



OF MICE AND MEN

The impact of whisker vibrations on cognitive performance in whole-body vibration studies

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Photo credit: UC Berkley News at <https://news.berkeley.edu/2017/06/27/a-mouses-view-of-the-world-seen-through-its-whiskers/>

Abstract

Whole body vibration (WBV) is a modality which has been considered as an alternative form of physical activity in absence of traditional physical exercise. Additionally, improved cognitive performance in both murid and human experiments have been observed, hence resulting in WBV being explored as a therapeutic treatment for neurocognitive and -degenerative disorders. However, mechanisms of action of the procedure on the central nervous system are largely unknown. Studies attempting to elucidate the biological underpinnings have been performed in rodent and human models, however the results generated in fMRI show distinct activation of brain regions, with little overlap. This could be the result of species-specific impact of sensory organs in perception of movement and space, such as the rodent whiskers. Literature reports a distinct sensory pathway activated by stimulation of the whiskers – the lemniscal pathway – which results in transmission of sensory information from the mystacial pad to the ventro-posterior medial nucleus, posterior thalamic nucleus, CA1 hippocampal subfield and a specialized area of the primary somatosensory cortex. Evidence suggests that perpetual stimulation of the lemniscal pathway due to whisker vibrations during WBV could account for increased cognitive performance due to remodelling of neural pathways and increased activity of cholinergic neurons, such as the one reported in the hippocampus. While the rodent lemniscal pathway bears some similarity to the human posterior column medial lemniscal pathway, the species specific-differences in the pathway (such as the presence of the barrel cortex and thalamic barreloids) could account for the differences observed in fMRI studies. Hence, caution is recommended when applying results generated from rodent WBV studies to humans, particularly when discussing system-wide changes observed after sessions.

Introduction

Whole-body vibration (WBV) is a term commonly used to describe the phenomenon of mechanic oscillations being transferred to a human body, through exposure to a vibrating surface. High-frequency WBV (most commonly generated by power tools, such as jackhammers) have been traditionally relegated to the status of occupational hazard as it carries an increased risk in development of musculoskeletal pathologies, cardiovascular and gastrointestinal disorders (Krajnak, 2018). Recently, applications of low-frequency WBV (up to 50 Hz) has been proposed as a novel non-invasive therapeutic methodology in physical recovery, as well as an exercise modality, in disabled patients (Gusso et al., 2016; Wollersheim et al., 2017). Studies in human patients have shown that deliberate exposure to short-interval low-frequency WBV provides benefit in a range of impairments, including recovery of muscle strength, arthritis, back pain, knee pain and diabetes among others (Baum et al., 2007; Kaeding et al., 2017; Rees et al., 2008; Rustler et al., 2019; Wang et al., 2015).

Low-frequency WBV has also been explored in the context of improving cognitive performance of patients suffering from neurocognitive disorders. While studies are sparse, there is some evidence that performance increased in The Stroop Color and Word Test amongst patients with unilateral brain lesions, dementia, stroke, ADHD and Down's Syndrome (Ferreira, 2020; Herren et al., 2018; Kim & Lee, 2018; A. Lee et al., 2020; Regterschot et al., 2014). Increased performance in cognitive tasks has also been reported in healthy adults across all age groups, however the persistence of the effect after cessation is yet to be explored (Boerema et al., 2018; de Bruin et al., 2020; Regterschot et al., 2014; Sanders et al., 2019).

Similar WBV trials have been performed in animal models, such as rats and mice, in order to understand the biological underpinnings of the improved cognitive performance. As with the human studies, rodent experiments have shown increased performance in novel-object recognition tasks,

lessened anxiety-like behaviours, as well as improvement in motor skills (Boerema et al., 2018; Cariati et al., 2021; Keijser et al., 2017; Peng et al., 2021). Curiously, fMRI has shown a very discrete change in the energy demands of the rodent brain, which contrasts the increased demands observed in human studies (Boerema, 2018; Li et al., 2012; see review on the topic Sanders et al., 2019). The discrepancy between fMRI images generated in human and mice studies is puzzling. While only a single study exists on the topic, it has reported increased glucose uptake exclusively in the murid nucleus basalis (Sanders et al., 2019). By contrast, human fMRI imaging post low-frequency WBV has shown increased activity in the caudate nucleus, sensory-motor, premotor and prefrontal cortex, similar to studies investigating the impact of physical exercise on the central nervous system (Fig. 1) (Choi et al., 2019; Kaut et al., 2016; A. Lee et al., 2020; Rajab et al., 2014).

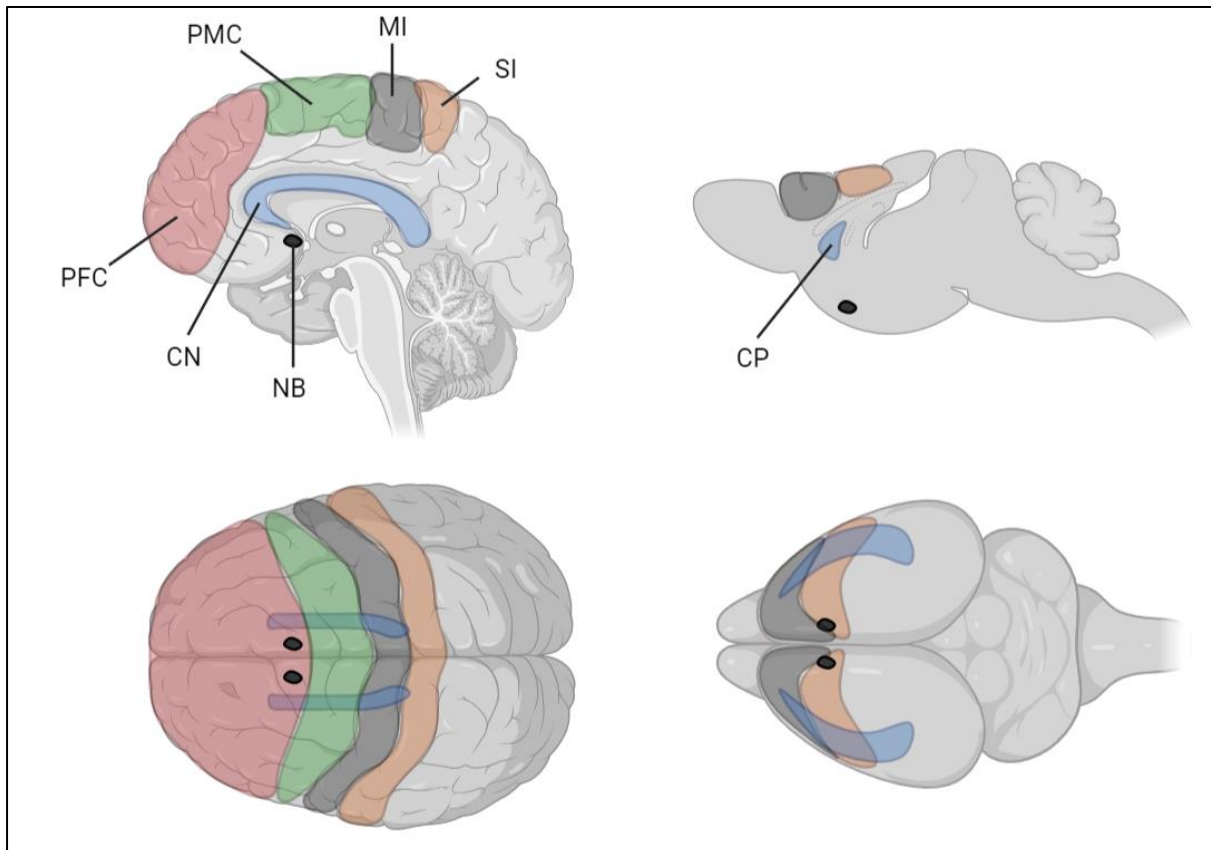


Figure 1: Brain structures activated post-WBV experiments in humans (left panel) and rodents (right panel). Human fMRI trials show activation of PFC, PMC, MI, SI and CN, while rodent studies show sole activation of NB. Image created using data from Li, et al, 2012, Choi et al., 2019, Kaut et al., 2016, Lee et al., 2020; Rajab et al., 2014 and Boerema, 2018. Brain regions were colour-coded according to the Allen Institute Human and Mouse Brain Atlases (Hawrylycz et al., 2012). *PFC: prefrontal cortex; PMC: premotor cortex; MI: primary motor cortex; SI: primary somatosensory cortex; CN: caudate nucleus; CP: caudoputamen.*

While this difference could be a result of humans and rodents inhabiting different ecological niches, and reacting species-appropriate to low-frequency WBV, this highlights a pervasive issue of non-applicability of data generated from rodents in humans. In order to fully comprehend why the response of rodents and humans to low-frequency WBV is distinct, we need to understand the impact of distinct sensory organs in the species.

