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Invited Review Article

Exercise is positively associated with cognitive Function: The role of exercise modalities

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Abstract

An increasing number of studies have explored the relationship between exercise and cognitive function. While the majority of studies have focused on the effects of aerobic exercise, some studies have shifted their attention to other exercise modalities such as resistance exercise and Tai Chi Chuan. The purpose of this brief review is to explore the effects of aerobic exercise, resistance exercise, and Tai Chi Chuan on cognitive function by reviewing previous research on each of those exercise modalities and their relationships to cognition, including the potential mechanisms underlying those relationships. Generally speaking, a positive effect of aerobic training on cognitive function is observed. While the research evidence regarding the effects of resistance exercise and Tai Chi Chuan on cognitive function are only somewhat established, their positive trend indicates that future studies are warranted to investigate them further.

Key words: Aerobic Training, Cognitive Function, Exercise Modality, Resistance Training, Tai Chi Chuan

Introduction

Cognitive function declines with advancing age, and while this cognitive decline is most dramatic in later life, the phenomenon is typically observable even in early adulthood, with declines beginning at around 20 years of age (Park et al., 2002; Salthouse, 2004). Cognitive decline is also associated with neurodegenerative disorders such as dementia, Alzheimer's disease, and Parkinson's disease (Kuster et al., 2017; Tonnies & Trushina, 2017; Wu, Lee, & Huang, 2017). Fortunately, according to the cognitive reserve hypothesis, cognitive decline can be prevented or reduced by engaging in exercise in early life that effectively optimizes brain development so as to facilitate neural enrichment, neuroplasticity, and cognitive function (Prince et al., 2015; Tucker & Stern, 2011).

Emerging evidence has demonstrated the positive effects of exercise on cognitive performance (Chang, Pan, Chen, Tsai, & Huang, 2011; Matura et al., 2017; Northey, Cherbuin, Pumpa, Smee, & Rattray, 2017). Recently, several meta-analytic and systematic reviews have further supported the view that cognitive function is facilitated in response to exercise both in the general and in clinical populations (Barha, Falck, Davis, Nagamatsu, & Liu-Ambrose, 2017; Cammisuli, Innocenti, Franzoni, & Pruneti, 2017; Firth et al., 2017; Lewis, Peiris, & Shields, 2017; Northey et al., 2017). The mechanisms underlying

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the effects of exercise on brain activity have been examined through the use of neuroimaging techniques such as event-related potential (ERP) and magnetic resonance imaging (MRI). For example, by using ERP, Chang, Huang, Chen, and Hung (2013) observed that highly fit individuals exhibit larger P3 amplitude and shorter P3 latency, suggesting that fitness is positively associated with the increased allocation of attentional resources and increased stimulus classification speed (Hillman, Castelli, & Buck, 2005). By using fMRI, Prehn et al. (2017) found that aerobic training improves cognitive performance, with the improvement being associated with increased resting-state functional connectivity between the dorsolateral prefrontal cortex and the superior parietal gyrus/precuneus.

Although the relationship between exercise and cognition has been linked, most research has focused on aerobic exercise. It should be noted that one meta-analytic review has indicated that the magnitudes of the effects of exercise on cognition are exercise modality-dependent (Colcombe & Kramer, 2003). Specifically, the review found that the effect size of aerobic exercise was 0.41, while the effect size of aerobic exercise combined with another exercise modality was 0.59. Moreover, there has been particular interest Tai Chi Chuan, a Chinese exercise modality that involves mind-body and multiple-aspect exercise characters (Chang, Nien, Tsai, & Etnier, 2010), as research has revealed that Tai Chi Chuan is as at least as beneficial to cognitive performance as Western forms of exercise (Taylor-Piliae et al., 2010). These findings reflect the importance of examining the role of exercise modality in the relationship between exercise and cognitive function.

The purpose of the present review is to explore the roles that aerobic exercise, resistance exercise, and Tai Chi Chuan play in preserving cognitive function. Specifically, we discuss (a) the effects of aerobic training on cognition and the mechanisms underlying those effects, (b) the effects of resistance exercise on cognition and the mechanisms underlying those effects, and (c) the effects of Tai Chi Chuan on cognition and the mechanisms underlying those effects.

