significantly more as the person consciously focuses on physiological interoceptive correlates and performs a motor task requiring synchronization, particularly when the task is socially framed.

3.3. Manipulation of interoception in the sports field

In the previous paragraph, it has been discussed how the manipulation of IA can affect the ability to synchronize and, only by way of example, dyadic sports, such as synchronized diving or dance were mentioned. However, during physical exercise, interoception provides the representation of the physiological condition of one's body in order to make possible this dynamic crosstalk between the CNS and the periphery of the body (Craig, 2002).

Interoceptive abilities have been linked to physical performance in recent studies, implying that interoception aids self-regulation during exercise (Georgiou et al., 2015; Zarza et al., 2019). For example, Herbert and colleagues discovered that when subjects were allowed to determine their own speed in a 15-minute exercise on a bicycle ergometer, good heartbeat perceivers had lower heart rates, stroke volume, and cardiac output, as well as a shorter recorded distance (Herbert et al., 2007). In this study, participants who had superior interoceptive accuracy set a more manageable pace and controlled their weariness better than those who had poor heartbeat perception. Children with a normal or high BMI and better interoceptive sensitivity covered a greater distance in a 6-minute running performance challenge (Georgiou et al., 2015). On the other hand, no differences in maximal performance were found between a group of poor and good heartbeat perceivers (Machado et al., 2019).

Interoception has a stronger impact on exercise performance in precision sports like shooting and archery. Shooting accuracy, for example, is dependent on the exact point of the cardiac cycle when the shot is triggered (Keast & Elliott, 1990). Helin and colleagues showed that athletes with better cardiac awareness and accuracy were able to pull the trigger at the points of the cardiac cycle where higher accuracy is achieved, that is during ventricular diastole, because the heart causes an almost imperceptible shake during systole, which can affect the bullet's trajectory (Helin et al., 1987). Furthermore, biofeedback given to eight junior experienced shooters resulted in increased awareness and improved performance (Daniels & Landers, 1981).

To sum up, these examples from physical exercise and sports disciplines show how interventions involving interoception manipulation could have a direct positive impact on sports performance.

REFERENCES

Arnold, A. J., Winkielman, P., & Dobkins, K. (2019). Interoception and Social Connection. *Frontiers in Psychology*, *10*, 1–6. https://doi.org/10.3389/fpsyg.2019.02589

Balconi, M, & Campanella, S. (2021). *Advances in Substance and behavioral addiction. The role of executive functions* (M Balconi & S. Campanella (eds.); 1st ed.). Springer, Cham. https://doi.org/https://doi.org/10.1007/978-3-030-82408-2

Balconi, M., & Angioletti, L. (2020). Fybromialgia, interoception and risk factor for emotional dysregulation: A single case pilot study. *Maltrattamento e Abuso All'infanzia*, *1*, 25–33. https://doi.org/10.3280/MAL2020-001003

Balconi, M., & Angioletti, L. (2022). Interoceptive attentiveness induces significantly more PFC activation during a synchronized linguistic task compared to a motor task as revealed by functional Near-Infrared Spectroscopy. *Brain Sciences*, *12*(3), 301. https://doi.org/10.3390/brainsci12030301

Balconi, M., & Molteni, E. (2016). Past and future of near-infrared spectroscopy in studies of emotion and social neuroscience. *Journal of Cognitive Psychology*, *28*(2), 129–146. https://doi.org/10.1080/20445911.2015.1102919

Balconi, M., & Vanutelli, M. E. (2017). Interbrains cooperation: Hyperscanning and self-perception in joint actions. *Journal of Clinical and Experimental Neuropsychology*, *39*(6), 607–620. https://doi.org/10.1080/13803395.2016.1253666

Carella, A. M., Antonucci, G., Conte, M., Di Pumpo, M., Giancola, A., & Antonucci, E. (2010). Antihypertensive Treatment with Beta-Blockers in the Metabolic Syndrome: A Review. *Current Diabetes Reviews*, *999*(999), 1–7. https://doi.org/10.2174/157321020459394399 8

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*, 201–215. https://doi.org/10.1038/nrn755

Craig, A. (2002). How do you feel? Interoception: the sense of the physiological condition of the body. *Nature Neuroscience*, *3*, 655–666. https://doi.org/10.1038/nrn894

Dahl, C., Lutz, A., Davidson, R. J., Dahl, C., Lutz, A., & Reconstructing, R. J. D.

(2015). Reconstructing and deconstructing the self : cognitive mechanisms in meditation practice To cite this version : HAL Id : hal-01599345 HHS Public Access. *Trends in Cognitive Sciences*, *19*(9), 515–523. https://doi.org/10.1016/j.tics.2015.07.001

Daniels, F. S., & Landers, D. M. (1981). Biofeedback and Shooting Performance: A Test of Disregulation and Systems Theory. *Journal of Sport and Exercise Psychology*, *3*(4), 271–282. https://doi.org/10.1123/jsp.3.4.271

Delaherche, E., Chetouani, M., Mahdhaoui, A., Saint-Georges, C., Viaux, S., & Cohen, D. (2012). Interpersonal Synchrony : A Survey Of Evaluation Methods Across Disciplines. *IEEE Transactions on Affective Computing*, *3*(3), 349–365.

