CHAPTER EIGHT

A precision-mapping approach to physical exercise interventions targeting cognitive function

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Abstract

Physical exercise confers numerous benefits to brain structure, function and cognition, however, considerable individual variability exists in these effects. Emerging paradigms focused on intraindividual dynamics provide novel opportunities to map and leverage individualized neural architectures underlying exercise-cognition relationships. Progress at the intersection of psychometrics, structural and functional neuroimaging, electrophysiology, and genetics can be integrated to elucidate each individual's potential for improvement, as well as the specific abilities that are most likely to benefit from exercise regimens. These personalized profiles can then guide targeted exercise programs tailored to effectively modulate the pathways identified as most promising for that individual. Such mapping-guided exercise interventions tailored to a person's neurocognitive profile allows optimizing cognitive improvements compared to results elicited by generic regimens. While still in its infancy, precision interventions represent an innovative future direction to advance exercise in support of brain health, toward potent, truly personalized cognitive enhancement.

Keywords: Cognitive enhancement, Cognitive training, Neuroplasticity, Behavioral remediation, Neuroimaging, Electrophysiology, Precision intervention, Personalized medicine

1. Introduction

A growing body of research has demonstrated the diverse benefits of physical exercise for both physical and mental health. Low fitness levels have been linked to increased risks for a wide range of conditions including stroke, cancer, diabetes, and cardiovascular diseases (Blair, 1995). Furthermore, sedentary lifestyles correlate with higher incidence of several neurological disorders, including autism, schizophrenia, attention deficit

Progress in Brain Research, Volume 283
ISSN 0079-6123
https://doi.org/10.1016/bs.pbr.2023.12.001

hyperactivity disorder (ADHD), dementia and Alzheimer's disease, which have all shown improvements through exercise interventions (Penedo and Dahn, 2005).

Beyond mitigating neurological impairment, greater fitness has also been associated with enhanced performance on tasks measuring executive function, such as planning, reasoning, problem-solving and inhibition (Colcombe and Kramer, 2003). Additional studies have shown these benefits extend across a broad array of cognitive domains beyond executive function (Moreau and Conway, 2013). Experimental research has further demonstrated the causal nature of this relationship, with exercise interventions eliciting cognitive improvements in both academic and professional settings (Castelli et al., 2007; Coe et al., 2006; Keeley and Fox, 2009; Moreau et al., 2017). These gains have also been documented in older populations, with exercise linked to better cognitive performance, quality of life (Cancela Carral and Ayán Pérez, 2007), mood and emotional stability (Blumenthal et al., 1991). A growing body of evidence has demonstrated that physical activity and fitness interventions can improve cognitive performance across the lifespan (Hillman et al., 2008; Moreau and Conway, 2013; Smith et al., 2010) and across a range of modalities—for example, both acute bouts of exercise and long-term training regimens have been associated with benefits to cognitive abilities including executive function, memory, processing speed, attention and academic achievement (Chang et al., 2012; Lambourne and Tomporowski, 2010; Moreau, 2022; Moreau and Chou, 2019; Moreau et al., 2017; Tomporowski, 2003).

The mechanisms mediating the exercise-cognition connection are now well-established. Exercise promotes neurogenesis and neuron survival (van Praag et al., 1999; Vaynman et al., 2006), increased brain volume (Colcombe et al., 2006), and enhanced brain vascularization (Black et al., 1990). Hormonal and neurotransmitter activity in the brain is also altered through physical activity (Mora et al., 2007)—one key mediator is brain-derived neurotrophic factor (BDNF), which shows substantial increases after exercise, most prominently in hippocampal regions (Neeper et al., 1995) but also across cortical and subcortical structures (Neeper et al., 1996). Elevated concentrations of BDNF can persist for weeks (Berchtold et al., 2001) and are thought to enable the neural plasticity underlying exercise-induced cognitive gains (Knaepen et al., 2010). Greater cardiorespiratory fitness has also been tied to increased white matter integrity in children (Chaddock-Heyman et al., 2014; Krafft et al., 2014; Schaeffer et al., 2014) and microstructural alterations in regions involved in cognition

(Alexander et al., 2007). Exercise has also been associated with changes in functional brain activity during cognitive tasks, measured via electroencephalography (EEG) and functional magnetic resonance imaging (fMRI; Chaddock-Heyman et al., 2013; Davis et al., 2011; Hillman et al., 2014; Kamijo et al., 2011, Kao et al., 2023a,b).