Humans rely primary on visual cues to discriminate their environment, a modality which is tested during the Stroop Colour and Word test in low-frequency WBV trials, as well as other cognitive

studies (Cho et al., 2016; Hutmacher, 2019; Scarpina & Tagini, 2017). By comparison, when similar cognitive tests are performed on rodents, they are subjected to novel-object perception tests, which are largely reliant on animals distinguishing between items using facial whiskers (Antunes & Biala, 2012; Mathiasen & Dicamillo, 2010). In order to understand what are the neurological underpinnings behind improved cognition in humans and rodents, we need to understand the impact of whiskers in sensory information processing.

Neural networks in whisker sensory processing

Whiskers, or *vibrissae*, are prominent sinus hair found across nearly all mammalian species that act as sensory organs (Ahl, 1986). In rodents, such as rats, they form a grid-wise layout on both sides of the snout, and are distinct from ordinary hair due to innervation of the enlarged hair follicle. The presence of dense nerve terminals and sensory receptors enable the whisker to act as a mechanical transducer (Brecht et al., 1997). The mystacial *vibrissae* are further specialized into *macrovibrassae* and *microvibrassae*. *Macrovibrassae* are thought to be capable of transmitting spatial information via “whisking” (sweeping of whiskers at high frequencies) and *microvibrassae* considered to be involved in object recognition, although there is evidence of some functional redundancy (Adibi et al., 2012; Adibi & Arabzadeh, 2011; Brecht et al., 1997; Von Heimendahl et al., 2007; Y. S. W. Yu et al., 2016a).

The innervated hair follicle is a host to a large range of mechanoreceptors sensitive to a variety of tactile stimulus parameters, such as amplitude, frequency, duration, velocity, acceleration and direction of the whisker (Gibson & Welker, 1983; Lichtenstein et al., 1990; Pubols et al., 1973; Zucker & Welker, 1969). The signal produced by the mechanoreceptors is transduced to the central nervous system via a modality-specialized highly sensitive trigeminal ganglion unit (Gibson & Welker, 1983; Lichtenstein et al., 1990; Pubols et al., 1973; Zucker & Welker, 1969). Curiously, a great majority of the ganglion cells are capable of adapting to stimulus, although the rate of adaptation differs (Gibson & Welker, 1983; Pubols et al., 1973).

The sensory information generated in the mystacial pad is transduced towards the barrel cortex via the brainstem, a discrete rodent-specific component of the somatosensory cortex (*Fig. 2*) (Durham & Woolsey, 1984; Woolsey & Van der Loos, 1970). The barrels are somatotopically arranged in a reflection of the mystacial pad, with the most dorsal posterior whiskers being represented by the most lateral posterior barrels (Woolsey & Van der Loos, 1970).

A secondary recipient of the signal transduced by the second-order trigeminal ganglions via the brainstem lies within the ventro-posterior medial nucleus (VPM) and posterior thalamic nucleus (POm) (Diamond et al., 1992; Veinante et al., 2000; Williams et al., 1994). Similarly, to the barrels of the somatosensory cortex, in the VPM the vibrissae are represented by oblong finger-like barreloids (Van Der Loos, 1976). POm does not have barreloid-like structures, however evidence shows they are organized topographically, similarly to the barrel cortex (Alloway et al., 2003; Diamond et al., 1992). Moreover, POm neurons have been shown to aggregate signal from multiple (6-9) whiskers, with a weaker response generated to movement of singular whiskers (Diamond et al., 1992).

The thalamic barreloids and cortical barrels form a dense neural network. In particular, VPM barreloids have shown a one-to-one connection to the cortical barrels, with no multi-barrel connections ever recorded in literature (Chmielowska et al., 1989; Lu & Lin, 1993). However, some innervation to the surrounding barrel tissue has been observed, such as the thalamic reticular nucleus and the ventral part of layer VI of the primary somatosensory cortex (Chmielowska et al., 1989; Jensen & Killackey, 1997; Lu & Lin, 1993). The ventral-lateral VPM neurons do not project to the barrels, instead receiving presynaptic inputs from the spinal nucleus and branch towards the

primary and secondary somatosensory cortices, forming the lemniscal pathway (Fig 2) (Pierret et al., 2000; C. Yu et al., 2006). Evidence suggests that the lemniscal pathway is involved in processing information related to touch (C. Yu et al., 2006). Additionally, the thalamic barreloids have been shown to be capable of receiving direct input from the principal trigeminal nucleus and cortico-basal ganglia-thalamo-cortical feedback from the whisker primary motor cortex due to the multi-receptive fields on the ventral parts of the structure (Furuta et al., 2009; Urbain & Deschênes, 2007).

POm neurons have not been recorded to be capable of forming direct networks with the cortical barrels or thalamic barreloids. Instead, POm neurons have been shown to project towards almost all areas of the sensory-motor cortex, with the terminal fields of the projects localized primarily in layer I and Va, thus forming the paralemniscal pathway (Fig 2) (Lu & Lin, 1993; Urbain & Deschênes, 2007).

Finally, the thalamic reticular nucleus (TRN) forms an inhibitory feedback loop in whisker-related neural pathways. Neurons of the TRN receive input from vibrissae-related input from layer VI of the primary somatosensory cortex via the infrabarrels, as well as axon collaterals from VPM and POm (Bourassa et al., 1995; Crandall et al., 2017; Harris, 1987). This feedback loop enables inhibition of VPM and POm via GABAergic projections, albeit the inhibition of the former occurs indirectly (Fig 2) (Bourassa et al., 1995; Desîlets-Roy et al., 2002; Lam & Sherman, 2007; Lavallée et al., 2005). Moreover, evidence suggests that attenuation of the inhibitory signal produced by the TRN upon VPM has been casually linked to latency and accuracy of responses in visual detection and discrimination tasks (Chen et al., 2016; Halassa et al., 2014; Wimmer et al., 2015).

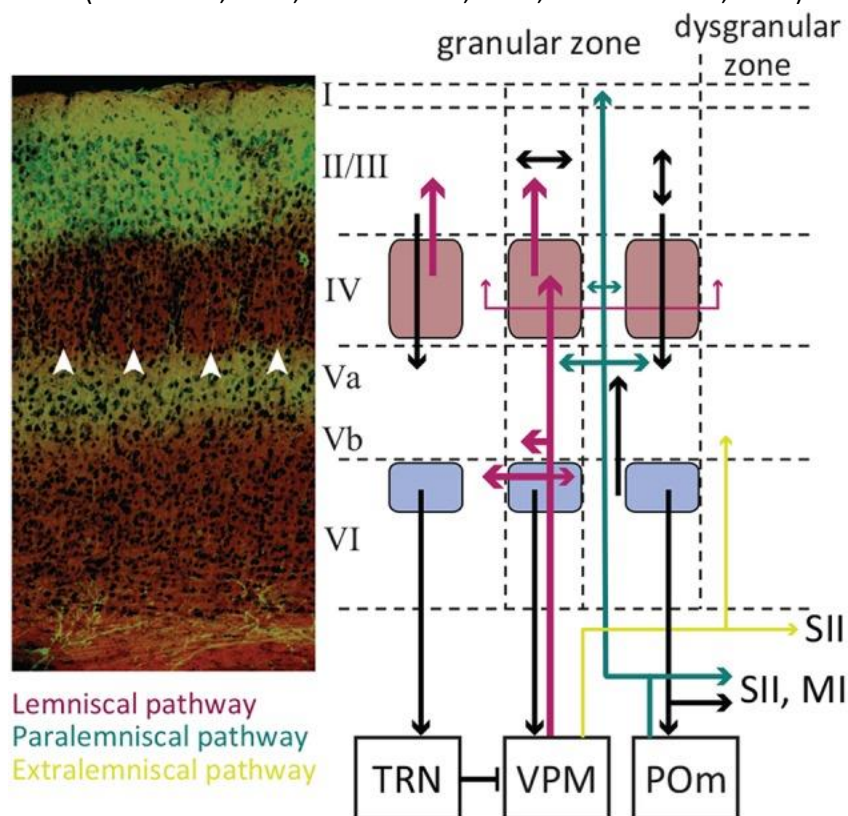


Figure 2: Pathways involved in the transduction of signal from whisker to the central nervous system. Left panel - coronal section of the cortical arrangement of the somatosensory cortex stained with Nissl. The white arrowheads indicate individual cortical barrels in layer IV. Right panel – the three excitatory pathways (in coloured arrows) involved in the transduction of signal from whiskers to the barrel cortex (pink boxes) and infrabarrels (blue boxes). Black arrows correspond to excitatory outputs. Image adopted from (Adibi, 2019). *SII*: secondary somatosensory cortex; *M1*: primary motor

cortex; TRN: thalamic reticular nucleus; VPM: ventro-posterior medial nucleus; POM: posterior thalamic nucleus.

The involvement of whiskers in hippocampal information processing

An often overlooked component of sensory processing and other cognitive functions within rodents is the hippocampus. Evidence from murine studies suggest that the hippocampus is involved in a multitude of processes outside of memory, such as working memory, processing speed, formation of spatial maps and a multitude of executive functions (Burghardt et al., 2012; Deacon et al., 2002; Kahn et al., 2012; Tzakis & Holahan, 2019; Zemla & Basu, 2017). By contrast, in humans, the prefrontal cortex is primarily responsible for cognitive performances, including executive functions such as thinking, reasoning, planning and decision-making (Cole et al., 2012; Funahashi, 2017; Yuan & Raz, 2014).

