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The Effect of Aerobic Exercise on the Hippocampal Volume of Older Adults

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Abstract: ***The hippocampus is a portion of the brain that encodes memories into long - term storage and tends to see a decline in function with age. As aging is often associated with memory problems (e. g. dementia, Alzheimer's), it is essential to understand how activities people do naturally during their lives may slow or reverse age - related decreases in hippocampal volume. In this literature review, we aim for a better understanding of the role that consistent aerobic exercise plays in slowing the decay of the hippocampus' volume, as well as the effects that age and specific types of exercise have on this relationship. We will review published papers that use observational methods to examine the effects of different kinds of aerobic exercise in individuals' lives on the volume of the hippocampus in relation to total brain volume. We will collect effect size statistics from the relevant published studies to provide quantitative measurements of the impact of aerobic exercise on hippocampal shrinkage. From this point, psychologists and neurologists can better understand what potential interventions may be effective in the reversal of age - related memory decline.***

Keywords: hippocampus, hippocampal volume, aerobic exercise, seniors, older adults, memory

1. Introduction

Evidence from both modern and historical bodies of research consistently shows that regular physical exercise promotes neuroplasticity, improves cognitive function, and reduces the risk of neurodegenerative diseases (Yu et al., 2021; Lenze et al., 2022). Among the various brain regions, the hippocampus—an area essential for memory and learning—has been highlighted as particularly responsive to aerobic exercise. Aerobic exercise is a subcategory of physical exercise that causes an increased breathing and heart rate, named so because it forces the body to take in more oxygen than normal. Walking, cycling, and swimming are common examples of aerobic exercise. This type of exercise has been shown to have significant effects on brain health, particularly in aging individuals. As individuals age, the volume of the hippocampus tends to decrease which contributes to memory decline and cognitive impairments (O'Shea et al., 2016). Emerging evidence suggests that aerobic exercise may attenuate age - associated decrease in hippocampus volume, a phenotype associated with neurodegenerative disease, in addition to reducing memory decline and maintaining cognitive health via promotion of hippocampal growth (Hötting et al., 2013). Thus, understanding the relationship between physical activity, specifically aerobic activity, and hippocampal volume in aging populations could provide critical insights into developing effective interventions to preserve cognitive function in aging populations (Erickson et al., 2011).

Given the growing interest in exercise as a non - pharmacological, behaviorally driven mechanism to enhance brain healthspan, this review aims to explore the role of passive aerobic exercise on hippocampal volume in older adults. This review will focus particularly on the question: *How do different amounts of aerobic exercise in older adults' everyday lives (i. e., without intervention) affect the volume of the hippocampus?* This review will explore findings from a variety of observational studies, focusing on how aerobic exercise specifically impacts cognitive longevity across one's lifespan, and will conclude with a discussion of the utility of widely applicable interventions like aerobic exercise that may be effective for combating age - related cognitive decline and improving quality of life across diverse populations.

Review of Age - Associated Memory Decline vs. Neurodegenerative Disorders

Age - associated memory decline typically begins around the age range of 50 - 60, although the process can vary widely between individuals (Ellison, 2024). Memory changes may be subtle at first, often affecting short - term memory, such as forgetting where objects were placed or missing appointments. In many cases, however, these changes can add up over time. Eventually, the cognitive decline can progress to a pathological state, where constant care must be taken to maintain a level of function. As people age, brain structures like the hippocampus—which is central to memory formation—shrink, and there is a reduction in the production of certain neurotransmitters like dopamine, leading to slower cognitive processing (Peters, 2006). However, consistent mental and physical activity has been shown to slow this decline, potentially aiding in maintenance of cognitive function for longer periods of time. Engaging in regular mental and physical activity early on is crucial, as it can help mitigate hippocampal decline and slow the progression of neurodegenerative changes before they become more severe. These changes to the hippocampus are considered part of normal aging and do not necessarily indicate a pathological state of neurodegenerative disease.