Here, we discuss the potential for precision-mapping techniques to guide targeted, individualized exercise interventions aimed at enhancing cognition. We first examine literature on maximizing exercise-induced cognitive improvements, through manipulation of exercise intensity and modalities. We then discuss sources of individual variability in the exercise-cognition relationship, and emerging research using neuroimaging and electrophysiology to map this heterogeneity. Building on these developments, we propose that comprehensive multimodal mapping of an individual's specific neural architecture could inform tailored exercise regimens focused on the abilities most likely to benefit for that person. After outlining an example framework for precision mapping-guided exercise interventions, we consider limitations of this approach, future research directions, and conclusions regarding the promise of personalized exercise prescriptions for optimizing cognitive gains. The overall focus of our review is on integrating insights across diverse fields including exercise science, cognitive psychology, neuroimaging, electrophysiology, and precision medicine to put forth precision mapping as an innovative strategy to advance individually optimized exercise for enhancing cognition.

2. Maximizing exercise-induced improvements

While traditional moderate-intensity aerobic exercise is well-established to enhance cognitive function (Hillman et al., 2008), emerging research indicates that high-intensity interval training (HIIT) can provide additional cognitive benefits beyond those gained from traditional regimens (see Fig. 1). HIIT involves brief bursts of vigorous activity interspersed with recovery periods. Though metabolically demanding, this form of exercise requires less time commitment than moderate continuous exercise. Single bouts of HIIT have been shown to acutely enhance executive functions, including inhibitory control, working memory, and cognitive flexibility, to a greater extent than moderate exercise (Alves et al., 2014; Tsukamoto et al., 2016).

Several physiological mechanisms may underlie HIIT's unique cognitive advantages. HIIT elicits greater release of catecholamines and neurotrophins,

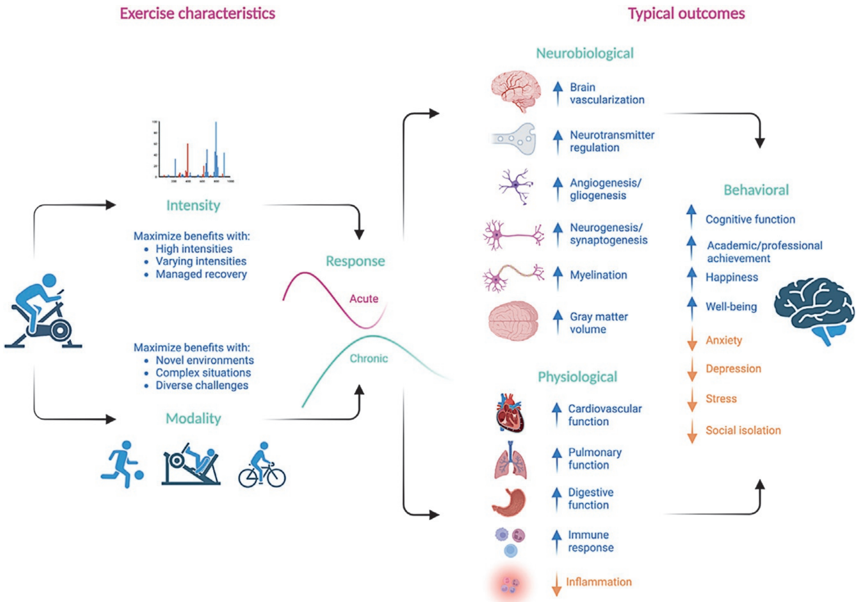

Fig. 1 Typical neurobiological, physiological, and behavioral outcomes of physical exercise. *Note*: Shown characteristics include exercise intensity, modalities, and response, which can be acute (short-term) or chronic (long-term). Neurobiological, physiological and behavioral outcomes are shown either in terms of increases (blue arrows) or decreases (orange arrows).