This discrepancy could also be, in part, attributed to the presence of whiskers, as the hippocampus has been shown to be involved in processing sensory information relayed from the primary trigeminal ganglion in the mystacial pad. Evidence suggests this is achieved via a match-mismatch system involving the CA1 and CA3 hippocampal subfields, as sensory inputs received in the CA1 are compared against stored spatiotemporal sequences in the CA3 (I. Lee et al., 2004). This is further supported by reported signal relays through VPM and the somatosensory cortex – both major components of the lemniscal pathway – to the CA1 hippocampal subfield (Grion et al., 2016; Pereira et al., 2007). The presence of this pathway suggests tactile processing may be located downstream of the lemniscal pathway. Moreover, bilateral trimming of whiskers in juvenile rodents resulted in decreased CA3 hippocampal subfield activity and subsequent reconfiguration of the CA1-CA3 system and showed significant change in performance in spatial-memory related tasks (Gonzalez-Perez et al., 2018; Milshtein-Parush et al., 2017). This suggests that sensory experiences may regulate computational processes performed by the hippocampus as well as its synaptic plasticity, which could impact behaviour.

Neural pathways in the context of whisker vibrations during WBV

During WBV trials, a rodent will experience vertical or lateral movements at a constant frequency and amplitude. This, in turn, will result in environmentally-induced whisker movement, due to changing direction of airflow, however it is impossible to say whether that will occur at whisker resonance frequency. Evidence suggests that the whisker movement due to airflow will result in a response in the trigeminal primary afferent neurons, with properties like velocity and direction positively correlating to the frequency of spike production (Bush et al., 2019; Leiser & Moxon, 2007; Y. S. W. Yu et al., 2016b). Curiously, each trigeminal afferent neuron coupled to a specific whisker would display a unique pattern in the firing rate, with little overlap. Additional evidence suggests firing rate is also modulated by both arclength and direction of the whisker (Bush et al., 2019). Moreover, the activity of trigeminal afferent neuron displays ramp-and-hold pattern during sustained unidirectional airflow stimulus, with immediate cessation of activity upon removal of stimulus (Y. S. W. Yu et al., 2016b). There is a very discrete attenuation of activity, however as the stimulus was applied for brief periods of time (15 seconds), it is unknown whether the whiskers are capable of adapting and fully filtering the signal. While the impact of changing direction of stimulus is currently not known, evidence has shown that discrimination of stimulus direction is performed by the lemniscal pathway (El-Boustani et al., 2020; Frangeul et al., 2014; Nakamura et al., 2009). As low-frequency WBV involves continuous movement of the mystacial whiskers, with no tactile component involved, we can assume that the primary pathway involved in the transduction of signal is done through the lemniscal pathway. Furthermore, while studies are sparse, low frequency WBV has shown to increase synaptic plasticity in the CA1 hippocampal subfield both young and old mice,

which could be the result of increased sensory information processing due to increased whisker movement (Cariati et al., 2021).

Further evidence on the involvement of the lemniscal pathway as a primary transducer of WBV-induced whisker vibration lies in the activity of cholinergic neurons in the barrel cortex. Data suggests that acetylcholine released by cholinergic neurons during whisking has shown to increase cortical activity, and reduced when the whisking ceases (Eggermann et al., 2014; Sachdev et al., 1998). Persistent movement of the whiskers during low-frequency WBV are much longer than the movement induced by the animal. I speculate that this phenomenon could result in elevated activity of cholinergic neurons due to constant stimulation of the lemniscal pathway, resulting in elevated cortical activity. Some evidence does support this hypothesis, as mice which underwent WBV did show elevated levels of acetylcholine-synthesizing enzyme choline acetyltransferase in contrast to control in immunohistological staining of the somatosensory cortex (Heesterbeek et al., 2017). Elevated levels of acetyltransferase have also been observed within the hippocampus, further underlining the potential importance of the cholinergic neurons in rodent cognitive performance (van der Zee, unpublished).

Acetylcholine activity during WBV results in higher cognitive performance in rodents

The impact of acetylcholine on cognition is known and well-studied. Studies that employed the use of drugs capable of blocking effects of acetylcholine in muscarine receptors have shown lowered performance cognitive tasks assessing memory function and the ability to maintain attention, with some patients experiencing complete cognitive breakdown (Beatty et al., 1986; Crow & Grove-White, 1973; Ostfeld & Aruguete, 1962). This is thought to be a result of the multifaceted function of acetylcholine within the central nervous system, as it has shown to be crucial in modulating neuronal behaviour, such as altering firing rate of neurons, reinforcing neuronal loops and cortical dynamics during learning, among others (Hasselmo, 2006; Letzkus, 2011).

In naturalistic and laboratory settings, reduction of acetylcholine has been associated with a variety of cognitive disorders in both animal models and human patients, such as Autism spectrum disorders, attention deficit disorder and neurodegeneration-induced memory loss, to name a few (Deutsch et al., 2010; Karvat & Kimchi, 2014; Martyn et al., 2012; Tata et al., 2014). The reduction of acetylcholine (either by reduction of transporters or increased activity of acetyltransferase) has been proposed to be a component of a variety of cognitive- and neurodegenerative disorders. However, current modalities of stimulation of production of acetylcholine *in vivo* are incredibly invasive, and have only been performed in animal models (Uberti et al., 2017; Vianney et al., 2014). If the stimulation of cholinergic neurons during WBV can also be observed outside of rodent models, this could be employed safely in therapeutic settings.

Translating rodent neuronal pathways to humans

The lemniscal pathway described in the rodent brain is distinct, and cannot be directly translated to humans. The closest possible equivalent pathway which is capable relaying sensory information such as proprioception, texture and vibration is the posterior column medial lemniscal pathway (PMLP) (Purves et al., 2001). Similarly to the rodent pathway, sensory information is perceived by peripheral mechanosensory ganglia in the epidermis and relayed toward the spinal cord (specific to the position of the neuron). The primary ganglia ascends ipsilaterally through the dorsal of the cord, all the way to the lower medulla, where it terminates by contacting second-order neurons in the gracile and cuneate nuclei. Subsequently, secondary neurons project towards the VPM, which relays signals from the facial trigeminal nerve, and ventral posterior lateral nucleus (VPL), which process signals

from the rest of the body (Brodal, 2004; Jones & Powell, 1970). The neurons of VPL and VPM, in turn, project towards the somatosensory cortex.

In spite of the differences, the rodent lemniscal pathway and the human PMPL pathway share common features, such as the stimulation of the thalamus and transmission of signal towards the somatosensory cortex via glutamatergic projections (Parent, 1995; Silkis, 2001). However, issues in comparisons arise when taking in account the presence of cholinergic projections of the murine barrel cortex towards the somatosensory cortex as well as their one-to-one connection to the thalamic barreloids, completely absent in the human brain (Eggermann et al., 2014; Sachdev et al., 1998). The lack of barrel cortex- thalamic barreloid direct connections in the human brain could impact of the relative speed of signal transduction, or excitatory pathways involved (such as the cholinergic projections of the barrel cortex versus the glutamatergic projections from the thalamus to the cortex) (Beitz, 1989; Paraskevopoulou et al., 2019).

In light of these differences, I speculate that the increase in cognitive function in humans after WBV could potentially be the result of a highly-stimulated cortico-basal ganglia-thalamo-cortical loop (CBGTC loop), rather than the action of cholinergic neurons directly onto the somatosensory cortex observed in the rodents, as a result of whisker movement. This is partly supported by data generated from fMRI imaging studies, that showed an increase in the activity of multiple components of the CBGTC loop, such as the caudate nucleus and multiple areas of the sensory-motor cortex (Choi et al., 2019; Kaut et al., 2016; A. Lee et al., 2020). This is congruent with the hypothesis suggesting that inhibition or disruption of the CBGTC loop is involved in neurocognitive disorders, such as ADHD, which has shown response to WBV treatment (Maia et al., 2008; Maia & Frank, 2011; Mills et al., 2012; Saad et al., 2020; Vicente et al., 2020). Additionally, transcranial stimulation of the CBGTC across a variety of psychiatric disorders have shown cognitive improvements similar to the ones observed after WBV, such as reduced arousal and increase in attention (Alyagon et al., 2020; Downar et al., 2016; Dunlop et al., 2016; Jung et al., 2020).

Alternatively, low-frequency WBV could be stimulating the basal forebrain, which does possess extensive cholinergic output into the neocortex, with evidence suggesting it is implicated in promoting attention and other cognitive processes (Bloem et al., 2014; Jiang et al., 2016; Sachdev et al., 1998; Villano et al., 2017). This would also be congruent with the documented increase in activity observed in the nucleus basalis of mice which underwent WBV, and reported activation upon non-noxious skin stimulation (Boerema et al., 2018; Hotta et al., 2014). However, it is not known whether activation of the basal forebrain in WBV occurs in humans as well.