Effects of Aerobic Training/ Aerobic Fitness on Cognition

Behavioral Study

A meta-analysis conducted by Colcombe and Kramer (2003) revealed that enhanced cardiovascular fitness has large beneficial effects on a variety of aspects of cognitive function, with the largest effects being on executive control, a higher process of cognitive function. Masley, Roetzheim, and Gualtieri (2009) conducted an interventional study regarding the dose-response relationship between aerobic training and cognitive function in healthy middle-aged adults. The participants were assigned into a moderately frequent exercise group (3-4 days/week), a highly frequent exercise group (5-7 days/week), and a control group. The findings revealed that aerobic training improves cognitive flexibility and that the magnitude of the effects on cognitive flexibility depends on the frequency of exercise. Lautenschlager et al. (2008) explored the delayed effects of aerobic training on cognition. The participants in an exercise group were instructed to perform a home-based exercise program for six months while a control group only received educational instruction. The results revealed that the exercise group exhibited improvements in cognitive performance and that these positive effects of the exercise persisted for more than 12 months after the treatment. These studies suggest that aerobic exercise training benefits cognitive function.

Neuroelectrical Mechanism

The mechanism underlying the relationship between aerobic training and cognitive performance has been examined through the use of ERP, especially through examining the P3 component. P3 is a large positive deflecting voltage occurring 300-700 ms after the onset of the stimulus. Hillman et al. (2005) assigned participants into four groups: a high-fitness adult group, low-fitness adult group, high-fitness children group, and low-fitness children group. The participants in each group were instructed to perform a stimulus discrimination task. The results revealed that the high-fitness participants had greater P3 amplitudes at Cz and Pz compared to the low-fitness participants, as well as shorter P3 latencies, suggesting that aerobic fitness was positively associated with the better allocation of attentional resources and better stimulus classification, as reflected by the larger P3 amplitudes and shorter P3 latencies, respectively. Similar positive effects of aerobic exercise have also been reported by other ERP-based research (Buck, Hillman, & Castelli, 2008).

Biochemical Mechanism

Matura et al. (2017) focused on the neurometabolic and molecular mechanisms underlying the effects of an aerobic training intervention on older adults. The participants were instructed to perform a cycle program at a moderate intensity for 30 min a day, three days a week, for a total of 12 weeks and were evaluated in terms of their levels of brain-derived neurotrophic factor (BDNF) and grey matter volumes. The results showed that the concentrations of cerebral choline, a marker of neurodegeneration, remained stable in the aerobic training group. However, the serum BDNF concentration level and cortical grey matter volumes were not significantly affected by aerobic training. These findings suggested that aerobic training may be efficient in terms of providing neuroprotection. In contrast, Voss, Vivar, Kramer, and van Praag (2013) indicated that the concentrations of BDNF, insulin-like growth factor 1 (IGF-1), and vascular endothelial growth factor (VEGF), as well as the temporal lobe connectivity between the bilateral parahippocampus and the bilateral middle temporal gyrus, were increased following a 1-year aerobic training intervention in older adults. These inconsistent findings suggest that the biochemical mechanism underlying aerobic training and cognitive function requires further examination.

Effects on Structural and Functional Brain

The first cross-sectional study that investigated the relationship between cardiorespiratory fitness and neural degeneration using voxel-based morphometric techniques was conducted by Colcombe et al. (2003). The authors indicated that higher cardiorespiratory fitness was associated with attenuated loss of brain tissue density due to the process of aging , particularly in fronto-parietal white and gray matter regions such as the prefrontal cortex, superior parietal cortex, and temporal cortex. The positive associations between fitness and these brain regions are important because these region provide the foundation for cognitive function. For example, the prefrontal cortex is an area of the brain that is crucial to cognitive performance (Kao et al., 2013) and the temporal lobes are crucial to long-term memory, whereas atrophy of these areas is associated with Alzheimer’s disease (Frings, Spehl, Weber, Hull, & Meyer, 2013).