such as brain-derived neurotrophic factor (BDNF) and vascular endothelial growth factor (VEGF), relative to moderate exercise (Hu et al., 2022; Khodadadi et al., 2023). These factors promote neuronal growth and survival, stimulate neurogenesis, and increase cerebral blood flow, effects that likely support cognitive improvements (Knaepen et al., 2010). HIIT also rapidly increases expression of genes involved in mitochondrial biogenesis throughout the body, enhancing overall metabolic function during cognition (Cuddy et al., 2019), and is thought to enhance hippocampal memory and neurogenesis (Okamoto et al., 2021).

Furthermore, HIIT's intrinsic demand for rapid intermittent bursts of effort and recovery makes it cognitively engaging (Moreau and Chou, 2019). The need for sustained attention, responsiveness to intrinsic physiological cues, and intermittent push-pull workload requires cognitive control and flexibility beyond moderate continuous exertion. This cognitive challenge likely contributes to the boosted cognitive gains from HIIT. Chronic HIIT training may also induce superior structural neural changes compared to traditional aerobic training, which probably subserve enhanced cognition (Ramos et al., 2015), though these largely remain speculative at this stage.

Through a host of physiological adaptations and intrinsic cognitive engagement, HIIT provides a time-efficient exercise strategy to acutely energize executive functions and chronically strengthen brain and cognition, outperforming traditional moderate-intensity training. Integrating some HIIT into aerobic training regimens may further amplify the well-established cognitive gains from physical exercise (Mulser and Moreau, 2023); however, more research is still needed on the mechanisms and optimal HIIT protocols for cognitive enhancement.

Combining physical exercise with other methods of enhancement may offer complementary benefits. Interventions pairing exercise with meditation (Astin et al., 2003), cognitive training (Curlik and Shors, 2013; Shatil, 2013; Wang et al., 2019a,b) or brain stimulation like tDCS (Ditye et al., 2012; Madhavan and Shah, 2012; Martin et al., 2013; Moreau et al., 2015a,b) have been found to have additive effects. Beyond traditional regimens based on aerobic activity, recent trends in exercise physiology research also suggest that HIIT may benefit cognition by inducing similar physiological adaptations (Gayda et al., 2016; Milanović et al., 2015) and even greater gains in some domains (Rognmo et al., 2004). Similarly, resistance training has also been shown to improve cognitive function despite underlying mechanisms that differ from those of aerobic exercise (Best et al., 2015; Liu-Ambrose et al., 2012). Finally, recent work has investigated the potential for combining acute exercise and mindfulness training in a single session, providing a proof-of-concept for the feasibility of this approach (Kao et al., 2023a,b).

Following on from a large body of work on motor expertise that has demonstrated the influential role of the motor system on cognition (Moreau, 2013b, 2015; Wang et al., 2017; Wexler et al., 1998; Wraga et al., 2003), an alternative approach is to incorporate cognitive challenges within physical training (Moreau et al., 2015b). Dedicated sports practice appears to confer unique benefits—for example, motor experts have been shown to recruit motor processes during mental rotation tasks with abstract shapes, while non-experts tend not to (Jordan et al., 2001; Kosslyn et al., 1998; Moreau, 2013a). This involvement of the motor system has been observed across diverse tasks, from language (Beilock et al., 2008) to reasoning (Beilock and Goldin-Meadow, 2010; Cook et al., 2008), and aligns with the motor simulation theory, which postulates shared neural substrates (Jeannerod, 2001; Jeannerod and Decety, 1995). Overall, this line of research suggests that motor activities can effectively enhance a wide array of cognitive abilities by solving perceptual, motor, and cognitive problems while simultaneously sustaining physical activity (Moreau and Conway, 2014).