Conversely, most human low-frequency WBV experiments use side-alternating vibrating plates to mimic human walking. This is of note as activities such as walking on the treadmill have been associated with increased cognitive performance in both children and adults (Huang et al., 2021; Muallem et al., 2018; Schaefer et al., 2010). WBV may cause the central nervous system into activate processes related to the action of walking, such as lower-limb muscle contractions and activation of the premotor and motor cortices (Choi et al., 2019; Kaut et al., 2016; Lienhard et al., 2015; Mikhael et al., 2010; Roelants et al., 2006).

Mountains out of mice – how can we mitigate the brain architectural differences between rodents and humans?

Translating information acquired from animal models, particularly rodent, are inherently difficult, particularly when attempting to apply a technique as a therapeutic modality in neurocognitive disorders. In order to assure that a study can be applied across species, you have to account for species-specific characteristics. In the case of low-frequency WBV, the influence of rodent whiskers

upon sensory processing, and their associated brain regions, are posing a challenge in untangling the biological changes underlying the therapeutic effect of WBV.

From an experimental stand-point, the removal of whiskers (by clipping or employing a whisker-less strain) would not result in a more human-accurate model, as they are a crucial component of normal murid development and would contribute more experimental factors (Arakawa & Erzurumlu, 2015; de la Zerda et al., 2020; Soumiya et al., 2016). Though, temporary blocking the primary ganglionic neurons in the mystacial pad via injection of pharmaceutical compounds during WBV trials could elucidate the contribution of the peripheral ganglionic neurons involved in the PMLP pathway in activation of murid brain circuits, as this would resemble human biology more closely. Employment of animal models such as non-human primates in the neural pathways stimulated by low-frequency WBV could result in a better understanding of the impact of the modality. However, trials with non-human primates are unlikely to ever occur due to ethical and financial considerations.

Additionally, one cannot discount the lack of experiments of the impact of low-frequency WBV in human disease within animal models. As of this writing, most human trials of WBV have involved distinct patient populations, both healthy and suffering from neurodegenerative and -cognitive disorders, such as Alzheimer's, autism spectrum disorder and ADHD. In my literature search, I have uncovered a single study of WBV as a therapeutic modality being used on a mouse population affected by a neurocognitive disorder, while the rest employed the traditional C57Bl/6J strain and a single unilateral stroke study in rats (Peng et al., 2021; Raval et al., 2018).

Conclusion

Low-frequency WBV is a promising non-invasive therapeutic modality, which has proven effectiveness in improving attention and lowering arousal in a variety of neurocognitive deficiencies. While similar responses are observed in murid studies, we cannot discount the difference in perception processing between humans and rodents, as proprioception can be perceived by different systems.

In the rodent case, the impact of mystacial whiskers on proprioception cannot be discounted and the size of its effect cannot be accurately estimated due to a lack of studies. The existence of the lemniscal pathway, and direct connections between thalamic barreloids and cortical barrels can imply a more efficient system of transmission of information, in contrast to the human one, which could impact the performance of mice in cognitive trials. Additionally, the lack of human and non-human primates studies in hominid-specific neuronal pathways doubles the difficulty in making a meaningful comparison between species. As a result, murid studies on the therapeutic effect of WBV should use caution when interpreting results and extrapolating the observed effect in rodents towards human patients.

Nevertheless, we cannot discount rodent studies altogether. Brain activity changes in both rodents and humans shows that WBV does impact functionality of the central nervous system in a meaningful way. In order to derive accurate comparisons between rodent and human studies, focus should be placed on regions and pathways with similar functionality (such as the human PFC and rodent hippocampus), rather than making direct comparisons between brain regions. Additionally, rodent proprioception outside of the once sensed by the whiskers, such as the PLMP should be explored, to understand the impact whisker vibration has on visual perception, as it may not be as large as it is speculated to be.

Bibliography

A, P., & LN, H. (1995). Functional anatomy of the basal ganglia. I. The cortico-basal ganglia-thalamo-

cortical loop. *Brain Research. Brain Research Reviews*, 20(1). [https://doi.org/10.1016/0165-0173\(94\)00007-C](https://doi.org/10.1016/0165-0173(94)00007-C)

- Adibi, M. (2019). Whisker-Mediated Touch System in Rodents: From Neuron to Behavior. *Frontiers in Systems Neuroscience*, 13, 40. <https://doi.org/10.3389/fnsys.2019.00040>
- Adibi, M., & Arabzadeh, E. (2011). A comparison of neuronal and behavioral detection and discrimination performances in rat whisker system. *Journal of Neurophysiology*, 105(1), 356–365. <https://doi.org/10.1152/jn.00794.2010>
- Adibi, M., Diamond, M. E., & Arabzadeh, E. (2012). Behavioral study of whisker-mediated vibration sensation in rats. *Proceedings of the National Academy of Sciences of the United States of America*, 109(3), 971–976. <https://doi.org/10.1073/pnas.1116726109>
- Ahl, A. S. (1986). The role of vibrissae in behavior: A status review. *Veterinary Research Communications*, 10(1), 245–268. <https://doi.org/10.1007/BF02213989>
- Alloway, K. D., Hoffer, Z. S., & Hoover, J. E. (2003). Quantitative comparisons of corticothalamic topography within the ventrobasal complex and the posterior nucleus of the rodent thalamus. *Brain Research*, 968(1), 54–68. [https://doi.org/10.1016/S0006-8993\(02\)04265-8](https://doi.org/10.1016/S0006-8993(02)04265-8)
- Alyagon, U., Shahar, H., Hadar, A., Barnea-Ygael, N., Lazarovits, A., Shalev, H., & Zangen, A. (2020). Alleviation of ADHD symptoms by non-invasive right prefrontal stimulation is correlated with EEG activity. *NeuroImage: Clinical*, 26. <https://doi.org/10.1016/j.nicl.2020.102206>
- Antunes, M., & Biala, G. (2012). The novel object recognition memory: Neurobiology, test procedure, and its modifications. In *Cognitive Processing* (Vol. 13, Issue 2, pp. 93–110). Springer. <https://doi.org/10.1007/s10339-011-0430-z>
- Arakawa, H., & Erzurumlu, R. S. (2015). Role of whiskers in sensorimotor development of C57BL/6 mice. *Behavioural Brain Research*, 287, 146–155. <https://doi.org/10.1016/j.bbr.2015.03.040>
- Baum, K., Votteler, T., & Schiab, J. (2007). Efficiency of vibration exercise for glycemic control in type 2 diabetes pa-tients. In *International Journal of Medical Sciences* (Vol. 4, Issue 3). www.medsci.org
- Beatty, W. W., Butters, N., & Janowsky, D. S. (1986). Patterns of memory failure after scopolamine treatment: Implications for cholinergic hypotheses of dementia. *Behavioral and Neural Biology*, 45(2), 196–211. [https://doi.org/10.1016/S0163-1047\(86\)90772-7](https://doi.org/10.1016/S0163-1047(86)90772-7)
- Beitz, A. J. (1989). Possible origin of glutamatergic projections to the midbrain periaqueductal gray and deep layer of the superior colliculus of the rat. *Brain Research Bulletin*, 23(1–2), 25–35. [https://doi.org/10.1016/0361-9230\(89\)90159-7](https://doi.org/10.1016/0361-9230(89)90159-7)
- Bloem, B., Schoppink, L., Rotaru, D. C., Faiz, A., Hendriks, P., Mansvelter, H. D., van de Berg, W. D. J., & Wouterlood, F. G. (2014). Topographic mapping between basal forebrain cholinergic neurons and the medial prefrontal cortex in mice. *Journal of Neuroscience*, 34(49), 16234–16246. <https://doi.org/10.1523/JNEUROSCI.3011-14.2014>
- Boerema, A. S., Heesterbeek, M., Boersma, S. A., Schoemaker, R., de Vries, E. F. J., van Heuvelen, M. J. G., & Van der Zee, E. A. (2018). Beneficial Effects of Whole Body Vibration on Brain Functions in Mice and Humans. *Dose-Response*, 16(4). <https://doi.org/10.1177/1559325818811756>
- Bourassa, J., Pinault, D., & Deschênes, M. (1995). Corticothalamic Projections from the Cortical Barrel Field to the Somatosensory Thalamus in Rats: A Single-fibre Study Using Biocytin as an Anterograde Tracer. *European Journal of Neuroscience*, 7(1), 19–30. <https://doi.org/10.1111/j.1460-9568.1995.tb01016.x>

