

Meditation and Brain Plasticity

Ruwan M Jayatunge

The human mind is a complex phenomenon built on the physical scaffolding of the brain. (Nunez, 2010; Bassett & Gazzaniga, 2011). The human brain is not a static organ. It has ability to change and adapt as a result of experience. Experience alters the brain (Kolb, Gibb, & Robinson, 2003). This phenomena is known as Brain plasticity or neural plasticity or cortical remapping.

Neuroplasticity can be defined as the ability of the nervous system to respond to intrinsic or extrinsic stimuli by reorganizing its structure, function and connections (Cramer et al., 2011). Siegel (2010) describes Neuroplasticity as the capacity for creating new neural connections and growing neurons in response to experience.

Plasticity is an innate property of the human brain and represents evolution's invention to enable the nervous system to escape the restrictions of its own genome and thus adapting to environmental pressures, physiologic changes, and experiences (Pascual-Leone et al., 2005). The entire central nervous system (CNS) is highly plastic and it changes continually throughout life.

The human brain can create new neural pathways and create novel memories. Neuronal connections and cortical maps are continuously remodeled by experience (Johansson, 2000). The brain has the capacity to undergo activity-dependent functional and morphological remodeling via mechanisms of plasticity (Bruel-Jungerman, Davis & Laroche, 2007). There are two major types of neural plasticity: functional plasticity and structural plasticity. The human brain has the capacity for both.

Brian Plasticity: Historical Background

Italian psychiatrist Ernesto Lugaro can be regarded as responsible for introducing the term plasticity into neurosciences as early as 1906 (Berlucchi, 2002). However before this time the American philosopher and psychologist William James hypothesized that brain plasticity existed. William James in *The Principles of Psychology* (1890) stated that nervous tissue endowed with an extraordinary degree of plasticity.

The Italian psychiatrist Eugenio Tanzi (1856–1934) hypothesized formation of new connections between cortical neurons. Tanzi postulated that practice and experience promote neuronal growth and shorten the minute spatial gaps between functionally associated neurons, thus facilitating their interactions (Berlucchi, 2002).

In his book, “*The Organization of Behavior*” the Canadian neuro-psychologist Donald O. Hebb (1904 – 1985) introduced the concepts of synaptic plasticity and cell assemblies to provide a

theory of the neurophysiological basis of behaviour (Brown, 2006). The synaptic plasticity theory of learning was rehabilitated in the late 1940s when Konorski and particularly Hebb argued successfully that there was no better alternative way to think about the mercurial nature of the brain by experience and practice (Berlucchi & Buchtel, 2009).

The Australian neurophysiologist Sir John Eccles (1903-1997) focused on plasticity at central synapses in the hippocampus, cerebellum, and neocortex. His endeavors extended from the plasticity associated with CNS lesions to the mechanisms responsible for the most complex and as yet mysterious products of neuronal plasticity, the substrates underlying learning and memory (Wolpaw & Carp, 2006).

Meditation and Neuroplasticity

Meditation is a conscious mental process. Meditation in a clinical capacity can be defined as a form of mental training that aims to improve an individual's core psychological capacities, such as attentional and emotional self-regulation (Tang, Holzel, & Posner, 2015). Meditation comprises a series of practices mainly developed in eastern cultures aimed at accepting emotions and enhancing attentional processes (Sperduti, Martinelli & Piolino, 2012). Furthermore meditation is a complex neurocognitive task that is often associated with alterations in body physiology and psychological measures (Newberg et al., 2010).

Meditation has lately received considerable interest from cognitive neuroscience (Braboszcz et al., 2013). Studies suggest that daily meditation leads to long lasting attentional and neuronal plasticity. (Braboszcz et al., 2013). Research has also shown that short courses can provide some degree of neuronal improvement as well. Various brain regions have been reported to be anatomically different between meditators and controls (Luders et al., 2012). According to Venkatesh and colleagues (1997) long term practice of meditation appears to produce structural as well as intensity changes in phenomenological experiences of consciousness.

Changes in Cerebral Blood Flow

Functional magnetic resonance imaging has detected changes in cerebral blood flow during meditation. Wang and team (2011) found that the frontal regions, anterior cingulate, limbic system and parietal lobes were affected during meditation and that there were different patterns of cerebral blood flow between the two meditation states ie- "focused-based" practice and a "breath-based" practice. Meditation increases regional cerebral blood flow (rCBF) in the prefrontal cortex (Deepeshwar et al., 2015). As reported by Newberg et al., (2010) cerebral blood flow of long-term meditators was significantly higher compared to non-meditators in the prefrontal cortex, parietal cortex, thalamus, putamen, caudate, and midbrain.