Neurodegenerative diseases like Alzheimer's and Parkinson's typically begin later in life, with Alzheimer's in particular often manifesting after age 65 (Ellison, 2024). These diseases are more severe than normal age - related cognitive decline because they involve the progressive loss of neurons and brain tissue which significantly impair a patient's capacity to function independently. Alzheimer's is characterized by memory loss, confusion, and changes in behavior, while Parkinson's affects movement and can lead to cognitive issues in its later stages (Ellison, 2024). While age is the primary risk factor for pathogenesis of neurodegenerative disease, it is not the sole factor as clinical results have demonstrated that not all aged individuals develop cognitive or motor impairment associated with neurodegenerative disease. Studies suggest that early intervention through physical exercise and cognitive stimulation may help delay or reduce the risk of these conditions (Santos - Lozano et al., 2016). This review examines how aerobic exercise influences normal age - related memory decline through its effects on the hippocampus, rather than focusing solely on its role in reducing the risk of neurodegenerative disease. By highlighting the mechanisms through which aerobic exercise supports hippocampal function and overall brain health, this discussion aims to provide insights into how maintaining this state can inform the development of targeted therapeutic interventions for cognitive aging in the general population.

Importance of Hippocampus in Age - Related Memory Decline

The hippocampus, one of the brain's most adaptable regions, is crucial for memory formation and emotional regulation due to its high neurogenesis level. Neurogenesis, which is the birth of new neurons, is a rare process in adults but is especially prominent in the hippocampus, which makes this region unique and essential for cognitive functioning (Bartsch & Wulff, 2015).

However, as people age, the hippocampus undergoes substantial changes, notably through synaptic loss, where the connections between neurons deteriorate. This synaptic degradation reduces the region's volume and impacts its structural integrity, which can hinder the hippocampus's ability to process and retain information. With aging, this reduced volume is linked to declines in episodic memory, a specific type of long - term memory that allows individuals to recall personal experiences and specific events (Persson et al., 2012). Because episodic memory is fundamental to maintaining personal identity and navigating everyday life, these changes in hippocampal structure have significant cognitive and social implications.

While there is general agreement on the association between hippocampal volume and memory performance, studies present conflicting evidence about the degree of volume reduction that occurs with age. Bettio et al. highlight that hippocampal volume loss in older adults is not uniform, with lifestyle factors, health status, and genetic predispositions affecting the extent of decline (Persson et al., 2012). For instance, some older adults maintain relatively stable hippocampal volumes and episodic memory performance, which suggests that certain protective factors may play a role. Without protective factors, research suggests that the hippocampus reduces in volume by 1.2 - 1.55% per year (Raz et al., 2004; Jack et al., 1998). This loss is associated with episodic memory loss, providing further evidence that the hippocampus's role in memory encoding and retrieval is susceptible to age - related structural changes (Bartsch & Wulff, 2015). However, the exact mechanisms behind these changes remain under investigation, suggesting that more research is needed to determine the consistency of hippocampal shrinkage across both time and individuals and identify ways to mitigate its effects, suggesting that further investigation is required to determine the relationship between external factors across lifespan, hippocampal volume reduction, and age - related memory decline and to identify behavioral therapeutic interventions appropriate for preventing further declines in cognitive function.

Mechanisms by which Aerobic Exercise Affects Hippocampus Volume

Studies have shown that in rat models exercise stimulates neurogenesis, Neurogenesis is a process which promotes the growth of new neurons and enhancement of synaptic plasticity. Neurogenesis occurs primarily in the dentate gyrus, a region of the brain located below the corpus callosum in the medial temporal lobe responsible for sorting spatial memories (van Praag et al., 1999). Neurogenesis is achieved through mechanisms such as increased Brain - Derived Neurotrophic Factor (BDNF) levels, improved cerebral blood flow, and modulation of stress - related hormonal responses, which collectively protect and enhance hippocampal function (Ehrhardt et al., 2024). The increased blood flow to the brain due to the stress of aerobic exercise in particular enhances the effect of these hormonal responses, which leads to the aforementioned increase in neurogenesis (van Praag et al., 1999).

Review of the Assorted Definitions of "Aerobic Exercise"

A variety of methods are used to measure what defines "aerobic exercise, " letting researchers see a wide range of how aerobic exercise impacts central nervous system function. Moderate and high - intensity aerobic exercise are often defined in research using heart rate and oxygen consumption (VO_2) as key metrics. Moderate - intensity aerobic activity is typically characterized by a heart rate that reaches 50–70% of the individual's maximum heart rate (HRmax), calculated as 220 minus their age. It is also associated with an oxygen consumption rate of approximately 40–60% of VO_2 max, which represents the maximum amount of oxygen the body can utilize during exercise.