- Brecht, M., Preilowski, B., & Merzenich, M. M. (1997). Functional architecture of the mystacial vibrissae. *Behavioural Brain Research*, *84*(1–2), 81–97. [https://doi.org/10.1016/S0166-4328\(97\)83328-1](https://doi.org/10.1016/S0166-4328(97)83328-1)
- Brodal, P. (2004). *The Central Nervous System : Structure and Function* (3rd ed.). Oxford University Press. <https://web-a-ebSCOhost-com.proxy-ub.rug.nl/ehost/ebookviewer/ebook/bmxlYmtfXzE3NjkwOV9fQU41?sid=130a56f8-95c8-4681-92fc-759143bf5930@sdC-v-sessmgr01&vid=0&format=EB&rid=1>
- Burghardt, N. S., Park, E. H., Hen, R., & Fenton, A. A. (2012). Adult-born hippocampal neurons promote cognitive flexibility in mice. *Hippocampus*, *22*(9), 1795–1808. <https://doi.org/10.1002/hipo.22013>
- Bush, N. E., Solla, S. A., & Hartmann, M. J. Z. (2019). Continuous, multidimensional coding of 3D complex tactile stimuli by primary sensory neurons of the vibrissal system. *BioRxiv*, 869255. <https://doi.org/10.1101/869255>
- Cariati, I., Bonanni, R., Pallone, G., Annino, G., Tancredi, V., & D'arcangelo, G. (2021). Modulation of synaptic plasticity by vibratory training in young and old mice. *Brain Sciences*, *11*(1), 1–11. <https://doi.org/10.3390/brainsci11010082>
- Chen, Z., Wimmer, R. D., Wilson, M. A., & Halassa, M. M. (2016). Thalamic Circuit Mechanisms Link Sensory Processing in Sleep and Attention. *Frontiers in Neural Circuits*, *9*(JAN2016), 83. <https://doi.org/10.3389/fncir.2015.00083>
- Chmielowska, J., Carvell, G. E., & Simons, D. J. (1989). Spatial organization of thalamocortical and corticothalamic projection systems in the rat Sml barrel cortex. *The Journal of Comparative Neurology*, *285*(3), 325–338. <https://doi.org/10.1002/cne.902850304>
- Cho, Y., Craig, J. C., Hsiao, S. S., & Bensmaia, S. J. (2016). Vision is superior to touch in shape perception even with equivalent peripheral input. *Journal of Neurophysiology*, *115*(1), 92–99. <https://doi.org/10.1152/jn.00654.2015>
- Choi, D. S., Lee, H. J., Shin, Y. I., Lee, A., Kim, H. G., & Kim, Y. H. (2019). Modulation of Cortical Activity by High-Frequency Whole-Body Vibration Exercise: An fNIRS Study. *Journal of Sport Rehabilitation*, *28*(7), 665–670. <https://doi.org/10.1123/jsr.2017-0012>
- Cole, M. W., Yarkoni, T., Repovš, G., Anticevic, A., & Braver, T. S. (2012). Global connectivity of prefrontal cortex predicts cognitive control and intelligence. *Journal of Neuroscience*, *32*(26), 8988–8999. <https://doi.org/10.1523/JNEUROSCI.0536-12.2012>
- Crandall, S. R., Patrick, S. L., Cruikshank, S. J., & Connors, B. W. (2017). Infrabarrels Are Layer 6 Circuit Modules in the Barrel Cortex that Link Long-Range Inputs and Outputs. *Cell Reports*, *21*(11), 3065–3078. <https://doi.org/10.1016/j.celrep.2017.11.049>
- Crow, T. J., & Grove-White, I. G. (1973). An analysis of the learning deficit following hyoscine administration to man. *British Journal of Pharmacology*, *49*(2), 322–327. <https://doi.org/10.1111/j.1476-5381.1973.tb08379.x>
- de Bruin, E. D., Baur, H., Brühlhart, Y., Luijckx, E., Hinrichs, T., & Rogan, S. (2020). Combining Stochastic Resonance Vibration With Exergaming for Motor-Cognitive Training in Long-Term Care; A Sham-Control Randomized Controlled Pilot Trial. *Frontiers in Medicine*, *7*, 507155. <https://doi.org/10.3389/fmed.2020.507155>
- de la Zerda, S. H., Netser, S., Magalnik, H., Briller, M., Marzan, D., Glatt, S., & Wagner, S. (2020). Social recognition in rats and mice requires integration of olfactory, somatosensory and auditory cues. *BioRxiv*, 2020.05.05.078139. <https://doi.org/10.1101/2020.05.05.078139>

- Deacon, R. M. J., Bannerman, D. M., Kirby, B. P., Croucher, A., & Rawlins, J. N. P. (2002). Effects of cytotoxic hippocampal lesions in mice on a cognitive test battery. *Behavioural Brain Research*, *133*(1), 57–68. [https://doi.org/10.1016/S0166-4328\(01\)00451-X](https://doi.org/10.1016/S0166-4328(01)00451-X)
- Desîlets-Roy, B., Varga, C., Lavallée, P., & Deschênes, M. (2002). Substrate for cross-talk inhibition between thalamic barreloids. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *22*(9), RC218–RC218. <https://doi.org/10.1523/jneurosci.22-09-j0002.2002>
- Deutsch, S. I., Urbano, M. R., Neumann, S. A., Burket, J. A., & Katz, E. (2010). Cholinergic abnormalities in autism: Is there a rationale for selective nicotinic agonist interventions? In *Clinical Neuropharmacology* (Vol. 33, Issue 3, pp. 114–120). Clin Neuropharmacol. <https://doi.org/10.1097/WNF.0b013e3181d6f7ad>
- Diamond, M. E., Armstrong-James, M., & Ebner, F. F. (1992). Somatic sensory responses in the rostral sector of the posterior group (POm) and in the ventral posterior medial nucleus (VPM) of the rat thalamus. *The Journal of Comparative Neurology*, *318*(4), 462–476. <https://doi.org/10.1002/cne.903180410>
- Downar, J., Blumberger, D. M., & Daskalakis, Z. J. (2016). The Neural Crossroads of Psychiatric Illness: An Emerging Target for Brain Stimulation. In *Trends in Cognitive Sciences* (Vol. 20, Issue 2, pp. 107–120). Elsevier Ltd. <https://doi.org/10.1016/j.tics.2015.10.007>
- Dunlop, K., Woodside, B., Olmsted, M., Colton, P., Giacobbe, P., & Downar, J. (2016). Reductions in Cortico-Striatal Hyperconnectivity Accompany Successful Treatment of Obsessive-Compulsive Disorder with Dorsomedial Prefrontal rTMS. *Neuropsychopharmacology*, *41*(5), 1395–1403. <https://doi.org/10.1038/npp.2015.292>
- Durham, D., & Woolsey, T. A. (1984). Effects of neonatal whisker lesions on mouse central trigeminal pathways. *The Journal of Comparative Neurology*, *223*(3), 424–447. <https://doi.org/10.1002/cne.902230308>
- Eggermann, E., Kremer, Y., Crochet, S., & Petersen, C. C. H. (2014). Cholinergic Signals in Mouse Barrel Cortex during Active Whisker Sensing. *Cell Reports*, *9*(5), 1654–1660. <https://doi.org/10.1016/j.celrep.2014.11.005>
- El-Boustani, S., Sermet, B. S., Foustoukos, G., Oram, T. B., Yizhar, O., & Petersen, C. C. H. (2020). Anatomically and functionally distinct thalamocortical inputs to primary and secondary mouse whisker somatosensory cortices. *Nature Communications*, *11*(1), 1–12. <https://doi.org/10.1038/s41467-020-17087-7>
- Ferreira, D. (2020). Acute effect of whole-body vibration on motor and cognitive function in children with Down syndrome: A series of case studies. *Kinesiology Dissertations*. https://scholarworks.gsu.edu/kin_health_diss/34
- Frangeul, L., Porrero, C., Garcia-Amado, M., Maimone, B., Maniglier, M., Clascá, F., & Jabaudon, D. (2014). Specific activation of the paralemniscal pathway during nociception. *European Journal of Neuroscience*, *39*(9), 1455–1464. <https://doi.org/10.1111/ejn.12524>
- Funahashi, S. (2017). Working memory in the prefrontal cortex. In *Brain Sciences* (Vol. 7, Issue 5). MDPI AG. <https://doi.org/10.3390/brainsci7050049>
- Furuta, T., Kaneko, T., & Deschênes, M. (2009). Septal neurons in barrel cortex derive their receptive field input from the lemniscal pathway. *Journal of Neuroscience*, *29*(13), 4089–4095. <https://doi.org/10.1523/JNEUROSCI.5393-08.2009>
- Gibson, J. M., & Welker, W. I. (1983). Quantitative studies of stimulus coding in first-order vibrissa afferents of rats. 1. Receptive Field properties and threshold distributions. *Somatosensory &*