3. The case for personalized interventions

The general benefits of exercise for the brain and cognition are well-established, yet there remains considerable variability between individuals in the nature and extent of these effects. In meta-analytic studies, estimates of effect sizes for exercise-induced changes in cognitive performance range extensively depending on factors such as the cognitive domain assessed, participant characteristics, exercise regimens, and the cognitive tests employed (Chang et al., 2012; Roig et al., 2013). Within a single experiment, some individuals can show major enhancements following an exercise intervention, while others exhibit little to no benefit in the same cognitive measures. These heterogenous responses highlight the influence of individual differences in determinants such as genetics, lifestyle, brain structure and function, and baseline fitness levels on the cognitive effects of exercise training (Barha et al., 2017).

Sources of this individual variability are beginning to be elucidated through neuroimaging studies comparing how exercise impacts brain structure and function across people. For example, research employing functional magnetic resonance imaging (fMRI) indicates that individual differences in baseline brain activity patterns can predict the subsequent cognitive improvements induced by an exercise intervention (Chaddock-Heyman et al., 2018). Structural MRI studies demonstrate that the effects of aerobic training on hippocampal volume vary significantly based on individual variation in genes regulating neuroplasticity. Exercise-induced changes in brain-derived neurotropic factor (BDNF), a key mediator of the cognitive benefits, also differ across individuals based on genetic factors (Erickson et al., 2012). Taken together, this research highlights the highly individualized nature of the neural mechanisms through which exercise enhances cognition.

Due to this heterogeneity, the "one-size-fits-all" approach to structured exercise programs results in variable, limited cognitive improvements at the group level and unpredictable benefits at the individual level (Moreau, 2018b). For example, classroom-based physical activity interventions demonstrate overall small-to-moderate gains in academic performance, but often produce great heterogeneity—typically, some students will benefit but others may not, or might even experience a decline in cognitive performance (Watson et al., 2017). Similarly, modest and variable effects are found from standardized exercise training in older adults (Kelly et al., 2014), likely stemming from an inability of universal programs to address each individual's unique cognitive needs.

In this context, targeting exercise to an individual's specific difficulties presents a means to enhance and optimize cognitive benefits. Preliminary support for this premise comes from studies showing that cognitive improvements are greatest when physical activity focuses on abilities that are suboptimal in a given individual. For example, children with low inhibitory control at baseline exhibit the greatest gains in this domain from interventions incorporating cognitively challenging exergames (Crova et al., 2014), and inhibitory control appears to moderate the causal effect of exercise on academic performance (Chou et al., 2023). Studies using individualized training targeted to a participant's heart rate variability, an index of arousal regulation, have found enhanced cognition in older adults (Albinet et al., 2016). While promising, this line of research still has tremendous untapped potential; more precise and comprehensive data on individual profiles are needed to guide maximally effective tailored exercise programming.

In parallel with these developments in the exercise literature, the fields of medicine and healthcare have seen the rise of targeted, personalized interventions to health and disease, and the emergence of so-called precision medicine. This approach uses detailed biological, environmental and lifestyle data to optimize and tailor prevention and treatment to an individual's specific profile (Jameson and Longo, 2015). Neuroscientists have recently begun to adopt these concepts through "precision mapping" of brain structure and function. For example, Newbold et al. (2020) demonstrated rapid disconnection of cortical regions associated with limb use from broader motor networks after short-term limb immobilization, a finding that implies regular activation may be necessary to maintain integration of distributed brain systems. In this context, precision functional mapping could identify any dysfunctional or underconnected neural circuits in an individual prior to starting an exercise intervention. For example, frontoparietal executive control networks frequently exhibit reduced connectivity in aging (Gratton et al., 2019). Targeted aerobic exercise could be prescribed to selectively reengage and reconnect those areas and associated cognitive processes, as aerobic training has been repeatedly shown to enhance function in fronto-parietal networks (Colcombe et al., 2004). Newbold et al. (2020) also observed large spontaneous "pulses" of activity in disused regions, possibly aiding local connectivity. If such pulses occur during exercise, it could further amplify reintegration of isolated networks. Analyzing the propagation of pulses through circuits could reveal optimal exercise doses and activities that enhance pulsatile drive to dysfunctional areas, and mapping before and after exercise sessions could help track evolving changes in connectivity of target networks, allowing adjustment of parameters to achieve complete reintegration.