Erickson et al. (2011) observed that older adults’ spatial memory was enhanced by aerobic exercise training, and that the volumes of the right and left hippocampus were significantly increased by 1.97% and 2.12%, respectively, following 1 year of aerobic exercise training, whereas the hippocampal volumes in control group participants were decreased. Nevertheless, contrasting findings have also been reported. Thomas et al. (2016) investigated the hippocampal volume response to a shorter 6-week aerobic training, in addition to exploring the issue of whether chronic training has immediate effects or delayed effects as of six weeks after the termination of training. The findings revealed that the hippocampal volume only temporarily increased after the 6-week aerobic training program but returned to its baseline level six weeks after the termination of the aerobic training.

Flodin, Jonasson, Riklund, Nyberg, and Boraxbekk (2017) randomly assigned sixty sedentary but still healthy older adults into either an aerobic exercise group or control group. The participants in the aerobic exercise group were supervised as they performed aerobic exercises, while the participants in the control group performed stretching and toning exercises. Both groups exercised for 30-60 min per day, 3 days a week, for a total of six months. All the participants were also administered cognitive tests including tests of executive function and episodic memory, while their neuroactivity levels were also examined using fMRI. The results showed that the aerobic exercise group exhibited greater aerobic fitness than the control group after the 6-month intervention. There were also positive correlations between aerobic fitness and functional connectivity in terms of increased connectivity between the default mode network and prefrontal cortex, as well as decreased sensorimotor-thalamic connectivity.

Prehn et al. (2017) examined the effects of a six-month aerobic training program on the brain structures of overweight adults, as well as its effects on their resting-state functional connectivity (RSFC), which has been recognized as an indicator of intervention-induced changes. The results revealed that the RSFC in the dorsolateral prefrontal cortex and superior parietal gyrus, brain structures related to executive function and default mode networks, was significantly increased in the adults that underwent aerobic training in comparison to a control group.

Brief Summary

Several lines of evidence have indicated the positive effects of aerobic training on cognitive performance. In addition, the results of various studies have indicated that the effects of aerobic training might be moderated by the amount of exercise. Specifically, training with higher exercise frequency appears to result in greater benefits than training with lower exercise frequency. Moreover, the improvements in executive function and stimulus classification that occur in response to aerobic training appear to result from the enhanced allocation of attentional resources, as reflected by the P3 component. Although the underlying biochemical mechanism requires further examination, the findings from a variety of MRI studies have revealed that aerobic training or higher aerobic fitness is associated with enhanced activation or increased volumes in particular brain regions (e.g., the prefrontal cortex, superior parietal cortex, dorsolateral prefrontal cortex, superior parietal gyrus, temporal cortex, and hippocampus), providing further support for the conclusion that aerobic training has positive effects on cognitive function.

Effects of Resistance Training on Cognition

Behavioral Study

While the literature examining the effects of exercise on cognition has focused frequently on aerobic exercise, an increasing number of studies in recent decades have investigated the effects of resistance exercise on cognitive function (Chang, Labban, Gapin, & Etnier, 2012; Chang, Tsai, Huang, Wang, & Chu, 2014; Dunsky et al., 2017; Hsieh, Chang, Hung, & Fang, 2016; Perrig-Chiello, Perrig, Ehrsam, Staehelin, & Krings, 1998).

Perrig-Chiello et al. (1998) indicated that an eight-week resistance-training program improved the free recall of the exercise group compared to a control group. Cassilhas et al. (2007) examined the effects of different intensities of resistance exercise on cognition, and explored the mechanisms (i.e., IGF-1) underlying the effects of resistance exercise. The participants were randomly assigned to one of three treatment conditions for 24 weeks: a high-intensity exercise group (80% of one-repetition maximum, 1RM), moderate-intensity exercise group (50% of 1RM), and control group. The executive function, short-term memory, visual modality of short-term memory, attention, and long-term episodic memory of the participants were assessed both before and after the 24-week treatments. The findings indicated that both exercise groups demonstrated superior cognitive performance compared to the control group, regardless of the exercise intensity. Additionally, increased IGF-1 levels induced by the exercise may be the biochemical mechanism responsible for these effects.