Motor Research, 1(1), 51–67. <https://doi.org/10.3109/07367228309144540>

- Gonzalez-Perez, O., López-Virgen, V., & Ibarra-Castaneda, N. (2018). Permanent Whisker Removal Reduces the Density of c-Fos+ Cells and the Expression of Calbindin Protein, Disrupts Hippocampal Neurogenesis and Affects Spatial-Memory-Related Tasks. *Frontiers in Cellular Neuroscience*, 12, 132. <https://doi.org/10.3389/fncel.2018.00132>
- Grion, N., Akrami, A., Zuo, Y., Stella, F., & Diamond, M. E. (2016). Coherence between Rat Sensorimotor System and Hippocampus Is Enhanced during Tactile Discrimination. *PLoS Biology*, 14(2), e1002384. <https://doi.org/10.1371/journal.pbio.1002384>
- Gusso, S., Munns, C. F., Colle, P., Derraik, J. G. B., Biggs, J. B., Cutfield, W. S., & Hofman, P. L. (2016). Effects of whole-body vibration training on physical function, bone and muscle mass in adolescents and young adults with cerebral palsy. *Scientific Reports*, 6(1), 1–7. <https://doi.org/10.1038/srep22518>
- Halassa, M. M., Chen, Z., Wimmer, R. D., Brunetti, P. M., Zhao, S., Zikopoulos, B., Wang, F., Brown, E. N., & Wilson, M. A. (2014). State-dependent architecture of thalamic reticular subnetworks. *Cell*, 158(4), 808–821. <https://doi.org/10.1016/j.cell.2014.06.025>
- Harris, R. M. (1987). Axon collaterals in the thalamic reticular nucleus from thalamocortical neurons of the rat ventrobasal thalamus. *The Journal of Comparative Neurology*, 258(3), 397–406. <https://doi.org/10.1002/cne.902580308>
- Hawrylycz, M. J., Lein, E. S., Guillozet-Bongaarts, A. L., Shen, E. H., Ng, L., Miller, J. A., Van De Lagemaat, L. N., Smith, K. A., Ebbert, A., Riley, Z. L., Abajian, C., Beckmann, C. F., Bernard, A., Bertagnolli, D., Boe, A. F., Cartagena, P. M., Mallar Chakravarty, M., Chapin, M., Chong, J., ... Jones, A. R. (2012). An anatomically comprehensive atlas of the adult human brain transcriptome. *Nature*, 489(7416), 391–399. <https://doi.org/10.1038/nature11405>
- Heesterbeek, M., Jentsch, M. C., Roemers, P., & Keijser, J. N. (2017). *Whole Body Vibration Enhances Choline Acetyltransferase-Immunoreactivity in Cortex and Amygdale Effect of Black currant bud extract as functional food on LPS-induced inflammatory responses on cognitive and motor functions in adult rats View project*. <https://www.researchgate.net/publication/320419072>
- Herren, K., Schmid, S., Rogan, S., & Radlinger, L. (2018). Effects of Stochastic Resonance Whole-Body Vibration in Individuals with Unilateral Brain Lesion: A Single-Blind Randomized Controlled Trial: Whole-Body Vibration and Neuromuscular Function. *Rehabilitation Research and Practice*, 2018, 1–11. <https://doi.org/10.1155/2018/9319258>
- Hotta, H., Watanabe, N., Piché, M., Hara, S., Yokawa, T., & Uchida, S. (2014). Non-noxious skin stimulation activates the nucleus basalis of Meynert and promotes NGF secretion in the parietal cortex via nicotinic ACh receptors. *Journal of Physiological Sciences*, 64(4), 253–260. <https://doi.org/10.1007/s12576-014-0313-z>
- Huang, Y. C., Hung, C. F., Hsu, S. T., Lin, P. Y., Lee, Y., Chong, M. Y., Chen, C. C., Kuo, Y. H., & Wang, L. J. (2021). Effects of aerobic walking on cognitive function in patients with schizophrenia: A randomized controlled trial. *Journal of Psychiatric Research*, 134, 173–180. <https://doi.org/10.1016/j.jpsychires.2020.12.062>
- Hutmacher, F. (2019). Why Is There So Much More Research on Vision Than on Any Other Sensory Modality? *Frontiers in Psychology*, 10, 2246. <https://doi.org/10.3389/fpsyg.2019.02246>
- I, S. (2001). The cortico-basal ganglia-thalamocortical circuit with synaptic plasticity. II. Mechanism of synergistic modulation of thalamic activity via the direct and indirect pathways through the basal ganglia. *Bio Systems*, 59(1). [https://doi.org/10.1016/S0303-2647\(00\)00135-0](https://doi.org/10.1016/S0303-2647(00)00135-0)

- Jensen, K. F., & Killackey, H. P. (1997). Terminal Arbors of Axons Projecting to the Somatosensory Cortex of the Adult Rat. I. The Normal Morphology of Specific Thalamocortical Afferents. In *The Journal of Neuroscience* (Vol. 7, Issue 11). <https://www.jneurosci.org/content/7/11/3529.short>
- Jiang, L., Kundu, S., Lederman, J. D. D., López-Hernández, G. Y. Y., Ballinger, E. C. C., Wang, S., Talmage, D. A. A., & Role, L. W. W. (2016). Cholinergic Signaling Controls Conditioned Fear Behaviors and Enhances Plasticity of Cortical-Amygdala Circuits. *Neuron*, *90*(5), 1057–1070. <https://doi.org/10.1016/j.neuron.2016.04.028>
- Jones, E. G., & Powell, T. P. S. (1970). Connexions of the somatic sensory cortex of the rhesus monkey: III.-Thalamic connexions. *Brain*, *93*(1), 37–56. <https://doi.org/10.1093/brain/93.1.37>
- Jung, D. H., Ahn, S. M., Pak, M. E., Lee, H. J., Jung, Y. J., Kim, K. B., Shin, Y. Il, Shin, H. K., & Choi, B. T. (2020). Therapeutic effects of anodal transcranial direct current stimulation in a rat model of adhd. *ELife*, *9*, 1–26. <https://doi.org/10.7554/ELIFE.56359>
- Kaeding, T. S., Karch, A., Schwarz, R., Flor, T., Wittke, T. C., Kück, M., Bösel, G., Tegtbur, U., & Stein, L. (2017). Whole-body vibration training as a workplace-based sports activity for employees with chronic low-back pain. *Scandinavian Journal of Medicine and Science in Sports*, *27*(12), 2027–2039. <https://doi.org/10.1111/sms.12852>
- Kahn, M. S., Kranjac, D., Alonzo, C. A., Haase, J. H., Cedillos, R. O., McLinden, K. A., Boehm, G. W., & Chumley, M. J. (2012). Prolonged elevation in hippocampal A β and cognitive deficits following repeated endotoxin exposure in the mouse. *Behavioural Brain Research*, *229*(1), 176–184. <https://doi.org/10.1016/j.bbr.2012.01.010>
- Karvat, G., & Kimchi, T. (2014). Acetylcholine elevation relieves cognitive rigidity and social deficiency in a mouse model of autism. *Neuropsychopharmacology*, *39*(4), 831–840. <https://doi.org/10.1038/npp.2013.274>
- Kaut, O., Becker, B., Schneider, C., Zhou, F., Fliessbach, K., Hurlmann, R., & Wüllner, U. (2016). Stochastic resonance therapy induces increased movement-related caudate nucleus activity. *Journal of Rehabilitation Medicine*, *48*(9), 815–818. <https://doi.org/10.2340/16501977-2143>
- Keijsers, J. N., van Heuvelen, M. J. G., Nyakas, C., Tóth, K., Schoemaker, R. G., Zeinstra, E., & van der Zee, E. A. (2017). WHOLE BODY VIBRATION IMPROVES ATTENTION AND MOTOR PERFORMANCE IN MICE DEPENDING ON THE DURATION OF THE WHOLE-BODY VIBRATION SESSION. *African Journal of Traditional, Complementary, and Alternative Medicines : AJTCAM*, *14*(4), 128–134. <https://doi.org/10.21010/ajtcam.v14i4.15>
- Kim, K. H., & Lee, H. B. (2018). The effects of whole body vibration exercise intervention on electroencephalogram activation and cognitive function in women with senile dementia. *Journal of Exercise Rehabilitation*, *14*(4), 586–591. <https://doi.org/10.12965/jer.1836230.115>
- Krajnak, K. (2018). Health effects associated with occupational exposure to hand-arm or whole body vibration. *Journal of Toxicology and Environmental Health - Part B: Critical Reviews*, *21*(5), 320–334. <https://doi.org/10.1080/10937404.2018.1557576>
- Lam, Y. W., & Sherman, S. M. (2007). Different topography of the reticulothalamic inputs to first- and higher-order somatosensory thalamic relays revealed using photostimulation. *Journal of Neurophysiology*, *98*(5), 2903–2909. <https://doi.org/10.1152/jn.00782.2007>
- Lavallée, P., Urbain, N., Dufresne, C., Bokor, H., Acsády, L., & Deschênes, M. (2005). Feedforward inhibitory control of sensory information in higher-order thalamic nuclei. *Journal of Neuroscience*, *25*(33), 7489–7498. <https://doi.org/10.1523/JNEUROSCI.2301-05.2005>
- Lee, A., Kim, H., Kim, J., Choi, D.-S., Jung, J. H., Lee, J., & Kim, Y.-H. (2020). Modulating Effects of