In contrast, high - intensity aerobic exercise is defined by a heart rate of 70–85% of HRmax and oxygen consumption levels between 60–85% of VO_2 max. These thresholds provide a physiological framework for distinguishing exercise intensities and tailoring regimens to individual capabilities. Studies such as Garber et al. emphasize these metrics to standardize intensity across populations, while clinical trials like Yu et al. use them to assess the effectiveness of interventions (Yu et al., 2021; Garber et al., 1970). By relying on these objective measures, researchers ensure consistency and accuracy when comparing outcomes related to aerobic exercise.

2. Analysis of Studies

Yu et al. implemented a supervised approach to ensure participants followed a consistent exercise intensity, which can be critical in detecting precise changes in hippocampal volume over time (Yu et al., 2021). Johansson et al. compared a more intensive, stationary cycling routine with a less demanding stretching program, providing insight into how aerobic exercise intensity and duration can influence cognitive outcomes (Johansson et al., 2022). Variations in research design clarify the specific modalities and intensities of exercise most beneficial for central nervous system health, additionally providing valuable clinical guidance for exercise recommendations aimed at aging adult populations. Overall, the collective evidence provided by the aforementioned studies highlights the potential of aerobic exercise to preserve cognitive function through neuroprotective effects on the hippocampus, particularly when structured and monitored over extended periods.

In terms of specific timing effects, research suggests that aerobic exercise over 6 months can have beneficial effects on hippocampal volume and cognitive health in aging populations. Yu et al. investigated the impact of aerobic activity on hippocampal structure through a six - month supervised cycling program (Yu et al., 2021). Participants cycled at a moderate intensity for 20–50 minutes, three times a week, resulting in measurable increases in cognitive performance using the AD Assessment Scale - Cognition (ADAS - Cog); discrete cognitive domains were measured using the AD Uniform Data Set battery. (Yu et al., 2021). The ADAS - Cog is a set of 11 tasks that are meant to measure the effect of dementia on certain patients, and gives them a score from 1 - 70, with higher numbers indicating higher cognitive impairment. This approach demonstrated that sustained, moderately - intense aerobic exercise could contribute to improved brain structure and function in older adults. Similarly, Johansson et al. examined how a six - month intervention using stationary home trainers compared to stretching exercises affected both hippocampal volume and central nervous system function. The study found that aerobic activities, such as cycling, appeared to yield better cognitive and brain volume outcomes than stretching alone, underscoring the potential of structured aerobic exercise to enhance hippocampal integrity and reduce age - related memory decline (Johansson et al., 2022). In addition, Erickson et al. used magnetic resonance imaging (MRI) to measure the effects of aerobic exercise against a stretching control group in older adults without dementia. The groups had no significant difference in baseline hippocampal volume, but the researchers found that the "aerobic exercise group demonstrated an increase in the volume of the left and right hippocampus by 2.12% and 1.97%, respectively, over the (1 year) period, whereas the stretching control group displayed a 1.40% and 1.43% decline over this same interval" (Erickson et al., 2011).

Compared to longer durations of aerobic training, exercise that occurs over 60 to 90 days does not appear to have as pronounced an effect on the hippocampus and memory. Niemann et al. conducted a study examining the effects of exercise on the basal ganglia, a brain region critical for motor control and procedural learning, rather than the hippocampus (Niemann et al., 2014). Procedural learning is the process of acquiring procedural memories, which are essentially the knowledge of how to perform a skill (e. g. typing or riding a bicycle). This kind of learning is distinct from episodic memory, which is the ability to remember specific events and information from those events (such as remembering what you had for lunch yesterday). Basal ganglia tend to be more important for procedural memory encoding than episodic, but are nonetheless important for determining cognitive function as it determines the ability to learn new skills over time and retain the ones that have already been learned. The study implemented a 12 - week exercise program involving moderate - intensity aerobic activity and measured its impact on basal ganglia volume using structural brain imaging techniques. While increases in basal ganglia volume were observed, the study found no significant effects on hippocampal structure within the shorter intervention window. This implies that the link between hippocampal volume and aerobic exercise is likely not a perfect correlation, and there are more factors involved in determining whether or not this kind of activity will have an effect on the brain's structure.