In another study, however, Kimura et al. (2010) investigated the effects of a 12-week resistance training program on cognition and health-related quality of life in older adults. The participants were assigned either to a resistance training group that exercised for 1.5 hours per session, twice a week, at a moderate intensity (60% of 1RM) for 3 months, or to a control group that received health education. The results revealed that the effect of resistance training on cognition was rather limited.

Effects on Structural and Functional Brain

A recent study examined the effects of strength training on hippocampal volume (Kim, Shin, Hong, & Kim, 2017). The participants in the resistance-training group performed resistance exercises for 50-80 min a day, three times a week, for a total of 24 weeks. The results revealed that the hippocampal volumes of these participants were significantly increased after the 24-week resistance training program, while those of the control group were significantly decreased.

Meanwhile, an empirical randomized controlled trial examined the relationship between resistance training and cognitive performance in older adults using fMRI screening (Liu-Ambrose, Nagamatsu, Voss, Khan, & Handy, 2012). The participants were assigned into one of the three groups. The participants in the exercise group 1 were instructed to perform resistance exercises once a week for 12 months (RT1 group), those in the exercise group 2 were instructed to perform resistance exercises twice a week for 12 months (RT2 group), and those in the control group were instructed to perform two-weekly balance and tone exercises for 12 months (BAT group). The results revealed that positive effects of RT2 were found on flanker task performance but that no such effects were found for RT1 and BAT groups. The RT2 group exhibited greater activation in the left anterior insula extending into lateral orbital frontal cortex and the anterior portion of the left medial temporal gyrus compared to the control group. These findings suggested that resistance training positively influences the functional plasticity in the cortex related to cognitive task assessments as well as to cognitive performance.

Brief Summary

Studies on the link between resistance exercise and cognitive function have been attracting increasing attention recently, however, the evidence regarding its association is somewhat inconsistent. One reason for these inconsistent results may be that the duration of training, where some studies may be too short to exhibit the effect. It should be noted that, however, resistance exercise may be linked to cognitive function through changed specific brain volumes and functional plasticity, and these research trend is worth to consider in the future.

Effects of Tai Chi Chuan on Cognition

Tai Chi Chuan is a traditional Chinese martial arts and a form of mind-body exercise (Chang et al., 2010). Given that exercises involving greater physical and cognitive demands may yield greater benefits to cognitive function (Dai, Chang, Huang, & Hung, 2013), it is suggested that Tai Chi Chuan may have a greater effect on cognitive function because it involves various abilities, including postural control, flexibility, mobility, coordination, and meditation, which have been linked to cognitive functions of different levels (Chang, Nien, Chen, & Yan, 2014; Wei et al., 2013)

Behavioral Study

Taylor-Piliae et al. (2010) compared the effects of Tai Chi and Western forms of exercise on cognition in older adults. The exercise interventions were separated into two phases, with each phase lasting 6 months. The adoption phase consisted of two class-based exercise sessions and three home-based exercise sessions, with each session lasting 60 min. The maintenance phase consisted of one class-based exercise session and three home-based exercise sessions. The participants in the Tai Chi group were instructed to perform the Yang short-form style of Tai Chi while the participants in the Western exercise group were instructed to perform endurance, resistance, and flexibility exercises. The participants in the control group were asked to meet once a week for approximately 90 min and were taught about reading food labels and selecting produce. The results showed that the Tai Chi group exhibited greater ability in balance and better cognitive performance compared to the Western exercise group and the control group, and that the benefits of Tai Chi were continuously maintained over 12 months. It is noteworthy that cognitive performance in the Western exercise group was not superior compared to the control group. Their failure to find any changes in the cognitive performance of the Western exercise group might be due to the fact that the participants had relatively high levels of physical and cognitive function. Furthermore, the findings of better cognitive performance in the Tai Chi group suggested that Tai Chi might have additional benefits stemming from the particular demands during perfroming the exercise, such as concentration.