- Whole-body Vibration on Cortical Activity and Gait Function in Chronic Stroke Patients. *Brain & Neurorehabilitation*, 13(2). <https://doi.org/10.12786/bn.2020.13.e12>
- Lee, I., Yoganarasimha, D., Rao, G., & Knierim, J. J. (2004). Comparison of population coherence of place cells in hippocampal subfields CA1 and CA3. *Nature*, 430(6998), 456–459. <https://doi.org/10.1038/nature02739>
- Leiser, S. C., & Moxon, K. A. (2007). Responses of Trigeminal Ganglion Neurons during Natural Whisking Behaviors in the Awake Rat. *Neuron*, 53(1), 117–133. <https://doi.org/10.1016/j.neuron.2006.10.036>
- Li, Z., Zhang, M., Li, J., Xin, Q., Chen, G., Li, J., & Liu, F. (2012). Spectral analysis of cerebral oxygenation responses to seated whole-body vibration in healthy men. *International Journal of Industrial Ergonomics*, 42(4), 341–346. <https://doi.org/10.1016/j.ergon.2012.03.002>
- Lichtenstein, S. H., Carvell, G. E., & Simons, D. J. (1990). Responses of rat trigeminal ganglion neurons to movements of vibrissae in different directions. In *Somatosensory & Motor Research* (Vol. 7, Issue 1, pp. 47–65). Informa Healthcare. <https://doi.org/10.3109/08990229009144697>
- Lienhard, K., Vienneau, J., Friesenbichler, B., Nigg, S., Meste, O., Nigg, B. M., & Colson, S. S. (2015). The effect of whole-body vibration on muscle activity in active and inactive subjects. *International Journal of Sports Medicine*, 36(7), 585–591. <https://doi.org/10.1055/s-0034-1398650>
- Lu, S. M., & Lin, R. C. S. (1993). Thalamic afferents of the rat barrel cortex: A light-and electron-microscopic study using phaseolus vulgaris leucoagglutinin as an anterograde tracer. *Somatosensory & Motor Research*, 10(1), 1–16. <https://doi.org/10.3109/08990229309028819>
- Maia, T. V., Cooney, R. E., & Peterson, B. S. (2008). The neural bases of obsessive - Compulsive disorder in children and adults. In *Development and Psychopathology* (Vol. 20, Issue 4, pp. 1251–1283). NIH Public Access. <https://doi.org/10.1017/S0954579408000606>
- Maia, T. V., & Frank, M. J. (2011). From reinforcement learning models to psychiatric and neurological disorders. *Nature Neuroscience*, 14(2), 154–162. <https://doi.org/10.1038/nn.2723>
- Martyn, A. C., De Jaeger, X., Magalhães, A. C., Kesarwani, R., Gonçalves, D. F., Raulic, S., Guzman, M. S., Jackson, M. F., Izquierdo, I., MacDonald, J. F., Prado, M. A. M., & Prado, V. F. (2012). Elimination of the vesicular acetylcholine transporter in the forebrain causes hyperactivity and deficits in spatial memory and long-term potentiation. *Proceedings of the National Academy of Sciences of the United States of America*, 109(43), 17651–17656. <https://doi.org/10.1073/pnas.1215381109>
- Mathiasen, J. R., & Dicamillo, A. (2010). Novel object recognition in the rat: A facile assay for cognitive function. *Current Protocols in Pharmacology*, Chapter 5(SUPPL. 49). <https://doi.org/10.1002/0471141755.ph0559s49>
- Mikhael, M., Orr, R., Amsen, F., Greene, D., & Fiatarone Singh, M. A. (2010). Effect of standing posture during whole body vibration training on muscle morphology and function in older adults: A randomised controlled trial. *BMC Geriatrics*, 10(1), 74. <https://doi.org/10.1186/1471-2318-10-74>
- Mills, K. L., Bathula, D., Dias, T. G. C., Iyer, S. P., Fenesy, M. C., Musser, E. D., Stevens, C. A., Thurlow, B. L., Carpenter, S. D., Nagel, B. J., Nigg, J. T., & Fair, D. A. (2012). Altered cortico-striatal-thalamic connectivity in relation to spatial working memory capacity in children with ADHD. *Frontiers in Psychiatry*, 3(JAN). <https://doi.org/10.3389/fpsy.2012.00002>
- Milshtein-Parush, H., Frere, S., Regev, L., Lahav, C., Benbenishty, A., Ben-Eliyahu, S., Goshen, I., &

- Slutsky, I. (2017). Sensory Deprivation Triggers Synaptic and Intrinsic Plasticity in the Hippocampus. *Cerebral Cortex*, 27(6), 3457–3470. <https://doi.org/10.1093/cercor/bhx084>
- Mualem, R., Leisman, G., Zbedat, Y., Ganem, S., Mualem, O., Amaria, M., Kozle, A., Khayat-Moughrabi, S., & Ornai, A. (2018). The Effect of Movement on Cognitive Performance. *Frontiers in Public Health*, 6, 100. <https://doi.org/10.3389/fpubh.2018.00100>
- Nakamura, S., Narumi, T., Tsutsui, K. I., & Iijima, T. (2009). Difference in the functional significance between the lemniscal and paralemniscal pathways in the perception of direction of single-whisker stimulation examined by muscimol microinjection. *Neuroscience Research*, 64(3), 323–329. <https://doi.org/10.1016/j.neures.2009.04.005>
- Ostfeld, A. M., & Aruguete, A. (1962). CENTRAL NERVOUS SYSTEM EFFECTS OF HYOSCINE IN MAN. *Journal of Pharmacology and Experimental Therapeutics*, 137(1).
- Paraskevopoulou, F., Herman, M. A., & Rosenmund, C. (2019). Glutamatergic innervation onto striatal neurons potentiates GABAergic synaptic output. *Journal of Neuroscience*, 39(23), 4448–4460. <https://doi.org/10.1523/JNEUROSCI.2630-18.2019>
- Peng, G., Yang, L., Wu, C. Y., Zhang, L. L., Wu, C. Y., Li, F., Shi, H. W., Hou, J., Zhang, L. M., Ma, X., Xiong, J., Pan, H., & Zhang, G. Q. (2021). Whole body vibration training improves depression-like behaviors in a rat chronic restraint stress model. *Neurochemistry International*, 142, 104926. <https://doi.org/10.1016/j.neuint.2020.104926>
- Pereira, A., Ribeiro, S., Wiest, M., Moore, L. C., Pantoja, J., Lin, S. C., & Nicolelis, M. A. L. (2007). Processing of tactile information by the hippocampus. *Proceedings of the National Academy of Sciences of the United States of America*, 104(46), 18286–18291. <https://doi.org/10.1073/pnas.0708611104>
- Pierret, T., Lavallé, P., & Deschê, M. (2000). Parallel Streams for the Relay of Vibrissal Information through Thalamic Barreloids. In *The Journal of Neuroscience* (Vol. 20, Issue 19). <https://www.jneurosci.org/content/20/19/7455.short>
- Pubols, B. H., Donovick, P. J., & Pubols, L. M. (1973). Opossum trigeminal afferents associated with vibrissa and rhinial mechanoreceptors. *Brain, Behavior and Evolution*, 7(5), 360–381. <https://doi.org/10.1159/000124423>
- Purves, D., Augustine, G. J., Fitzpatrick, D., Katz, L. C., LaMantia, A.-S., McNamara, J. O., & Williams, S. M. (2001). The Major Afferent Pathway for Mechanosensory Information: The Dorsal Column-Medial Lemniscus System. In *Neuroscience* (2nd ed.). Sinauer Associates. <https://www.ncbi.nlm.nih.gov/books/NBK11142/>
- Rajab, A. S., Crane, D. E., Middleton, L. E., Robertson, A. D., Hampson, M., & MacIntosh, B. J. (2014). A single session of exercise increases connectivity in sensorimotor-related brain networks: a resting-state fMRI study in young healthy adults. *Frontiers in Human Neuroscience*, 8(AUG), 625. <https://doi.org/10.3389/fnhum.2014.00625>
- Raval, A. P., Schatz, M., Bhattacharya, P., D'adesky, N., Rundek, T., Dietrich, W. D., & Bramlett, H. M. (2018). Whole body vibration therapy after ischemia reduces brain damage in reproductively senescent female rats. *International Journal of Molecular Sciences*, 19(9). <https://doi.org/10.3390/ijms19092749>
- Rees, S. S., Murphy, A. J., & Watsford, M. L. (2008). *Effects of Whole-Body Vibration Exercise on Lower-Extremity Muscle Strength and Power in an Older Population: A Randomized Clinical Trial Background and Purpose*. www.ptjournal.org
- Regterschot, G. R. H., Van Heuvelen, M. J. G., Zeinstra, E. B., Fuermaier, A. B. M., Tucha, L., Koerts, J.,