Desbordes, G., Gard, T., Hoge, E. A., Hölzel, B. K., Kerr, C., Lazar, S. W., Olendzki, A., & Vago, D. R. (2015). Moving beyond Mindfulness: Defining Equanimity as an Outcome Measure in Meditation and Contemplative Research. *Mindfulness*, *6*(2), 356–372. https://doi.org/10.1007/s12671-013-0269-8.Moving

Farb, N. A. S., Segal, Z. V., & Anderson, A. K. (2013a). Attentional modulation of primary interoceptive and exteroceptive cortices. *Cerebral Cortex*, *23*(1), 114–126. https://doi.org/10.1093/cercor/bhr385

Farb, N. A. S., Segal, Z. V., & Anderson, A. K. (2013b). Mindfulness meditation training alters cortical representations of interoceptive attention. *Social Cognitive and Affective Neuroscience*, *8*(1), 15–26. https://doi.org/10.1093/scan/nss066

Farb, N., Daubenmier, J., Price, C. J., Gard, T., Kerr, C., Dunn, B. D., Klein, A. C., Paulus, M. P., & Mehling, W. E. (2015). Interoception, contemplative practice, and health. *Frontiers in Psychology*, *6*, 1–26. https://doi.org/10.3389/fpsyg.2015.00763

Farmer, H., & Tsakiris, M. (2012). The Bodily Social Self: A Link Between Phenomenal and Narrative Selfhood. *Review of Philosophy and Psychology*, *3*(1), 125–144. https://doi.org/10.1007/s13164-012-0092-5

Fox, K. C. R., Dixon, M. L., Nijeboer, S., Girn, M., Floman, J. L., Lifshitz, M., Ellamil, M., Sedlmeier, P., & Christoff, K. (2016). Functional neuroanatomy of meditation: A review and meta-analysis of 78 functional neuroimaging investigations. *Neuroscience and Biobehavioral Reviews*, *65*, 208–228. https://doi.org/10.1016/j.neubiorev.2016.03.021

Georgiou, E., Matthias, E., Kobel, S., Kettner, S., Dreyhaupt, J., Steinacker, J. M., & Pollatos, O. (2015). Interaction of physical activity and interoception in children. *Frontiers in Psychology*, *6*(APR), 1–8. https://doi.org/10.3389/fpsyg.2015.00502

Grassi, G., Quarti-Trevano, F., Seravalle, G., Arenare, F., Volpe, M., Furiani, S., Delloro, R., & Mancia, G. (2011). Early sympathetic activation in the initial clinical stages of chronic renal failure. *Hypertension*, *57*(4), 846–851. https://doi.org/10.1161/HYPERTENSIONAHA.110.164780

Grossman, P. (2010). Mindfulness for Psychologists: Paying Kind Attention to the Perceptible. *Mindfulness*, *1*(2), 87–97. https://doi.org/10.1007/s12671-010-0012-7

Helin, P., Sihvonen, T., & Hanninen, O. (1987). Timing of the triggering action of shooting in relation to the cardiac cycle. *British Journal of Sports Medicine*, *21*(1), 33–36.

Herbert, B. M., Ulbrich, P., & Schandry, R. (2007). Interoceptive sensitivity and physical effort: Implications for the self-control of physical load in everyday life. *Psychophysiology*, *44*(2), 194–202. https://doi.org/10.1111/j.1469-8986.2007.00493.x

Herrero, J. L., Khuvis, S., Yeagle, E., Cerf, M., & Mehta, A. D. (2018). Breathing above the brain stem: Volitional control and attentional modulation in humans. *Journal of Neurophysiology*, *119*(1), 145–159. https://doi.org/10.1152/jn.00551.2017

Keast, D., & Elliott, B. (1990). Fine body movements and the cardiac cycle in archery. *Journal of Sports Sciences*, *8*(3), 203–213.

Khalsa, S. S., Adolphs, R., Cameron, O. G., Critchley, H. D., Davenport, P. W., Feinstein, J. S., Feusner, J. D., Garfinkel, S. N., Lane, R. D., Mehling, W. E., Meuret, A. E., Nemeroff, C. B., Oppenheimer, S., Petzschner, F. H., Pollatos, O., Rhudy, J. L., Schramm, L. P., Simmons, W. K., Stein, M. B., … Zucker, N. (2018). Interoception and Mental Health: A Roadmap. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *3*(6), 501–513. https://doi.org/10.1016/j.bpsc.2017.12.004

Kirschner, H., Kuyken, W., Wright, K., Roberts, H., Brejcha, C., & Karl, A. (2019). Soothing Your Heart and Feeling Connected: A New Experimental Paradigm to Study the Benefits of Self-Compassion. *Clinical Psychological Science*, *7*(3), 545–565. https://doi.org/10.1177/2167702618812438