Neuroelectrical Mechanism

Using a cross-sectional design, Fong, Chi, Li, and Chang (2014) recruited 48 older adults with ages ranging from 65 to 75 years old and 16 young adults with ages ranging from 20 to 30 years old and assigned these participants into four groups based on their age and experience of physical activity. The older adults regularly performed a specific modality of exercise at least three times per week, 30 min per session, for five years. The participants in the older adults endurance exercise (OEE) group were older adults who performed regularly endurance exercise, in the older adults Tai Chi (OTC) group were older adults who performed regularly Tai Chi, in the older adult sedentary lifestyle (OSL) group were older adults with a sedentary lifestyle, and in the YA group were young adults. The results revealed that the YA group had the shortest reaction time (that is, compared to the other three groups with older adults); however, OSL group had the longest reaction time. In terms of ERP data, the YA, OEE, and OTC groups had larger P3 amplitudes compared to the OSL group in both conditions through task-switching. These findings suggest the positive association between exercise on the behavioral and neurophysiological aspects of cognitive performance is regardless of the exercise modality (i.e., aerobic exercise and Tai Chi Chuan).

Effects on Structural Brain

Wei et al. (2013) explored the effects of Tai Chi on brain structures. The findings revealed that the participants who had an average of 14-year regular Tai Chi Chuan practice experience had thicker cortex in the precentral gyrus, insula sulcus, and middle frontal sulcus in the right hemisphere and in the superior temporal gyrus and medial occipito-temporal sulcus and lingual sulcus in the left hemisphere. Furthermore, Tao et al. (2017) indicated that 12-week Tai Chi training significantly improved visual reproduction as assessed by the Wechsler Memory Scale-Chinese revised, in addition to resulting in increased grey matter volume in the insula, medial temporal lobe, and putamen. The researchers suggested that Tai Chi Chuan may prevent memory deficits through these changes in brain structures. Interestingly, a meta-analytic review demonstrated that healthy adults exhibit larger effects from Tai Chi on executive function, while older adults with cognitive impairment had positive effects from Tai Chi Chuan on global cognitive function (Wayne et al., 2014).

Brief Summary

A few studies has started to examine the Tai Chi Chuan and cognitive function. Based upon these small amount of studies, Tai Chi Chuan not only positively associated with postural control, flexibility, mobility, coordination, and meditation, but also linked positively to cognitive function. While whether Tai Chi Chuan has additional effect on cognitive function and brain reminds further examination, Tai Chi Chuan at least has similar effect as western style exercise, suggesting the type of modality could be one of candidate treatments.

Conclusion

Most relevant studies have found that aerobic training has positive effects on cognitive performance. In addition, some research has suggested that the effects of aerobic training might be moderated by exercise frequency. The improvements in executive function and stimulus classification that occur in response to aerobic training might be as the result of the enhanced allocation of attentional resources or enhancing activation or increased volumes in particular brain regions, such as the prefrontal cortex, superior parietal cortex, dorsolateral prefrontal cortex, superior parietal gyrus, temporal cortex, and hippocampus. A few studies have examined other types of exercise modalities. The research evidence regarding resistance training has been inconsistent and the short duration of this type of training may be a reason. However, the link between resistance exercise and cognitive function, as observed via changes in the structural and functional brain, seems to be a promising field and requires further examination. Like western style exercise, Tai Chi Chuan is also linked positively to cognitive function as well as the structural and functional brain. These research findings suggest that the relationship between exercise and cognitive function from the perspective of exercise modality warrants further investigation.

Reference

Barha, C. K., Falck, R. S., Davis, J. C., Nagamatsu, L. S., & Liu-Ambrose, T. (2017). Sex differences in aerobic exercise efficacy to improve cognition: A systematic review and meta-analysis of studies in older rodents. Frontiers in Neuroendocrinology, **46**, 86-105. doi:10.1016/j.yfrne.2017.06.001

Buck, S. M., Hillman, C. H., & Castelli, D. M. (2008). The relation of aerobic fitness to stroop task performance in preadolescent children. Medicine and Science in Sports and Exercise, **40**(1), 166-172. doi:10.1249/mss.0b013e318159b035 [doi]

