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Roles of Physical Activity and Nutritional Patterns in Optimizing Cognitive Function, Enhancing Neuroplasticity, and Preventing Cognitive Decline across the Lifespan

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ABSTRACT

Modern neuroscience increasingly recognizes the critical roles of both diet and physical activity in promoting cognitive function and brain plasticity. While exercise has been widely acknowledged as a modulator of neurogenesis and synaptic function, nutritional patterns also significantly affect neurochemical balance, inflammatory processes, and neuronal integrity. There are multiple brain functions for example development and maintenance of brain functions, memory and learning process, the healing process of brain damage and environmental adaption, all depend completely on neuroplasticity. In this review, we examine the enormous potential of neuroplasticity in relation to several facets of brain function in both the setting of sickness and throughout life. We'll also go over how the aging brain changes and how important neuroplasticity is for preserving cognitive function as we age. This review consolidates recent evidence on the synergistic effects of diet and exercise in enhancing cognitive performance and structural brain plasticity. The combination of nutrition and exercise provides a potent remedy for mental well-being and aging longevity. We may develop a robust mind and give our lives more vitality and meaning by adopting an active lifestyle and practicing mindful eating. Drawing from human clinical trials, epidemiological data, and mechanistic animal studies, we explore the biological pathways involved, including neurotrophin regulation, oxidative stress modulation, and gut-brain interactions. The review article concludes by discussing translational implications and proposing integrated lifestyle strategies for lifelong cognitive health.

INTRODUCTION

Neuroplasticity is defined as the ability of brain to adapt and identify itself in response to internal and external stimuli, plays a basic important role in learning, memory, and recovery from injury [1]. Cognitive decline, traditionally associated with aging and neurodegenerative diseases, is now increasingly understood to be influenced by modifiable lifestyle factors such as diet and physical activity [2,4]. Emerging research highlights that these lifestyle components can influence brain function through shared mechanisms including synaptic remodeling, neurotrophin regulation, and inflammation control [5,7]. The synergistic potential of diet and exercise, when implemented together, may offer more robust neuroprotective benefits than either alone [8,9].

Due to the complexity of neuroplasticity, the composition and outcome of the brain can be impacted by multiple types of plasticity. Structural neuroplasticity is the capability of the brain to adjust to changing experiences and environments through changes in the quantity, form, strength, and connectivity of synapses as well as other physical properties of neurons and neural networks. Numerous investigations have shown that this structural plasticity occurs during expansion and carry on with until maturity. Functional neuroplasticity, on the contrary, refers to modifications in neural network properties like synaptic synchronization, firmness, and efficiency. Numerous behavioral and cognitive processes related to perception, memory, and attention are altered by rapid functional plasticity [51].

A growing body of research suggests that physical activity (PA) may improve cognition, provide protection against neurodegenerative diseases like AD and PD, and lower the incidence and severity of numerous psychological conditions, including common mood disorders, anxiety, and depression. PA also has positive effects on brain health at all stages of life. In the past, physical activity was believed to indirectly influence these results by lowering the incidence of diseases like obesity, diabetes, cardiovascular disease, and cancer that can impair brain function. But mounting data from research on humans and animals shows PA also plays a more direct role, improving brain health by affecting both structure and function. Potential pathways through which PA may affect brain health include stress, inflammation, insulin sensitivity, neurotrophic factors, and cardiovascular health.

Additionally, PA is believed to support neurogenesis, or the production of new neurons, and neuroplasticity, or the brain's capacity to continuously adapt throughout life.

METHODOLOGY

This review employed a narrative methodology, sourcing literature from databases including PubMed, ScienceDirect, Scopus, and Google Scholar. Search terms included "exercise," "physical activity," "diet," "nutrition," "cognitive function," "neuroplasticity," "brain health," and "neurotrophic factors." Peer-reviewed articles from 2000 to 2023 were considered, with a focus on studies published in the last 10 years. Inclusion criteria encompassed both human and animal studies, relevance to diet and exercise as they relate to cognition, and publication in English [10,12]. A total of 50 articles were selected after careful screening and quality appraisal using the PRISMA guidelines [13].