Machado, D. G. da S., Farias Junior, L. F. de, Nascimento, P. H. D. do, Tavares, M. P. M., Anselmo da Silva, S. K., Agrícola, P. M. D., Nascimento Neto, L. I. do, Fonteles, A. I., Elsangedy, H. M., Li, L. M., & Okano, A. H. (2019). Can interoceptive accuracy influence maximal performance, physiological and perceptual responses to exercise? *Physiology and Behavior*, *204*, 234–240. https://doi.org/10.1016/j.physbeh.2019.02.038

McKay, L. C., Evans, K. C., Frackowiak, R. S. J., & Corfield, D. R. (2003). Neural correlates of voluntary breathing in humans. *Journal of Applied Physiology*, *95*(3), 1170–1178. https://doi.org/10.1152/japplphysiol.00641.2002

Nardi, A. E., Freire, R. C., & Zin, W. A. (2009). Panic disorder and control of breathing. *Respiratory Physiology and Neurobiology*, *167*(1), 133–143. https://doi.org/10.1016/j.resp.2008.07.011

Park, J., Marvar, P. J., Liao, P., Kankam, M. L., Norrholm, S. D., Downey, R. M., McCullough, S. A., Le, N. A., & Rothbaum, B. O. (2017). Baroreflex dysfunction and augmented sympathetic nerve responses during mental stress in veterans with post-traumatic stress disorder. *Journal of Physiology*, *595*(14), 4893–4908. https://doi.org/10.1113/JP274269

Petersen, S. E., & Posner, M. I. (2012). The Attention System of the Human Brain: 20 Years After Steven. *Annual Review of Neuroscience*, *21*(35), 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525.The

Piscopo, D. M., Weible, A. P., Rothbart, M. K., Posner, M. I., & Niell, C. M. (2018). Changes in white matter in mice resulting from low-frequency brain stimulation. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(27), E6339–E6346. https://doi.org/10.1073/pnas.1802160115

Price, C. J., & Hooven, C. (2018). Interoceptive awareness skills for emotion regulation: Theory and approach of mindful awareness in body-oriented therapy (MABT). *Frontiers in Psychology*, *9*(MAY), 1–12. https://doi.org/10.3389/fpsyg.2018.00798

Price, C. J., Thompson, E. A., Crowell, S., & Pike, K. (2019). Longitudinal effects of interoceptive awareness training through mindful awareness in body-oriented therapy (MABT) as an adjunct to women's substance use disorder treatment: A randomized controlled trial. *Drug and Alcohol Dependence*, *198*(February), 140–149. https://doi.org/10.1016/j.drugalcdep.2019.02.012

Price, C. J., Wells, E. A., Donovan, D. M., & Rue, T. (2012). Mindful awareness in body-oriented therapy as an adjunct to women's substance use disorder treatment: A pilot feasibility study. *Journal of Substance Abuse Treatment*, *43*(1), 94–107. https://doi.org/10.1016/j.jsat.2011.09.016

Quigley, K. S., Kanoski, S., Grill, W. M., Barrett, L. F., & Tsakiris, M. (2021). Functions of Interoception: From Energy Regulation to Experience of the Self. *Trends in Neurosciences*, *44*(1), 29–38. https://doi.org/10.1016/j.tins.2020.09.008

Seals, D. R., Suwarno, N. O., & Dempsey, J. A. (1990). Influence of lung volume on sympathetic nerve discharge in normal humans. *Circulation Research*, *67*(1), 130–141. https://doi.org/10.1161/01.RES.67.1.130

Sharma, M., Frishman, W. H., & Gandhi, K. (2011). RESPeRATE: Nonpharmacological treatment of hypertension. *Cardiology in Review*, *19*(2), 47–51. https://doi.org/10.1097/CRD.0b013e3181fc1ae6

Tang, Y. Y., Tang, R., Rothbart, M. K., & Posner, M. I. (2019). Frontal theta activity and white matter plasticity following mindfulness meditation. *Current Opinion in Psychology*, *28*, 294–297. https://doi.org/10.1016/j.copsyc.2019.04.004

Tsakiris, M., & De Preester, H. (2018). *The interoceptive mind: from homeostasis to awareness*. Oxford University Press.

Weng, H. Y., Feldman, J. L., Leggio, L., Napadow, V., Park, J., & Price, C. J. (2021). Interventions and Manipulations of Interoception. *Trends in Neurosciences*, *44*(1), 52–62. https://doi.org/10.1016/j.tins.2020.09.010

Weng, H. Y., Fox, A. S., Shackman, A. J., Stodola, D. E., Caldwell, J. Z. K., Olson, M. C., Rogers, G. M., & Davidson, R. J. (2013). Compassion Training Alters Altruism and Neural Responses to Suffering. *Psychological Science*, *24*(7), 1171–1180. https://doi.org/10.1177/0956797612469537

Zarza, J. A., Sanabria, D., & Perakakis, P. (2019). Can increased interoception explain exercise-induced benefits on brain function and cognitive performance? *Experimental Psychology*, 1–16.