Cammisuli, D. M., Innocenti, A., Franzoni, F., & Pruneti, C. (2017). Aerobic exercise effects upon cognition in Mild cognitive impairment: A systematic review of randomized controlled trials. Archives Italiennes de Biologie, **155**(1-2), 54-62. doi:10.12871/000398292017126

Cassilhas, R. C., Viana, V. A., Grassmann, V., Santos, R. T., Santos, R. F., Tufik, S., & Mello, M. T. (2007). The impact of resistance exercise on the cognitive function of the elderly. Medicine and Science in Sports and Exercise, **39**(8), 1401-1407. doi:10.1249/mss.0b013e318060111f

Chang, Y. K., Huang, C. J., Chen, K. F., & Hung, T. M. (2013). Physical activity and working memory in healthy older adults: An ERP study. Psychophysiology, **50**(11), 1174-1182. doi:10.1111/psyp.12089

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. Brain Research, **1453**, 87-101. doi:10.1016/j.brainres.2012.02.068

Chang, Y. K., Nien, Y. H., Chen, A. G., & Yan, J. (2014). Tai Ji Quan, the brain, and cognition in older adults. Journal of Sport and Health Science, **3**(1), 36-42. doi:10.1016/j.jshs.2013.09.003

Chang, Y. K., Nien, Y. H., Tsai, C. L., & Etnier, J. L. (2010). Physical activity and cognition in older adults: The potential of Tai Chi Chuan. Journal of Aging and Physical Activity, **18**(4), 451-472.

Chang, Y. K., Pan, C. Y., Chen, F. T., Tsai, C. L., & Huang, C. C. (2011). Effect of resistance exercise training on cognitive function in healthy older adults: A review. Journal of Aging and Physical Activity, **20**(4), 497-517. doi:10.1123/japa.20.4.497

Chang, Y. K., Tsai, C. L., Huang, C. C., Wang, C. C., & Chu, I. H. (2014). Effects of acute resistance exercise on cognition in late middle-aged adults: General or specific cognitive improvement? Journal of Science and Medicine in Sport, **17**(1), 51-55. doi:10.1016/j.jsams.2013.02.007

Colcombe, S., Erickson, K. I., Raz, N., Webb, A. G., Cohen, N. J., McAuley, E., & Kramer, A. F. (2003). Aerobic fitness reduces brain tissue loss in aging humans. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences., **58**(2), 176-180. doi:10.1093/gerona/58.2.M176

Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: A meta-analytic study. Psychological Science, **14**(2), 125-130. doi:10.1111/1467-9280.t01-1-01430

Dai, C. T., Chang, Y. K., Huang, C. J., & Hung, T. M. (2013). Exercise mode and executive function in older adults: An ERP study of task-switching. Brain and Cognition, **83**(2), 153-162. doi:10.1016/j.bandc.2013.07.007

Dunsky, A., Abu-Rukun, M., Tsuk, S., Dwolatzky, T., Carasso, R., & Netz, Y. (2017). The effects of a resistance vs. an aerobic single session on attention and executive functioning in adults. PLoS One, **12**(4), e0176092. doi:10.1371/journal.pone.0176092

Erickson, K. I., Voss, M. W., Prakash, R. S., Basak, C., Szabo, A., Chaddock, L., . . . 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. doi:10.1073/pnas.1015950108

Firth, J., Stubbs, B., Rosenbaum, S., Vancampfort, D., Malchow, B., Schuch, F., . . . Yung, A. R. (2017). Aerobic exercise improves cognitive functioning in people with Schizophrenia: A systematic review and meta-analysis. Schizophrenia Bulletin, **43**(3), 546-556. doi:10.1093/schbul/sbw115

Flodin, P., Jonasson, L. S., Riklund, K., Nyberg, L., & Boraxbekk, C. J. (2017). Does aerobic exercise influence intrinsic brain activity? An aerobic exercise intervention among healthy old adults. Frontiers in Aging Neuroscience, **9**, 267. doi:10.3389/fnagi.2017.00267