Further advances in brain mapping techniques, together with the emergence of precision approaches in neuroscience (DiNicola et al., 2020; Gilmore et al., 2021; Gordon et al., 2017; Gordon and Nelson, 2021; Laumann et al., 2017; Marek and Greene, 2021; Naselaris et al., 2021; Poldrack, 2017) provide an avenue through which personalized exercise interventions can be developed to optimize cognitive improvements. Recent work has begun bridging the gap between neuroimaging-based brain maps and personalized interventions. For example, Lynch et al. (2023) have shown that functional connectivity mapping of individual brain network organization can help identify target nodes for non-invasive brain stimulation, effectively providing testable pathways for cognitive interventions. Together with prior work that has identified core hubs of executive control networks that can modulate associated cognitive processes (Muldoon et al., 2016), recent developments suggest that individual neurocognitive maps could prove useful in implementing personalized cognitive interventions.

Specifically, multimodal imaging, electrophysiology, genetics, and extensive cognitive testing can provide maps of an individual's distinct neural architecture and dynamics underlying cognition (Castellanos et al., 2013). For example, these maps may detail how memory performance relates to hippocampal structure (Mueller et al., 2010), frontal lobe activation (McDermott et al., 1999) and cholinergic gene variants (Erickson et al., 2008; Nagel et al., 2008) within a single person. Once established, an individual's neurocognitive maps can potentially guide targeted interventions to correct deficiencies and enhance abilities based on their specific needs. Based on this idea, individualized maps have been used to tailor transcranial magnetic brain stimulation to boost motor function in stroke patients by targeting areas of needed increased excitability (Bashir et al., 2011). Similarly, early pharmaceutical trials employed neuroimaging to generate detailed maps of neurotransmitter deficiencies in order to guide targeted drug treatments (Gustavsson et al., 1997). While still an emerging approach, precision mapping thus shows promise to inform targeted, individualized interventions for cognitive enhancement.

4. Applying precision mapping to exercise interventions

Personalized interventions have gained momentum in physiology and exercise science. Optimizing training programs and performance through individualized plans tailored to a person's unique physiological makeup has become commonplace—coaches and trainers regularly assess biomarkers and trait characteristics such as VO^2_{max}, muscle fiber typing, flexibility, strength, and other metrics to design customized regimens for athletes and clients. Based on the assumption that training focused on individual needs, capacities, and biological predispositions is more effective than a one-size-fits-all approach, this precision methodology has helped enhance outcomes in physical training (Bird and Hawley, 2016; Kinnafick et al., 2018; Mann et al., 2014).

Echoing this general trend in training and conditioning, application of precision neurocognitive mapping techniques to exercise training could significantly enhance the magnitude and optimization of cognitive improvements compared to generic, standardized programs (Moreau, 2018a,b). In recent years, advanced neuroimaging and electrophysiological techniques have allowed extensive assessment of how physical exercise impacts brain structure and function related to cognition. For example, structural MRI studies have demonstrated exercise-induced growth in brain regions like the hippocampus and prefrontal cortex that support cognitive processes (Broadhouse et al., 2020; Erickson et al., 2011; Mahalakshmi et al., 2020), while functional MRI has revealed that exercise leads to altered neural activation during cognitive tasks, reflecting increased efficiency and plasticity of brain networks (Voss et al., 2010). Similarly, electrophysiological evidence indicates exercise improves the synchronization of slow brain wave oscillations involved in attention and memory (Galinsky and Frank, 2023; Wilckens et al., 2018).