Diet and Cognitive Function

Macronutrients and Brain Metabolism

Macronutrients especially omega-3 fatty acids and complex carbohydrates play critical roles in supporting neuronal membrane integrity and neurotransmission [14]. Deficiencies in essential fatty acids like DHA have been linked to reduced cognitive performance and increased risk of psychiatric disorders [15,16]. Docosahexaenoic acid which is a type of omega 3 fatty acid are core components of neuronal membranes, influencing fluidity and receptor function. Adequate intake of complex carbohydrates ensures a steady supply of glucose, the primary energy source for the brain, thereby supporting optimal cognitive performance.

Micronutrients and Neuroprotection

Minerals and vitamins include zinc, magnesium, vitamin D, and B-complex vitamins support neurogenesis, antioxidant defense, and neural transmission [17, 18]. The metabolism of homocysteine depends on B vitamins, such as B6, B9 (folate), and B12; high homocysteine levels are linked to cognitive deterioration. The brain contains many vitamin D receptors, and a lack of this vitamin has been connected to cognitive decline. Deficits in magnesium and zinc may result in cognitive deficits since these elements are important for synaptic transmission and plasticity. [19].

Dietary Patterns

The antioxidant and anti-inflammatory qualities of the Mediterranean diet have been repeatedly associated with decreased risks of Alzheimer's disease and cognitive decline [20,21]. This diet places a modest emphasis on eating fish and chicken and encourages the consumption of fruits, vegetables, whole grains, legumes, nuts, and olive oil. In older populations, the MIND diet, which combines aspects of the DASH and Mediterranean diets, is also associated with improved cognitive results [22]. It emphasizes the significance of berries and green leafy vegetables in particular, as they are high in nutrients that are good for brain function.

Exercise and Neuroplasticity

Structural and Functional Brain Changes

Physical activity, particularly aerobic exercise, has been associated with increased hippocampal volume, improved connectivity between brain regions, and enhanced memory [23,25]. Regular aerobic exercise promotes angiogenesis, leading to improved cerebral blood flow and oxygen delivery, which are critical for maintaining neuronal health and function.

Molecular Mechanisms

Exercise stimulates multiple molecular mechanisms including brain-derived neurotrophic factor, insulin-like growth factor-1, and vascular endothelial growth factor, which collectively support synaptic plasticity and neurogenesis [26,28]. Brain-derived neurotrophic factor in particular, plays a pivotal role in supporting the survival of existing neurons and encouraging the growth and differentiation of new neurons and synapses.

Cognitive Outcomes

Clinical studies reveal that moderate-to-vigorous physical activity significantly improves executive functions such as attention, working memory, and processing speed, especially in aging populations [29,31]. These cognitive enhancements are attributed to the neurobiological changes induced by regular physical activity, including increased neurogenesis and synaptic plasticity.

Functional Neuroplasticity

It is believed that memory formation, skill development, and injury recovery are all influenced by functional neuroplasticity. Long-term potentiation (LTP), the continuous strengthening of synapses in response to repeated stimulation, is an illustration of functional neuroplasticity. One of the main mechanisms governing memory and learning is believed to be LTP. On the other hand, long-term depression (LTD) affects memory and learning and is characterized by a chronic weakening of synapses.

Cortical rearrangement, the process by which experience or injury can alter the brain's sensory maps, is another illustration of functional neuroplasticity. Gaining new skills alters the functional connectivity of the brain regions related to attention, motor control, and sensory processing. For instance, because to brain remodelling, blind people may have improved sensory processing in other modalities, like touch and hearing [51].

Synergistic Effects of Diet and Exercise

The combined application of dietary and exercise-based interventions has consistently demonstrated superior cognitive benefits when compared to isolated strategies. Among the most compelling evidence is the Finnish Geriatric Intervention Study to Prevent Cognitive Impairment and Disability (FINGER), a landmark randomized controlled trial which revealed that older adults receiving coordinated guidance on nutrition, exercise, cognitive training, and vascular risk monitoring exhibited significantly improved cognitive function over two years, relative to controls [32]. This multidomain approach reinforces the hypothesis that diet and exercise act not merely in parallel but synergistically. The integration of aerobic and resistance training with adherence to dietary patterns rich in unsaturated fats, polyphenols, and micronutrients provides complementary stimuli to neural plasticity pathways, resulting in enhanced memory, executive function, and processing speed [32].