Fong, D. Y., Chi, L. K., Li, F., & Chang, Y. K. (2014). The benefits of endurance exercise and Tai Chi Chuan for the task-switching aspect of executive function in older adults: An ERP study. Frontiers in Aging Neuroscience, **6**, 295. doi:10.3389/fnagi.2014.00295

Frings, L., Spehl, T. S., Weber, W. A., Hull, M., & Meyer, P. T. (2013). Amyloid-beta load predicts medial temporal lobe dysfunction in Alzheimer dementia. Journal of Nuclear Medicine, **54**(11), 1909-1914. doi:10.2967/jnumed.113.120378

Hillman, C. H., Castelli, D. M., & Buck, S. M. (2005). Aerobic fitness and neurocognitive function in healthy preadolescent children. Medicine and Science in Sports and Exercise, **37**(11), 1967-1974. doi:10.1249/01.mss.0000176680.79702.ce

Hsieh, S. S., Chang, Y. K., Hung, T. M., & Fang, C. L. (2016). The effects of acute resistance exercise on young and older males' working memory. Psychology of Sport and Exercise, **22**, 286-293. doi:10.1016/j.psychsport.2015.09.004

Kao, Y. C., Liu, Y. P., Lien, Y. J., Lin, S. J., Lu, C. W., Wang, T. S., & Loh, C. H. (2013). The influence of sex on cognitive insight and neurocognitive functioning in schizophrenia. Progress in Neuro-Psychopharmacology and Biological Psychiatry, **44**, 193-200. doi:10.1016/j.pnpbp.2013.02.006

Kim, Y. S., Shin, S. K., Hong, S. B., & Kim, H. J. (2017). The effects of strength exercise on hippocampus volume and functional fitness of older women. Experimental Gerontology, **97**, 22-28. doi:10.1016/j.exger.2017.07.007

Kimura, K., Obuchi, S., Arai, T., Nagasawa, H., Shiba, Y., Watanabe, S., & Kojima, M. (2010). The influence of short-term strength training on health-related quality of life and executive cognitive function. Journal of Physiological Anthropology, **29**(3), 95-101. doi:10.2114/jpa2.29.95

Kuster, O. C., Laptinskaya, D., Fissler, P., Schnack, C., Zugel, M., Nold, V., . . . von Arnim, C. A. F. (2017). Novel blood-based biomarkers of cognition, stress, and physical or cognitive training in older adults at risk of dementia: Preliminary evidence for a role of BDNF, irisin, and the kynurenine pathway. Journal of Alzheimer's Disease, **59**(3), 1097-1111. doi:10.3233/jad-170447

Lautenschlager, N. T., Cox, K. L., Flicker, L., Foster, J. K., van Bockxmeer, F. M., Xiao, J., . . . Almeida, O. P. (2008). Effect of physical activity on cognitive function in older adults at risk for Alzheimer disease: A randomized trial. Jama, **300**(9), 1027-1037. doi:10.1001/jama.300.9.1027

Lewis, M., Peiris, C. L., & Shields, N. (2017). Long-term home and community-based exercise programs improve function in community-dwelling older people with cognitive impairment: A systematic review. Journal of Physiotherapy, **63**(1), 23-29. doi:10.1016/j.jphys.2016.11.005

Liu-Ambrose, T., Nagamatsu, L. S., Voss, M. W., Khan, K. M., & Handy, T. C. (2012). Resistance training and functional plasticity of the aging brain: A 12-month randomized controlled trial. Neurobiology of Aging, **33**(8), 1690-1698. doi:10.1016/j.neurobiolaging.2011.05.010

Masley, S., Roetzheim, R., & Gualtieri, T. (2009). Aerobic exercise enhances cognitive flexibility. Journal of Clinical Psychology in Medical Settings, **16**(2), 186-193. doi:10.1007/s10880-009-9159-6

Matura, S., Fleckenstein, J., Deichmann, R., Engeroff, T., Füzéki, E., Hattingen, E., . . . Pantel, J. (2017). Effects of aerobic exercise on brain metabolism and grey matter volume in older adults: Results of the randomised controlled SMART trial. Translational Psychiatry, **7**(7), e1172. doi:10.1038/tp.2017.135