Mindfulness Meditation

Mindfulness meditation is a set of attention-based, regulatory, and self-inquiry training regimes (Allen et al., 2012). It is also referred to as "insight meditation" or "Vipassana practice," is playing an increasingly large role in defining how meditation can contribute to therapeutic growth and personal development (Lehrer, Woolfolk & Sime, 2007). According to Kabat-Zinn (1994) Mindfulness is paying attention in a particular way: on purpose, in the present moment, and nonjudgementally. In the last few decades, mindfulness meditation has gained prominence as an adjunctive psychotherapeutic technique (Wolkin, 2015).

Mindfulness has been shown to lead to significant changes in the brain (Widdett, 2014). As indicated by Hölzel et al., (2010) mindfulness practice is associated with changes in gray matter concentration in brain regions involved in learning and memory processes, emotion regulation, self-referential processing, and perspective taking.

Loving-kindness Meditation

Loving-kindness meditation has been used for centuries in the Buddhist tradition to develop love and transform anger into compassion (Carson et al., 2005). Loving-kindness meditation is a practice designed to enhance feelings of kindness and compassion for self and others (Kearney et al., 2013). These Kindness-based contemplative practices enhance prosocial emotions, social cognitive skills, and wellbeing. According to Leung et al., (2013) experience in LKM may influence brain structures associated with affective regulation and they further found increased gray matter volume in the right angular and posterior parahippocampal gyri in loving-kindness meditators.

Empathy and Brain Changes

Empathy is about both sharing and understanding the emotional state of others in relation to oneself. It is an affective dimension that involves a shared affective experience and also a cognitive dimension that includes the ability to understand or have some degree of conscious awareness that the affective experience is evoked by another (Mascaro et al., 2015).

Functional Magnetic Resonance Imaging (fMRI) indicates that when a person emphasizes brain regions such as insula, medial/anterior cingulate cortex become active (Lamm, Meltzoff & Decety, 2010). Klimecki and colleagues (2013) observed that, compared with a memory control group, compassion training elicited activity in a neural network including the medial

orbitofrontal cortex, putamen, pallidum, and ventral tegmental area—brain regions previously associated with positive affect and affiliation.

Vedananupassana Meditation

Mindfulness of sensation or contemplation of sensation is known as Vedananupassana or Body scan meditation. Vedananupassana meditation consists of minutely observing feelings such as aversion and desire as well as pleasant and unpleasant ones. It is a form of Vipassana meditation that is geared to enhance mind/body awareness (interoceptive awareness). According to Mirams , Poliakoff , Brown and Lloyd (2013) brief body-scan meditation practice improves somatosensory perceptual decision making. Fox and colleagues (2012) reported that long-term meditators provide more accurate introspective reports than novices.

Mediation Induced Morphological Changes of the Brain

The human brain is composed of approximately 100 billion neurons. The brain has many specialized cells, harboring sets of both common, widely distributed, as well as specialized and discretely localized proteins (Sjöstedt et al., 2015). Experience produces multiple, dissociable changes in the brain including increases in dendritic length, increases (or decreases) in spine density, synapse formation, increased glial activity, and altered metabolic activity (Kolb & Whishaw ,1998). Psychopathology can cause detrimental changes in the brain. For instance in PTSD brain areas such as medial prefrontal cortex, hippocampus, and amygdala undergo changes. Brain imaging studies show that PTSD patients have increased amygdala reactivity during fear acquisition (Bremner et al., 2008).

Healthy brain structural changes have been reported following meditation practice. Meditation is associated with neuroplastic changes. Magnetic resonance imaging (MRI) and positron emission tomography (PET) reports of meditators indicate such changes. Kang and team (2013) indicate that meditators, compared with controls, showed significantly greater cortical thickness in the anterior regions of the brain, located in frontal and temporal areas, including the medial prefrontal cortex, superior frontal cortex, temporal pole and the middle and interior temporal cortices.

Human Cerebral Cortex

The human cerebral cortex is a highly folded sheet of neurons the thickness of which varies between 1 and 4.5 mm, with an overall average of approximately 2.5 mm (1–3).The thickness of the cortex is of great interest in both normal development as well as a wide variety of

neurodegenerative and psychiatric disorders. Accurate and automated methods for measuring the thickness of human cerebral cortex could provide powerful tools for diagnosing and studying a variety of neurodegenerative and psychiatric disorders (Fischl & Dale, 2000).