In addition, Hotting and Röder explored how various durations of exercise influence neuroplasticity, finding that prolonged aerobic activity facilitates more substantial growth of brain - derived neurotrophic factor (BDNF), a key molecule involved in hippocampal neurogenesis (Hötting et al., 2013). Their meta - analysis emphasized that while even short - term exercise may boost mood and cognitive performance temporarily, structural changes in the brain, particularly in the hippocampus, require sustained engagement in aerobic activity. Furthermore, Santos - Lozano et al. identified similar trends in their study on exercise as a protective factor against Alzheimer's disease, noting that prolonged physical activity contributed to slower hippocampal atrophy and improved memory retention (2016).

Interestingly, the modality of aerobic exercise can influence its impact on the hippocampus. Voluntary running, for example, has demonstrated significant benefits compared to forced or structured activities like routine treadmill walking or electrical muscle stimulation to mimic natural walking gait (Ke et al., 2011). Findings from studies probing animal models suggest that voluntary exercise increases neurogenesis and hippocampal plasticity, potentially due reduced metabolic requirements for CNS processes required to follow a prescription or a non - voluntary prescribed action. Comparatively, moderate - intensity exercises like voluntary walking or cycling have been shown to improve hippocampal health in humans, highlighting the importance of maintaining individual preference in exercise regimens (Yu et al., 2021; Erickson et al., 2011).

The timing of aerobic exercise may also play a role in its effects. Some studies suggest that diurnal exercising during the early part of the day, aligning with the circadian rhythm, may optimize the release of neuroprotective proteins like brain - derived neurotrophic factor (BDNF), compared to evening workouts (Ehrhardt et al., 2024). Other animal models have found that exercise during the dark phase (i. e., the active phase in nocturnal species) enhances hippocampal gene expression (Stranahan et al., 2010). Together, this research suggests that the most effective timing for exercise might depend on individual chronotypes and habits providing further impetus and evidence for future investigations into how chronotypes may impact humans which remains to be discovered.

For older adults (i. e., adults over age 60), aerobic exercise serves as a potent intervention to mitigate age - related hippocampal atrophy, which is associated with cognitive decline and an increased risk of neurodegenerative conditions like Alzheimer's disease. Regular moderate - intensity exercise in this population has been found to not only preserve but also increase hippocampal volume, improving memory performance and overall brain health.

In adults aged 18 to 50, aerobic exercise contributes to maintaining hippocampal integrity, enhancing cognitive flexibility, and preventing age - induced atrophy. This age group benefits from exercise as a tool to counteract the costs of other factors, such as genetic risk for neurodegenerative disease or natural decay due to the aging process and improve academic and workplace productivity through enhanced learning and memory functions.

3. Conclusions

The central role of the hippocampus in memory and its vulnerability to age - related structural decline, while also showcasing the potential of aerobic exercise as a protective measure. The above studies demonstrate that moderate - intensity aerobic activities, such as cycling or walking, performed consistently over at least six months can lead to measurable increases in hippocampal volume and the corresponding cognitive benefits (Yu et al., 2021; Johansson et al., 2022). This neuroplastic response suggests that increase of physical activity, specifically aerobic activities, may counteract the hippocampal shrinkage often seen with aging, offering a non - invasive and accessible strategy to preserve cognitive function. Taken together, these findings provide compelling evidence that aerobic exercise could serve as a cornerstone for prescribing strategies aimed at improving brain health, particularly amongst aged populations of adults who are at increased risk for cognitive decline.

However, several limitations within the existing body of research must be addressed to fully realize the potential of these findings. Selection bias is a notable issue, as most studies have predominantly included White participants, leaving significant gaps in understanding how these interventions might benefit Black, Latino, or other populations which are underrepresented in current data provided from current published research. Additionally, the small sample sizes common to many of these studies reduce their statistical power and limit the reliability of their conclusions across heterogenous populations. Another challenge is the variability in participants' baseline fitness levels and cognitive abilities, which may affect the extent to which individuals benefit from aerobic exercise interventions. This variability raises questions about whether exercise programs could be tailored based on individual differences, such as pre - existing fitness or cognitive capacity in order to maximize therapeutic efficacy. In addition, the participants of the studies tended to be healthy when evaluated (both psychologically and physically), which poses additional questions to evaluate how to translate these findings to be generalized to populations with chronic illness or disabilities. To develop a comprehensive understanding of aging, hippocampal structure, and aerobic exercise in the hopes of mitigating memory and cognitive dysfunction, future research must focus on recruiting larger, more diverse cohorts while standardizing protocols to enhance the reproducibility and applicability of findings.