Exercise and dietary interventions converge on several molecular and systemic pathways that underpin brain function. Both elevate levels of brain-derived neurotrophic factor (BDNF), which plays a critical role in synaptic plasticity, dendritic arborization, and neurogenesis, particularly in the hippocampus [33]. Concurrently, both modalities attenuate neuroinflammatory processes by reducing pro-inflammatory cytokines such as TNF-α and IL-6 [34]. Additionally, these interventions bolster antioxidant defense mechanisms and upregulate enzymes such as superoxide dismutase and glutathione peroxidase, thereby mitigating oxidative damage to neuronal membranes and DNA [35]. A growing body of research also implicates modulation of the gut-brain axis, whereby both physical activity and dietary fibers, polyphenols, and fermented foods modulate microbial diversity and short-chain fatty acid production, influencing cognition via epigenetic and neuroimmune signaling pathways [36].

Preclinical studies further validate the additive benefits of combining physical activity with dietary modifications. In rodent models, the pairing of voluntary wheel running with polyphenol- rich diets (e.g., blueberries, green tea catechins) produced a more robust increase in hippocampal neurogenesis and dendritic complexity than either intervention alone [37]. These animals also displayed superior performance in spatial memory tasks such as the Morris water maze, suggesting a synergistic enhancement of both cellular plasticity and cognitive function. Moreover,

markers synaptic integrity, such as synapsin-I and PSD-95, were elevated in these combination groups, indicating greater functional connectivity in brain regions critical for learning and memory [37].

Age-Specific and Population-Specific Effects

During periods of rapid brain development, such as childhood and adolescence, the brain exhibits heightened sensitivity to environmental inputs, including nutrition and exercise. Studies have demonstrated that children consuming balanced diets high in omega-3 fatty acids, whole grains, and fruits, alongside engaging in regular physical activity, perform better in cognitive tasks, particularly in areas involving attentional control, working memory, and academic achievement [38]. Longitudinal research supports the notion that early interventions emphasizing both structured physical activity and healthy eating habits are associated with sustained cognitive benefits, and may reduce the risk of behavioral disorders and metabolic syndromes in later life [39].

In middle-aged populations, the combination of aerobic training and adherence to Mediterranean or DASH dietary patterns has been shown to preserve cognitive faculties, particularly executive functions and verbal memory [40]. As aging is associated with increased oxidative stress and vascular rigidity, lifestyle interventions targeting cardiovascular health also confer neurological protection. Older adults engaging in 150 minutes of moderate-intensity exercise per week, combined with nutrient-dense meals (including antioxidants, flavonoids, and polyunsaturated fatty acids), display slower rates of age-related cortical thinning and reduced hippocampal atrophy [41]. These interventions not only improve cognition but also reduce the incidence of frailty, depression, and insulin resistances, all of which are associated with cognitive decline.

Among individuals at risk for or already experiencing neurodegenerative disorders such as Alzheimer's disease or mild cognitive impairment (MCI), multidomain interventions have demonstrated encouraging outcomes. The MAPT and PreDIVA trials support the effectiveness of combining physical activity with nutritional counseling in delaying cognitive deterioration in aging populations [42]. Mechanistically, such approaches influence mitochondrial biogenesis, neurovascular coupling, and the clearance of neurotoxic proteins. For instance, both dietary polyphenols and aerobic exercise have been shown to reduce amyloid-beta plaque accumulation and tau hyperphosphorylation in transgenic mouse models of Alzheimer's disease [43]. Clinical trials also report improvement in cognitive assessments such as MMSE and ADAS-Cog following these interventions [44].