The Anterior Cingulate Cortex (ACC)

The anterior cingulate cortex (ACC) also known as Area 25, is a region that is located towards the front of the corpus callosum, in the medial frontal lobe. It is a part of the brain's limbic system. The ACC is important in decision making and emotional regulation. In addition the ACC plays an important role in attentional control (Crottaz-Herbette & Menon, 2006). The anterior cingulate cortex has an important role in focused problem-solving, error recognition, and adaptive response to changing conditions (Allman et al., 2001). Meditation increases the ACC activity (Tang et al., 2010) and white matter change (Tang et al., 2012), and improves self-regulation.

Neocortex

The neocortex is the most developed of the cerebral tissues (Dorland, 2012) and serves as the center of higher mental functions for humans. The neocortex contains 100 billion cells and enables the most complex mental activities. Evolution of the neocortex in mammals is considered to be a key evolution that enabled higher cognitive function (Lui, Hansen & Kriegstein, 2011). The neocortex is a particularly relevant region for plasticity because it performs sensory, motor, and cognitive tasks with strong learning components (Feldman, 2009).

Brain Stem

The brainstem is the region of the brain that connects the cerebrum with the spinal cord. It consists of the midbrain, medulla oblongata, and the pons. The brainstem has integrative functions especially in awareness, and consciousness. Using magnetic resonance imaging Vestergaard-Poulsen and team (2009) observed higher gray matter density in lower brain stem regions of experienced meditators compared with age-matched non-meditators.

Insula

The human insula is hidden in the depth of the cerebral hemisphere by the overlying frontal and temporal opercula, and consists of three cytoarchitecturally distinct regions: the anterior agranular area, posterior granular area, and the transitional dysgranular zone; each

has distinct histochemical staining patterns and specific connectivity (Cauda et al., 2011). The insula is responsible for human ability to empathize with others. According to Tang and colleagues (2015) short-term meditation increases blood flow in anterior cingulate cortex and insula.

Corpus Callosum

The corpus callosum is involved in communication between brain hemispheres and facilitates interhemispheric communication. The corpus callosum is the largest white matter structure in the human brain, connecting cortical regions of both hemispheres (Van der Knaap & Van der Ham ,2011). As indicated by Kurth et al., (2015) an increased fractional anisotropy and greater thickness in the anterior parts of the corpus callosum in meditation practitioners compared with control subjects .

Hippocampus

The hippocampus is a small organ located within the brain's medial temporal lobe. The hippocampus plays a crucial role in memory (King et al., 2004) both in memory encoding and retrieval (Naber et al., 2000). The hippocampus atrophies with chronic stress and aging. The human hippocampus shows structural differences between meditators and non-meditators and larger hippocampal dimensions found in meditation practitioners (Luders , Thompson & Kurth 2015). A study done by Desbordes and team (2012) indicated that Mindful-Attention Training may promote neuroplasticity in the hippocampus in healthy subjects who engage in regular meditation practice over the course of 8 weeks.

Amygdala

The amygdala is an almond-shaped group of nuclei at the heart of the telencephalon — it has been associated with a range of cognitive functions, including emotion, learning, memory, attention and perception (Baxter & Murray, 2002). Taren,Creswell and Gianaros (2013) hypothesized that higher levels of dispositional mindfulness would be associated with decreased grey matter volume in the amygdala.

Concluding Thoughts

In the last few decades the neuroimaging research has shown evidence confirming the effects of meditation and its impact upon brain plasticity. Meditation enhances cortical remapping and

brain functions. Neuroimaging studies have shown the increased regional cerebral blood flow during meditation. Further studies have indicated neural pathways and synapse changes among mediators. These results indicate that meditation is not merely an altered state of consciousness or a merely a state of relaxation. Meditation helps to uplift mental health and causes healthy changes in the brain. Therefore meditation is one of the unique modes to improve mental health.