Northey, J. M., Cherbuin, N., Pumpa, K. L., Smee, D. J., & Rattray, B. (2017). Exercise interventions for cognitive function in adults older than 50: A systematic review with meta-analysis. British Journal of Sports Medicine. doi:10.1136/bjsports-2016-096587

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. Psychology and Aging, **17**(2), 299-320. doi:10.1037/0882-7974.17.2.299

Perrig-Chiello, P., Perrig, W. J., Ehrsam, R., Staehelin, H. B., & Krings, F. (1998). The effects of resistance training on well-being and memory in elderly volunteers. Age Ageing, **27**(4), 469-475. doi:10.1093/ageing/27.4.469

Prehn, K., Lesemann, A., Krey, G., Witte, A. V., Kobe, T., Grittner, U., & Floel, A. (2017). Using resting-state fMRI to assess the effect of aerobic exercise on functional connectivity of the DLPFC in older overweight adults. Brain and Cognition. doi:10.1016/j.bandc.2017.08.006

Prince, M. J., Wu, F., Guo, Y., Gutierrez Robledo, L. M., O'Donnell, M., Sullivan, R., & Yusuf, S. (2015). The burden of disease in older people and implications for health policy and practice. Lancet, **385**(9967), 549-562. doi:10.1016/s0140-6736(14)61347-7

Salthouse, T. A. (2004). What and when of cognitive aging. Current Directions in Psychological Science, **13**(4), 140-144. doi:10.1111/j.0963-7214.2004.00293.x

Tao, J., Liu, J., Liu, W., Huang, J., Xue, X., Chen, X., . . . Kong, J. (2017). Tai Chi Chuan and Baduanjin increase grey matter volume in older adults: A brain imaging study. Journal of Alzheimer's Disease. doi:10.3233/jad-170477

Taylor-Piliae, R. E., Newell, K. A., Cherin, R., Lee, M. J., King, A. C., & Haskell, W. L. (2010). Effects of Tai Chi and Western exercise on physical and cognitive functioning in healthy community-dwelling older adults. Journal of Aging and Physical Activity, **18**(3), 261-279. doi:10.1123/japa.18.3.261

Thomas, A. G., Dennis, A., Rawlings, N. B., Stagg, C. J., Matthews, L., Morris, M., . . . Johansen-Berg, H. (2016). Multi-modal characterization of rapid anterior hippocampal volume increase associated with aerobic exercise. NeuroImage, **131**, 162-170. doi:10.1016/j.neuroimage.2015.10.090

Tonnies, E., & Trushina, E. (2017). Oxidative stress, synaptic dysfunction, and Alzheimer's disease. Journal of Alzheimer's Disease. doi:10.3233/jad-161088

Tucker, A. M., & Stern, Y. (2011). Cognitive reserve in aging. Current Alzheimer Research, **8**(4), 354-360. doi:10.2174/156720511795745320

Voss, M., W., Vivar, C., Kramer, A. F., & van Praag,

H. (2013). Bridging animal and human models of exercise-induced brain plasticity. Trends in Cognitive Sciences, **17**(10), 525-544. doi:10.1016/j.tics.2013.08.001

Wayne, P. M., Walsh, J. N., Taylor-Piliae, R. E., Wells, R. E., Papp, K. V., Donovan, N. J., & Yeh, G. Y. (2014). The impact of Tai Chi on cognitive performance in older adults: A systematic review and meta-analysis. Journal of the American Geriatrics Society, **62**(1), 25-39. doi:10.1111/ jgs.12611

Wei, G. X., Xu, T., Fan, F. M., Dong, H. M., Jiang, L. L., Li, H. J., . . . Zuo, X. N. (2013). Can Taichi reshape the brain? A brain morphometry study. PLoS One, **8**(4), e61038. doi:10.1371/journal.pone.0061038

Wu, P. L., Lee, M., & Huang, T. T. (2017). Effectiveness of physical activity on patients with depression and Parkinson's disease: A systematic review. PLoS One, **12**(7), e0181515. doi:10.1371/journal.pone.0181515