- Tucha, O., & Van Der Zee, E. A. (2014). Whole body vibration improves cognition in healthy young adults. *PLoS ONE*, *9*(6), 100506. <https://doi.org/10.1371/journal.pone.0100506>
- Roelants, M., Verschueren, S. M. P., Delecluse, C., Levin, O., & Stijnen, V. (2006). Whole-body-vibration-induced increase in leg muscle activity during different squat exercises. *Journal of Strength and Conditioning Research*, *20*(1), 124–129. <https://doi.org/10.1519/R-16674.1>
- Rustler, V., Däggelmann, J., Streckmann, F., Bloch, W., & Baumann, F. T. (2019). Whole-body vibration in children with disabilities demonstrates therapeutic potentials for pediatric cancer populations: a systematic review. *Supportive Care in Cancer*, *27*(2), 395–406. <https://doi.org/10.1007/s00520-018-4506-5>
- Saad, J. F., Griffiths, K. R., & Korgaonkar, M. S. (2020). A systematic review of imaging studies in the combined and inattentive subtypes of attention deficit hyperactivity disorder. *Frontiers in Integrative Neuroscience*, *14*, 31. <https://doi.org/10.3389/fnint.2020.00031>
- Sachdev, R. N. S., Lu, S.-M., Wiley, R. G., & Ebner, F. F. (1998). Role of the Basal Forebrain Cholinergic Projection in Somatosensory Cortical Plasticity. *Journal of Neurophysiology*, *79*(6), 3216–3228. <https://doi.org/10.1152/jn.1998.79.6.3216>
- Sanders, L. M. J., Hortobágyi, T., la Bastide-van Gemert, S., van der Zee, E. A., & van Heuvelen, M. J. G. (2019). Dose-response relationship between exercise and cognitive function in older adults with and without cognitive impairment: A systematic review and meta-analysis. *PLOS ONE*, *14*(1), e0210036. <https://doi.org/10.1371/journal.pone.0210036>
- Scarpina, F., & Tagini, S. (2017). The stroop color and word test. In *Frontiers in Psychology* (Vol. 8, Issue APR, p. 557). Frontiers Research Foundation. <https://doi.org/10.3389/fpsyg.2017.00557>
- Schaefer, S., Lövdén, M., Wieckhorst, B., & Lindenberger, U. (2010). Cognitive performance is improved while walking: Differences in cognitive-sensorimotor couplings between children and young adults. *European Journal of Developmental Psychology*, *7*(3), 371–389. <https://doi.org/10.1080/17405620802535666>
- Soumiya, H., Godai, A., Araiso, H., Mori, S., Furukawa, S., & Fukumitsu, H. (2016). Neonatal Whisker Trimming Impairs Fear/Anxiety-Related Emotional Systems of the Amygdala and Social Behaviors in Adult Mice. *PLOS ONE*, *11*(6), e0158583. <https://doi.org/10.1371/journal.pone.0158583>
- Tata, A., Velluto, L., D'Angelo, C., & Reale, M. (2014). Cholinergic System Dysfunction and Neurodegenerative Diseases: Cause or Effect? *CNS & Neurological Disorders - Drug Targets*, *13*(7), 1294–1303. <https://doi.org/10.2174/1871527313666140917121132>
- Tzakis, N., & Holahan, M. R. (2019). Social Memory and the Role of the Hippocampal CA2 Region. In *Frontiers in Behavioral Neuroscience* (Vol. 13, p. 233). Frontiers Media S.A. <https://doi.org/10.3389/fnbeh.2019.00233>
- Uberti, F., Bardelli, C., Morsanuto, V., Ghirlanda, S., Cochis, A., & Molinari, C. (2017). Stimulation of the Nonneuronal Cholinergic System by Highly Diluted Acetylcholine in Keratinocytes. *Cells Tissues Organs*, *203*(4), 215–230. <https://doi.org/10.1159/000451023>
- Urbain, N., & Deschênes, M. (2007). A new thalamic pathway of vibrissal information modulated by the motor cortex. *Journal of Neuroscience*, *27*(45), 12407–12412. <https://doi.org/10.1523/JNEUROSCI.2914-07.2007>
- Van Der Loos, H. (1976). Barreloids in mouse somatosensory thalamus. *Neuroscience Letters*, *2*(1), 1–6. [https://doi.org/10.1016/0304-3940\(76\)90036-7](https://doi.org/10.1016/0304-3940(76)90036-7)

- Veinante, P., Jacquin, M. F., & Desch \heartsuit nes, M. (2000). Thalamic projections from the whisker-sensitive regions of the spinal trigeminal complex in the rat. *The Journal of Comparative Neurology*, 420(2), 233–243. [https://doi.org/10.1002/\(SICI\)1096-9861\(20000501\)420:2<233::AID-CNE6>3.0.CO;2-T](https://doi.org/10.1002/(SICI)1096-9861(20000501)420:2<233::AID-CNE6>3.0.CO;2-T)
- Vianney, J. M., Miller, D. A., & Spitsbergen, J. M. (2014). Effects of acetylcholine and electrical stimulation on glial cell line-derived neurotrophic factor production in skeletal muscle cells. *Brain Research*, 1588, 47–54. <https://doi.org/10.1016/j.brainres.2014.09.024>
- Vicente, A. M., Martins, G. J., & Costa, R. M. (2020). Cortico-basal ganglia circuits underlying dysfunctional control of motor behaviors in neuropsychiatric disorders. In *Current Opinion in Genetics and Development* (Vol. 65, pp. 151–159). Elsevier Ltd. <https://doi.org/10.1016/j.gde.2020.05.042>
- Villano, I., Messina, A., Valenzano, A., Moscatelli, F., Esposito, T., Monda, V., Esposito, M., Precenzano, F., Carotenuto, M., Viggiano, A., Chieffi, S., Cibelli, G., Monda, M., & Messina, G. (2017). Basal forebrain cholinergic system and orexin neurons: Effects on attention. *Frontiers in Behavioral Neuroscience*, 11, 10. <https://doi.org/10.3389/fnbeh.2017.00010>
- Von Heimendahl, M., Itskov, P. M., Arabzadeh, E., & Diamond, M. E. (2007). Neuronal activity in rat barrel cortex underlying texture discrimination. *PLoS Biology*, 5(11), 2696–2708. <https://doi.org/10.1371/journal.pbio.0050305>
- Wang, P., Yang, X., Yang, Y., Yang, L., Zhou, Y., Liu, C., Reinhardt, J. D., & He, C. (2015). Effects of whole body vibration on pain, stiffness and physical functions in patients with knee osteoarthritis: A systematic review and meta-analysis. *Clinical Rehabilitation*, 29(10), 939–951. <https://doi.org/10.1177/0269215514564895>
- Williams, M. N., Zahm, D. S., & Jacquin, M. F. (1994). Differential Foci and Synaptic Organization of the Principal and Spinal Trigeminal Projections to the Thalamus in the Rat. *European Journal of Neuroscience*, 6(3), 429–453. <https://doi.org/10.1111/j.1460-9568.1994.tb00286.x>
- Wimmer, R. D., Schmitt, L. I., Davidson, T. J., Nakajima, M., Deisseroth, K., & Halassa, M. M. (2015). Thalamic control of sensory selection in divided attention. *Nature*, 526(7575), 705–709. <https://doi.org/10.1038/nature15398>
- Wollersheim, T., Haas, K., Wolf, S., Mai, K., Spies, C., Steinhagen-Thiessen, E., Wernecke, K. D., Spranger, J., & Weber-Carstens, S. (2017). Whole-body vibration to prevent intensive care unit-acquired weakness: Safety, feasibility, and metabolic response. *Critical Care*, 21(1), 9. <https://doi.org/10.1186/s13054-016-1576-y>
- Woolsey, T. A., & Van der Loos, H. (1970). The structural organization of layer IV in the somatosensory region (S I) of mouse cerebral cortex. The description of a cortical field composed of discrete cytoarchitectonic units. *Brain Research*, 17(2), 205–242. [https://doi.org/10.1016/0006-8993\(70\)90079-X](https://doi.org/10.1016/0006-8993(70)90079-X)
- Yu, C., Derdikman, D., Haidarliu, S., & Ahissar, E. (2006). Parallel Thalamic Pathways for Whisking and Touch Signals in the Rat. *PLoS Biology*, 4(5). <https://doi.org/10.1371/journal.pbio.0040124>
- Yu, Y. S. W., Graff, M. M., & Hartmann, M. J. Z. (2016a). Mechanical responses of rat vibrissae to airflow. *Journal of Experimental Biology*, 219(7), 937–948. <https://doi.org/10.1242/jeb.126896>
- Yu, Y. S. W., Graff, M. M., & Hartmann, M. J. Z. (2016b). Mechanical responses of rat vibrissae to airflow. *Journal of Experimental Biology*, 219(7), 937–948. <https://doi.org/10.1242/jeb.126896>
- Yuan, P., & Raz, N. (2014). Prefrontal cortex and executive functions in healthy adults: A meta-analysis of structural neuroimaging studies. In *Neuroscience and Biobehavioral Reviews* (Vol.

42, pp. 180–192). Elsevier Ltd. <https://doi.org/10.1016/j.neubiorev.2014.02.005>

Zemla, R., & Basu, J. (2017). Hippocampal function in rodents. In *Current Opinion in Neurobiology* (Vol. 43, pp. 187–197). Elsevier Ltd. <https://doi.org/10.1016/j.conb.2017.04.005>

Zucker, E., & Welker, W. I. (1969). Coding of somatic sensory input by vibrissae neurons in the rat's trigeminal ganglion. *Brain Research*, *12*(1), 138–156. [https://doi.org/10.1016/0006-8993\(69\)90061-4](https://doi.org/10.1016/0006-8993(69)90061-4)