Acknowledgements

- 1) Dr. Joseph Barnby - Researcher at MAPrc (Alfre Hospital) - Melbourne, Australia
- 2) Professor Y.Y. Tang - Institute of Neuroinformatics and Lab for Body and Mind, Dalian University of Technology

References

- Allen, M. , Dietz, M., Blair, K.S, van Beek, M., Rees, G., Vestergaard-Poulsen, P., Lutz A, Roepstorff ,A. (2012). J Neurosci. 31;32(44):15601-10.
- Allman ,J.M., Hakeem, A., Erwin, J.M., Nimchinsky, E, Hof P.(2001).The anterior cingulate cortex. The evolution of an interface between emotion and cognition. Ann N Y Acad Sci. ;935:107-17.
- Bassett, D. S., and Gazzaniga, M. S. (2011). Understanding complexity in the human brain. Trends Cogn. Sci. 15, 200–209.
- Baxter, M.G., Murray, E.A., 2002. The amygdala and reward. Nature Reviews. Neuroscience 3, 563-573.
- Berlucchi, G. (2002). The origin of the term plasticity in the neurosciences: Ernesto Lugaro and chemical synaptic transmission.JHistNeurosci. 11(3):305-9.
- Berlucchi, G, Buchtel HA.(2009).Neuronal plasticity: historical roots and evolution of meaning.Exp Brain Res. ;192(3):307-19.
- Braboszcz, C , Cahn BR , Balakrishnan B , Maturi RK Grandchamp R , Delorme A . (2013).Plasticity of visual attention in Isha yoga meditation practitioners before and after a 3-month retreat.Front Psychol. 12;4:914.
- Bremner, J.D, Elzinga B, Schmahl C, Vermetten E.(2008). Structural and functional plasticity of the human brain in posttraumatic stress disorder.Prog Brain Res. ;167:171-86.

Brown ,R.E. (2006). The life and work of Donald OldingHebb. *ActaNeurol Taiwan.* ;15(2):127-42.

Bruel-Jungerman,E. , Davis, S., Laroche, S.(2007).Brain plasticity mechanisms and memory: a party of four. *Neuroscientist.* ;13(5):492-505.

Carson, J.W. , Keefe FJ, Lynch TR, Carson KM, Goli V, Fras AM, Thorp SR. (2005). Loving-kindness meditation for chronic low back pain: results from a pilot trial.*J Holist Nurs.* ;23(3):287-304.

Cramer, S.C., Sur, M., Dobkin, B.H., O'Brien, C., Sanger, T.D, Trojanowski, J.Q, Rumsey, J.M, Hicks, R., Cameron, J, Chen, D, Chen, W.G., Cohen, L.G., deCharms C, Duffy, C.J., Eden, G.F., Fetz, E.E., Filart, R., Freund, M., Grant, S.J., Haber, S., Kalivas, P.W., Kolb, B., Kramer, A.F., Lynch, M., Mayberg, H.S., McQuillen, P.S., Nitkin, R., Pascual-Leone, A., Reuter-Lorenz, P., Schiff, N., Sharma, A., Shekim, L., Stryker, M., Sullivan, E.V., Vinogradov, S. (2011).Harnessing neuroplasticity for clinical applications.*Brain.* 134(Pt 6):1591-609.

Cauda, F. D'Agata, F., Sacco, K., Duca, S., Geminiani, G, Vercelli, A.(2011).Functional connectivity of the insula in the resting brain. *Neuroimage.* 1;55(1):8-23.

Crottaz-Herbette, S. and Menon, V. (2006) Where and when the anterior cingulate cortex modulates attentional response: Combined fMRI and ERP evidence. *Journal of Cognitive Neuroscience,* 18, 766-780.

Deepeshwar, S. , Vinchurkar, S.A. , Visweswaraiah ,N.K. , Nagendra, H.R. (2015).Hemodynamic responses on prefrontal cortex related to meditation and attentional task.*Front Syst Neurosci.* 17;8:252.

Desbordes, G, Negi, L.T., Pace, T.W., Wallace, B.A., Raison, C.L., Schwartz, E.L. (2012). Effects of mindful-attention and compassion meditation training on amygdala response to emotional stimuli in an ordinary, non-meditative state.*Front Hum Neurosci.* 1;6:292.

Dorland (2012). *Dorland's Illustrated Medical Dictionary* (32nd ed.). Elsevier Saunders. p. 1238.

Doyère, V., Burette, F., Negro, C.R., Laroche, S.(1993).Long-term potentiation of hippocampal afferents and efferents to prefrontal cortex: implications for associative learning. *Neuropsychologia.* ;31(10):1031-53.

Feldman, D.E.(2009).Synaptic mechanisms for plasticity in neocortex. *Annu Rev Neurosci.*;32:33-55.

Fisch,l B., Dale, A.M.(2000).Measuring the thickness of the human cerebral cortex from magnetic resonance images. *ProcNatlAcadSci U S A.* 26;97(20):11050-5.