These neuroplastic changes elicited by exercise occur in specific neural circuits and networks supporting various cognitive faculties. For example, hippocampal enlargement following aerobic training has been tied to improved spatial memory (Erickson et al., 2011), while exercise-induced increments in middle frontal gyrus activity are associated with better executive function (Colcombe et al., 2004). Similarly, slow-wave synchronization between prefrontal and posterior cortical regions correlates with enhanced attention after training (Sarnthein et al., 1998; Stephen et al., 2020). Hence, mapping techniques can link localized and network-level brain plasticity effects with exercise-induced cognitive improvements at the group level. However, as discussed, there is considerable individual variability in these effects. In this context, precision mapping is needed to elucidate how exercise impacts the specific neural architecture underlying cognition within a given person. Specifically, integrative precision mapping of an individual's neural structure and function—the collection and synthesis of multimodal neuroimaging, electrophysiological, genetic and cognitive data to delineate an individual's unique neural patterns associated with cognitive performance and plasticity (Gabrieli et al., 2015)—can be used to guide targeted exercise training regimens for enhancing cognition.

Once individual profiles are established, they can inform specifically tailored exercise prescriptions to improve cognitive function in a focused way (see Fig. 2 for an example intervention protocol). For example, if an individual's profile reveals hippocampal connectivity and theta power during memory tasks are predictors of performance, the mapping would suggest exercise types known to enhance hippocampal plasticity and theta synchronization should be prescribed, such as moderate-intensity aerobic activity (Kandola et al., 2016) and coordinative exergames (Schmidt et al., 2015). Likewise, mapping showing dorsolateral prefrontal function predicts working memory could suggest benefits from HIIT, which is thought to help upregulate dopamine signaling in those circuits (Alves et al., 2014). In this way, mapping could provide a blueprint for selecting personalized exercise types, intensities, and cognitive components to selectively target cognitive processes needing enhancement.

Exercise types, intensities, durations, and cognitive engagement components are then selected based on that specific individual's neurocognitive characteristics and needs. In addition, precision mapping administered before and after an exercise intervention can help identify the distinct neural circuits modified by physical activity in a given individual. Of note, to remain precise mapping needs to be updated dynamically in response to individual changes, and this approach can enable iterative refinements of exercise regimens to maximize cognitive gains. For example, if assessments indicate exercise increased prefrontal but not hippocampal activation associated with improved executive function, the program could be adjusted to better target mediotemporal plasticity. This is a promising approach through which the general benefits of exercise to brain and cognition can be leveraged and optimized in an individualized manner.