For individuals, aerobic exercise is a highly effective and accessible way to stave off the almost inevitable decay of cognitive faculties that comes with age. The frequency, cadence, and particularly the duration of exercise are the principal components involved in mitigation of cognitive decline or memory impairment. Thus this review advocates for further inquiry regarding the role of motivation and voluntary action with respect to exercise as a method for reducing memory deficiencies. To address these unresolved questions, it is imperative to design studies based on comprehensive assessment of existing research in order to develop scalable exercise programs that are accessible to all populations, regardless of socioeconomic or cultural background, should be a public health priority. In addition, future studies must make sure to include behavioral and neurological measures within the same population, so that researchers can draw more accurate conclusions about how aerobic exercise is connected to both neural and cognitive changes. For healthcare professionals, this research suggests that encouraging older adults to engage in regular aerobic exercise remains a simple yet evidence - based recommendation to support central nervous system structural integrity associated with health and cognitive function. With advancements in technology, experimental design and capacity to perform meta - analyses on previous findings leading to increased inter - population inclusion, aerobic exercise has the potential to emerge as a robust, widely applicable intervention for combating age - related cognitive decline and improving quality of life across diverse populations.

References

[1] Yu, F., Vock, D. M., Zhang, L., Salisbury, D., Nelson, N. W., Chow, L. S., Smith, G., Barclay, T. R., Dysken, M., & Wyman, J. F. (2021). Cognitive Effects of Aerobic Exercise in Alzheimer's Disease: A Pilot Randomized Controlled Trial. Journal of Alzheimer's disease: *JAD*, 80 (1), 233–244. https: //doi. org/10.3233/JAD - 201100

[2] Lenze, E. J., Voegtle, M., Miller, J. P., Ances, B. M., Balota, D. A., Barch, D., Depp, C. A., Diniz, B. S., Eyler, L. T., Foster, E. R., Gettinger, T. R., Head, D., Hershey, T., Klein, S., Nichols, J. F., Nicol, G. E., Nishino, T., Patterson, B. W., Rodebaugh, T. L., Schweiger, J., … Wetherell, J. L. (2022). Effects of Mindfulness Training and Exercise on Cognitive Function in Older Adults: A Randomized Clinical Trial. *JAMA*, 328 (22), 2218–2229. https: //doi. org/10.1001/jama.2022.21680

[3] Hötting, K., & Röder, B. (2013). Beneficial effects of physical exercise on neuroplasticity and cognition. Neuroscience and biobehavioral reviews, 37 (9 Pt B), 2243–2257. https: //doi. org/10.1016/j. neubiorev.2013.04.005

[4] Erickson, K. I., Voss, M. W., Prakash, R. S., Basak, C., Szabo, A., Chaddock, L., Kim, J. S., Heo, S., Alves, H., White, S. M., Wojcicki, T. R., Mailey, E., Vieira, V. J., Martin, S. A., Pence, B. D., Woods, J. A., McAuley, E., & Kramer, A. F. (2011). Exercise training increases size of hippocampus and improves memory. *Proceedings of the National Academy of Sciences of the United States of America*, 108 (7), 3017–3022. https: //doi. org/10.1073/pnas.1015950108

[5] Loprinzi, P. D., Roig, M., Etnier, J. L., Tomporowski, P. D., & Voss, M. (2021). Acute and Chronic Exercise Effects on Human Memory: What We Know and

Where to Go from Here. *Journal of clinical medicine,* 10 (21), 4812. https: //doi. org/10.3390/jcm10214812

[6] O'Shea, A., Cohen, R. A., Porges, E. C., Nissim, N. R., & Woods, A. J. (2016). Cognitive Aging and the Hippocampus in Older Adults. *Frontiers in aging neuroscience,* 8, 298. https: //doi. org/10.3389/fnagi.2016.00298

[7] Ellison, J. M. (2024, February 9). Alzheimer's vs. Parkinson's: A comparison. *BrightFocus.* https: //www.brightfocus. org/alzheimers/article/alzheimers - and - parkinsons - disease - similarities - and - differences