Adult Neurogenesis

Although American neuroscientist Joseph Altman's groundbreaking research in the 1960s provided the first evidence in favor of adult neurogenesis, it wasn't until the mid-1990s that this phenomenon gained widespread acceptance after Eriksson et al. (1998) showed that newly generated neurons in the human hippocampal dentate gyrus contained bromodeoxyuridine (BrdU, a nucleotide analog) in their DNA. Since then, a number of studies have established that neural stem cells do exist in both juvenile and adult brains and that neurogenesis still takes place in a few specific areas of the adult mammalian brain. The most significant and extensively researched of these areas are the subventricular zone (SVZ) of the lateral ventricles and the subgranular zone (SGZ) of the hippocampus dentate gyrus. Other brain regions, known as "noncanonical" neurogenic areas, such as the striatum, neocortex, amygdala, cerebellum, and hypothalamus, have also been reported to contain newborn neurons. Notably, it is believed that adult neurogenesis has functional relevance. For instance, a number of emotional and cognitive processes, including as memory, pattern recognition, mood management, and spatial learning, are influenced by adult hippocampus neurogenesis [51].

Gut-Brain Axis and Microbiome Interactions

The gut-brain axis represents a vital communication network between the gastrointestinal system and the central nervous system, playing a pivotal role in cognitive health. Both dietary choices and physical activity modulate this axis through effects on gut microbiota composition and function. Diets rich in fiber, prebiotics, and polyphenols enhance microbial diversity and increase the production of short-chain fatty acids (SCFAs), such as butyrate, which have neuroprotective

and anti-inflammatory properties [45]. These metabolites can cross the blood–brain barrier and influence brain-derived neurotrophic factor (BDNF) expression and serotonin synthesis, directly impacting mood and cognition [46].

Physical activity also positively affects gut microbial richness, promoting the growth of taxa such as *Akkermansia muciniphila* and *Faecalibacterium prausnitzii*, which are associated with improved metabolic profiles and reduced systemic inflammation [47]. Emerging findings suggest that combining exercise with microbiota-supporting diets results in more significant cognitive enhancements than either approach alone. For example, studies in humans and rodents indicate that concurrent aerobic activity and high-prebiotic diets can reduce neuroinflammation, promote neurogenesis, and improve memory recall [48].

Furthermore, the gut microbiome plays a role in regulating the hypothalamic-pituitary-adrenal (HPA) axis, thereby modulating stress responses that affect cognitive resilience. Dysbiosis, or microbial imbalance, has been associated with increased permeability of the gut lining ("leaky gut"), systemic inflammation, and the development of depressive symptoms and cognitive dysfunction [49]. By improving gut health through combined lifestyle interventions, individuals may achieve better emotional regulation and sharper cognitive performance.

Limitations and Future Directions

Despite substantial progress, the current literature on diet and exercise synergism in cognitive health remains constrained by several methodological limitations. Heterogeneity in intervention designs, duration, and measurement tools complicates cross-study comparisons. Moreover, most randomized controlled trials have relatively short follow-up periods, limiting understanding of long-term cognitive outcomes [50]. Observational studies, while informative, are susceptible to confounding factors such as socioeconomic status, educational level, and access to healthcare, which can all influence both lifestyle behaviors and cognitive outcomes.

Another limitation lies in the individual variability in response to interventions, which may be mediated by genetic polymorphisms, baseline microbiome composition, and pre-existing health conditions. These factors underscore the importance of moving toward personalized lifestyle interventions tailored to genetic, epigenetic, and psychosocial profiles [51].

Future research should emphasize long-term, large-scale, multicenter trials employing standardized cognitive assessments, biomarker tracking, and neuroimaging modalities. The integration of digital health tools and wearable devices could also improve intervention adherence and facilitate real-time monitoring of behavioral changes. Moreover, studies must continue exploring molecular pathways, such as BDNF signaling, mitochondrial efficiency, and synaptic plasticity, to better elucidate how dietary and physical factors converge to promote neurocognitive resilience [52].

CONCLUSION

Compelling evidence from human and animal studies alike illustrates the profound influence of diet and exercise on cognitive health and neuroplasticity. These lifestyle components, when combined, appear to exert synergistic effects that surpass the benefits of isolated interventions. Mechanistically, they modulate shared pathways involving neurotrophic support, anti-inflammatory action, redox balance, and gut microbiota integrity.

From childhood through old age, maintaining a physically active lifestyle coupled with a nutrient-rich diet offers a practical, non-pharmacological means of preserving cognitive function, delaying neurodegenerative progression, and enhancing life quality. As research advances, a more personalized approach to integrating these strategies could revolutionize preventative and therapeutic paradigms for cognitive decline.

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