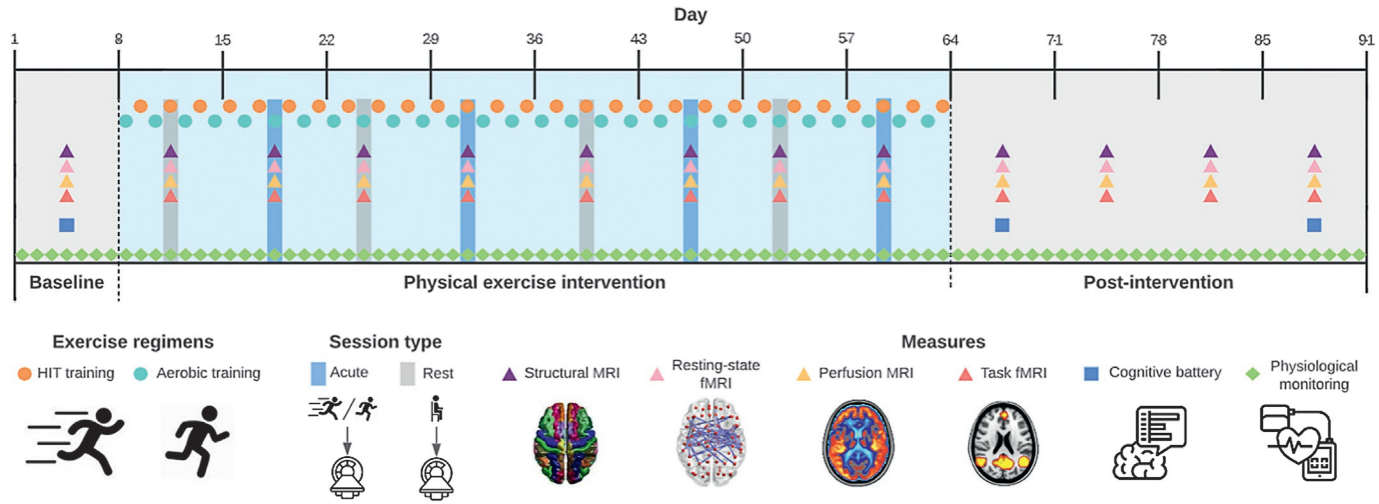

Fig. 2 Example design for a precision intervention. *Note*: The illustrated intervention includes a week-long baseline measurement period, followed by an 8-week physical exercise regimen alternating between aerobic and high-intensity sessions, and a 4-week post-intervention period. Measurements include structural fMRI, perfusion MRI, task fMRI, a cognitive battery, and continuous physiological monitoring.

5. Limitations of the precision-mapping approach

While promising, the proposed approach of using precision mapping to guide individualized exercise interventions also has several limitations requiring consideration. A primary challenge is integrating diverse structural, functional, and physiological data modalities into coherent profiles that accurately characterize an individual's exercise-cognition relationships (Woo et al., 2017). Given the complexity of these relationships, current neuroimaging and mapping techniques may lack sufficient resolution to fully capture critical individual differences (Dubois and Adolphs, 2016). For example, limitations in spatial resolution may occlude fine-grained patterns of exercise-induced plasticity within brain structures that could inform individually tailored interventions (Thomas et al., 2016). Temporal resolution may be insufficient to capture subsecond neural dynamics relevant to exercise-cognition effects. Expanding the imaging modalities applied could help overcome these resolution barriers. The resource intensity of comprehensive mapping protocols is another barrier, as it typically requires extensive participant testing with neuroimaging, genetics, and behavioral assessments (Fisher et al., 2018).

Relatedly, the analytical complexity involved in linking mapping data to tailored exercise prescriptions could also be prone to errors like overfitting or failing to generalize (Yarkoni and Westfall, 2017), especially given that the overall efficacy of mapping-guided interventions remains unknown pending large-scale randomized controlled validation trials. This is in addition to open questions regarding the ecological validity of lab-based mapping approaches (Silberzahn et al., 2018) and potential tradeoffs—for example, focused modulation of specific neural circuits could potentially have unintended effects on other domains like personality or motivation (Falk et al., 2013). Even if validated, implementing mapping protocols and analysis in real-world settings presents feasibility issues that may limit accessibility due to high costs and specialized equipment requirements (Marek and Dosenbach, 2018), as well as ethical issues surrounding the use of mapping data derived from assessments (Illes and Bird, 2006). Consequently, underrepresented populations could face additional barriers to accessing these promising but burdensome interventions, raising concerns about equity (Falk et al., 2013).

Another potential limitation of the proposed precision-mapping approach is reliance on standard psychological constructs and tests to assess cognition. Prevailing constructs like executive function and working memory may represent "local optima" that do not fully capture the breadth of human cognitive abilities (Moreau and Wiebels, 2021, 2022, 2023), due to researchers refining constructs based on their initial operationalizations rather than exploring alternative ways to characterize cognition. Consequently, the cognitive tests typically used to measure exercise effects may not represent the best delineation of improvements exercise can potentially impart. This limiting aspect raises concerns in and of itself—precision mapping guided by standard constructs might miss alternative ways exercise could improve ecologically valid aspects of cognition. For example, mapping exercise-related changes in executive function per se may not fully capture other relevant improvements of cognitive abilities, not because of limitations of the regimen but rather due to shortcomings in our understanding of executive processes. To circumvent this limitation, the proposed approach could be expanded to incorporate more diverse operationalizations of cognition beyond established psychological tests. This might involve developing novel tasks and environments that better approximate real-world cognitive challenges. Mapping how exercise changes performance on these innovative measures could reveal additional cognitive benefits missed by reliance on prevailing constructs.