[8] Santos - Lozano, A., Pareja - Galeano, H., Sanchis - Gomar, F., Quindós - Rubial, M., Fiuza - Luces, C., Cristi - Montero, C., Emanuele, E., Garatachea, N., & Lucia, A. (2016). Physical Activity and Alzheimer Disease: A Protective Association. *Mayo Clinic proceedings*, 91 (8), 999–1020. https: //doi. org/10.1016/j. mayocp.2016.04.024

[9] Bartsch, T., & Wulff, P. (2015). The hippocampus in aging and disease: From plasticity to vulnerability. *Neuroscience,* 309, 1–16. https: //doi. org/10.1016/j. neuroscience.2015.07.084

[10] Bettio, L. E., Rajendran, L., & Gil - Mohapel, J. (2017). The effects of aging in the hippocampus and cognitive decline. Neuroscience & Biobehavioral Reviews, 79, 66 - 86.

[11] Johansson, M. E., Cameron, I. G. M., Van der Kolk, N. M., de Vries, N. M., Klimars, E., Toni, I., Bloem, B. R., & Helmich, R. C. (2022). Aerobic Exercise Alters Brain Function and Structure in Parkinson's Disease: A Randomized Controlled Trial. *Annals of neurology*, *91* (2), 203–216. https: //doi. org/10.1002/ana.26291

[12] Persson, J., Pudas, S., Lind, J., Kauppi, K., Nilsson, L. G., & Nyberg, L. (2012). Longitudinal structure - function correlates in elderly reveal MTL dysfunction with cognitive decline. *Cerebral cortex (New York, N. Y.: 1991), 22* (10), 2297–2304. https: //doi. org/10.1093/cercor/bhr306

[13] Raz, N., Rodrigue, K. M., Head, D., Kennedy, K. M., & Acker, J. D. (2004). Differential aging of the medial temporal lobe. *Neurology*, *62* (3), 433–438. https: //doi. org/10.1212/01. wnl.0000106466.09835.46

[14] Jack, C. R., Petersen, R. C., Xu, Y., O'Brien, P. C., Smith, G. E., Ivnik, R. J., Tangalos, E. G., & Kokmen, E. (1998). Rate of medial temporal lobe atrophy in typical aging and Alzheimer's disease. *Neurology*, *51* (4), 993–999. https: //doi. org/10.1212/wnl.51.4.993

[15] Peters R. (2006). Ageing and the brain. *Postgraduate medical journal*, *82* (964), 84–88. https: //doi. org/10.1136/pgmj.2005.036665

[16] Garber, C. E., Blissmer, Bryan Deschenes, Michael R. Franklin, Barry A. Lamonte, Michael J. Lee, I - Min Nieman, David C. Swain, David P. (1970b, January 1). Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and Neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. Academic Commons. https: //academiccommons. columbia. edu/doi/10.7916/D8CR5T2R

[17] Ke, Z., Yip, S. P., Li, L., Zheng, X. X., & Tong, K. Y. (2011). The effects of voluntary, involuntary, and forced exercises on brain - derived neurotrophic factor and motor function recovery: a rat brain ischemia model. *PloS one*, *6* (2), e16643. https: //doi. org/10.1371/journal. pone.0016643

[18] Niemann, C., Godde, B., Staudinger, U. M., & Voelcker - Rehage, C. (2014). Exercise - induced changes in basal ganglia volume and cognition in older adults. *Neuroscience 281.*

[19] Stranahan, A. M., Lee, K., Becker, K. G., Zhang, Y., Maudsley, S., Martin, B., Cutler, R. G., & Mattson, M. P. (2010). Hippocampal gene expression patterns underlying the enhancement of memory by running in aged mice. *Neurobiology of aging, 31 (11), 1937–1949. https: //doi. org/10.1016/j. neurobiolaging.2008.10.016*

[20] Ehrhardt, M., Schreiber, S., Duderstadt, Y., Braun - Dullaeus, R., Borucki, K., Brigadski, T., Müller, N. G., Leßmann, V., & Müller, P. (2024). Circadian rhythm of brain - derived neurotrophic factor in serum and plasma*. Experimental physiology, 109 (10), 1755–1767. https: //doi. org/10.1113/EP091671*

[21] van Praag, H., Kempermann, G. & Gage, F. (1999). Running increases cell proliferation and neurogenesis in the adult mouse dentate gyrus. *Nat Neurosci 2, 266–270 (1999). https: //doi. org/10.1038/6368*