- Fox, K.C, Zakarauskas, P., Dixon, M., Ellamil, M., Thompson, E., Christoff, K.(2012). Meditation experience predicts introspective accuracy. *PLoS One.* ;7(9):e45370.
- Hölscher, C. (1999).Synaptic plasticity and learning and memory: LTP and beyond. *J Neurosci Res.* 1;58(1):62-75.
- Hölzel, B.K., Carmody, J., Vangel, M., Congleton, C., Yerramsetti, S.M., Gard, T., Lazar, S.W.(2011). Mindfulness practice leads to increases in regional brain gray matter density. *Psychiatry Res.* 30;191(1):36-43.
- Johansson, B.B. (2000).Brain plasticity and stroke rehabilitation. The Willis lecture. *Stroke.* 2000 Jan;31(1):223-30.
- Kabat-Zinn, J., (1994). *Wherever You Go, There You Are: Mindfulness meditation in everyday life*, Hyperion, New York.
- Kang, D.H., Jo, H.J., Jung, W.H., Kim, S.H., Jung, Y.H., Choi, C.H., Lee, U.S., An, S.C., Jang, J.H., Kwon, J.S. (2013). The effect of meditation on brain structure: cortical thickness mapping and diffusion tensor imaging.*Soc Cogn Affect Neurosci.* ;8(1):27-33.
- Kearney, D.J. , Malte, C.A., McManus, C., Martinez, M.E., Felleman, B., Simpson, T.L. (2013). Loving-kindness meditation for posttraumatic stress disorder: a pilot study.*J Trauma Stress.* 26(4):426-34.
- King, J.A., Trinkler, I., Hartley, T., Vargha-Khadem, F., Burgess, N.(2004).The hippocampal role in spatial memory and the familiarity--recollection distinction: a case study. *Neuropsychology.* 2004 Jul;18(3):405-17.
- Klimecki, O.M. , Leiberg, S., Lamm C, Singer, T.(2013).Functional neural plasticity and associated changes in positive affect after compassion training. *Cereb Cortex.* ;23(7):1552-61.
- Kolb, B., Whishaw, I.Q.(1998).Brain plasticity and behavior. *Annu Rev Psychol.* 1998;49:43-64.
- Kolb, B., Gibb, R., & Robinson, T.E. (2003). Brain plasticity and behavior. *Current Directions in Psychological Science*, 14: 1-5.
- Kurth, F. , MacKenzie-Graham, A. , Toga, A.W ., Luders, E.(2015).Shifting brain asymmetry: the link between meditation and structural lateralization.*Soc Cogn Affect Neurosci.* ;10(1):55-61.
- Lamm, C., Meltzoff, A.N., Decety, J.(2010).How do we empathize with someone who is not like us? A functional magnetic resonance imaging study.*J Cogn Neurosci.* ;22(2):362-76.
- Laroche, S. (1994).[Long term potentiation of the synaptic efficacy: mechanisms, functional properties and role in learning and memory].*C R SeancesSocBiolFil.* ;188(5-6):415-58.

Lehrer, R.L. Woolfolk & W.E. Sime. (2007). Principles and Practice of Stress Management. 3rd Edition. New York: Guilford Press.

Leung, M.K., Chan, C.C., Yin, J., Lee, C.F., So, K.F., Lee, T.M. (2013). Increased gray matter volume in the right angular and posterior parahippocampal gyri in loving-kindness meditators. *Soc Cogn Affect Neurosci.* 2013 Jan;8(1):34-9.

Luders, E., Kurth, F., Mayer, E.A., Toga, A.W., Narr, K.L., Gaser, C. (2012). The unique brain anatomy of meditation practitioners: alterations in cortical gyrification. *Front Hum Neurosci.* 29;6:34.

Luders, E., Thompson, P.M., Kurth, F. (2015). Larger hippocampal dimensions in meditation practitioners: differential effects in women and men. *Front Psychol.* 6;6:186.

Lui, J.H., Hansen, D.V., Kriegstein, A.R. (2011). Development and evolution of the human neocortex. *Cell.* 8;146(1):18-36.

Mascaro, J.S., Darcher, A., Negi, L.T., Raison, C.L. (2015). The neural mediators of kindness-based meditation: a theoretical model. *Front Psychol.* 12;6:109.

McEachern, J.C., Shaw, C.A. (1999). The plasticity-pathology continuum: defining a role for the LTP phenomenon. *J Neurosci Res.* 1;58(1):42-61.

Mirams, L., Poliakoff, E., Brown, R.J., Lloyd, D.M. (2013). Brief body-scan meditation practice improves somatosensory perceptual decision making. *Conscious Cogn.* ;22(1):348-59.

Naber, P. A., Witter, M. P., and Lopes Silva, F. H. (2000). Networks of the hippocampal memory system of the rat. The pivotal role of the subiculum. *Ann. N.Y. Acad. Sci.* 911, 392–403.

Newberg, A.B., Wintering, N., Waldman, M.R., Amen, D., Khalsa, D.S., Alavi, A. (2010). Cerebral blood flow differences between long-term meditators and non-meditators. *Conscious Cogn.* ;19(4):899-905.

Nunez, P.L. (2010) *Brain, Mind, and the Structure of Reality*, Oxford University Press.

Pascual-Leone, A., Amedi, A., Fregni, F., Merabet, L.B. (2005). The plastic human brain cortex. *Annu Rev Neurosci.* ;28:377-401.

Sarvey, J.M., Burgard, E.C., Decker, G. (1989). Long-term potentiation: studies in the hippocampal slice. *J Neurosci Methods.* ;28(1-2):109-24.

Siegel, D. (2010). *Mindsight*. New York: Random House Publishing Group

- Sjöstedt, E. , Fagerberg, L. , Hallström, B.M. , Häggmark, A. , Mitsios ,N. , Nilsson, P. , Pontén, F. , Hökfelt ,T. , Uhlén, M. , Mulder, J. (2015). Defining the Human Brain Proteome Using Transcriptomics and Antibody-Based Profiling with a Focus on the Cerebral Cortex. *PLoS One*. 15;10(6):e0130028.
- Sperduti, M., Martinelli, P., Piolino, P.(2012).A neurocognitive model of meditation based on activation likelihood estimation (ALE) meta-analysis.*ConsciousCogn.* ;21(1):269-76.
- Tang, Y.Y. , Lu Q, Geng, X., Stein, E.A., Yang, Y., Posner, M.I.(2010). Short-term meditation induces white matter changes in the anterior cingulate.*Proc Natl Acad Sci U S A*. 31;107(35):15649-52.
- Tang ,Y.Y., Lu, Q., Fan, M., Yang, Y., Posner, M.I.(2012).Mechanisms of white matter changes induced by meditation. *Proc Natl Acad Sci U S A*. 26;109(26):10570-4.
- Tang, Y.Y. , Lu, Q. , Feng, H. , Tang, R. , Posner, M.I.(2015).Short-term meditation increases blood flow in anterior cingulate cortex and insula. *Front Psychol.* 26;6:212.
- Tang, Y., Holzel, B.K., & Posner, M.I. (2015). The neuroscience of mindfulness meditation. *Nature Reviews: Neuroscience*, 16, 213-226.
- Taren, A.A., Creswell, J.D., Gianaros, P.J.(2013).Dispositional mindfulness co-varies with smaller amygdala and caudate volumes in community adults. *PLoS One*. 22;8(5):e64574
- Teyler, T.J., Fountain, S.B.(1987).Neuronal plasticity in the mammalian brain: relevance to behavioral learning and memory.*Child Dev.* ;58(3):698-712.
- van der Knaap, L.J, van der Ham, I.J.(2011).How does the corpus callosum mediate interhemispheric transfer? A review. *Behav Brain Res.* 30;223(1):211-21.
- Venkatesh, S., Raju, T.R., Shivani, Y., Tompkins, G., Meti, B.L.(1997).A study of structure of phenomenology of consciousness in meditative and non-meditative states.*Indian J PhysiolPharmacol.* ;41(2):149-53.
- Vestergaard-Poulsen P, van Beek M, Skewes J, Bjarkam CR, Stubberup M, Bertelsen J, Roepstorff A. (2009).Long-term meditation is associated with increased gray matter density in the brain stem. *Neuroreport.* 28;20(2):170-4.
- Wang, D.J., Rao, H., Korczykowski ,M., Wintering, N., Pluta, J., Khalsa, D.S., Newberg, A.B. (2011).Cerebral blood flow changes associated with different meditation practices and perceived depth of meditation.*Psychiatry Res.* 30;191(1):60-7.
- Widdett, R. (2014). "Neuroplasticity and Mindfulness Meditation" (2014). Honors Theses. Paper 2469.

Wolkin, J.R.(2015).Cultivating multiple aspects of attention through mindfulness meditation accounts for psychological well-being through decreased rumination.Psychol Res Behav Manag. 2015 Jun 29;8:171-80.

Wolpaw, J.R., Carp, J.S.(2006).ProgNeurobiol. 2006 Feb-Apr;78(3-5):233-63.