Furthermore, creatively exploring new ways to operationalize cognitive function aligned with daily demands could not only help better characterize the effects of exercise on mental function, but also help leverage exercise to understand cognition (Moreau et al., 2023). Machine learning approaches integrating brain mapping data, genetics, physiological data, and extensive behavioral testing could help empirically derive cognitive frameworks optimized to the specific improvements elicited by exercise (Vladisauskas et al., 2022). This more open-ended, data-driven approach may supersede prevailing constructs by better delineating the true scope of exercise-induced cognitive benefits. In this context, moving beyond standard psychological measures could be key for precision mapping to fully capture the breadth of cognitive improvements exercise confers, as well as to better characterize brain and mind.

6. Future directions

While promising, further research is needed to fully develop and validate the utility of precision mapping to guide targeted exercise interventions for cognitive enhancement. Key priorities will be expanding the mapping modalities employed and applying machine learning to increasingly large datasets to create optimized models predicting individualized exercise-cognition dose-responses. Additionally, implementation research can help translate validated mapping-based exercise prescriptions from controlled trials into real-world clinical and community settings.

Expanding mapping modalities will be an important step. Current structural and functional neuroimaging methods provide useful but incomplete assessment of an individual's potential responsiveness to exercise. The integration of complementary modalities assessing additional aspects of brain structure, brain function, physiology, and cognition would enable more comprehensive precision exercise-cognition mapping (Wierenga et al., 2014). Diffusion tensor imaging and spectroscopy methods can, respectively, measure white matter microstructure and neurotransmitter levels in mapped brain circuits modifiable by exercise, and thus provide important information about the determinants and characteristics of cognitive malleability (Maddock et al., 2016). Complementary techniques like magnetoencephalography and direct brain stimulation provide higher temporal resolution than fMRI to map rapid exercise effects on neural oscillations and plasticity (Strube et al., 2016).

Genetic mapping, proteomics and metabolomics can help elucidate molecular exercise-cognition mechanisms underlying mapped brain biomarkers. Incorporating emerging wearable mobile brain imaging into exercise training studies would facilitate cost-effective high-density temporal mapping of acute exercise-cognition dose responses. For instance, portable EEG systems allow studying brain dynamics in naturalistic exercising conditions compared to restricted lab settings (Thompson et al., 2008). Likewise, functional near-infrared spectroscopy (fNIRS) enables wearable imaging of oxygenation changes during physical activity (Piper et al., 2014). These tools could provide key insights into the neural processes supporting natural motor learning and control enhanced through exercise. Applying these multivariate approaches within individuals would enable more precise elucidation of the diverse neural systems through which physical activity enhances cognition.

Machine learning techniques leveraging big data will also be key to effective implementation. The aggregation of big datasets from large neuroimaging consortiums and genetic biobanks is enabling advanced machine learning techniques to derive individualized biomarker patterns predicting medication responses and disease risk. Similar data science approaches can be applied to exercise-cognition mapping, using large, aggregated datasets of multimodal brain imaging, genetics, blood biomarkers and cognitive testing before and after exercise interventions. Deep learning algorithms leveraging millions of mapped exercise-related biological parameters could generate highly specified models predicting which precise neural pathways modulated by exercise can enhance cognitive skills in a given individual. Big data analytical techniques can help address the current limitations of small sample sizes and single mapping modalities in exercise neuroscience studies. High resolution predictive modeling can also facilitate more automated and cost-effective individualized mapping and exercise prescription grounded in robust aggregated evidence. However, careful validation using controlled trials will be critical to ensure accuracy and prevent overfitting as mapping-guided exercise interventions translate into clinical practice.

Finally, once validated using multimodal big data modeling, further research will be needed to effectively implement neurocognitive mapping protocols to guide targeted exercise programming in real world settings like schools, clinics and community programs. Pragmatic hybrid trials comparing cognition outcomes from mapping-based vs standardized exercise regimens can determine the efficacy, costs, and feasibility of delivering personalized interventions within existing institutional frameworks (Scott et al., 2019). Implementation studies are necessary in this context to identify optimal processes for efficiently collecting, analyzing, and communicating precision mapping data to professionals prescribing tailored exercise in diverse settings. User-centered design engaging all stakeholders such as students, teachers, clinicians, and health system administrators can help tailor protocols and generate effective strategies for uptake and sustained delivery of mapping-guided exercise interventions.

For widescale public health implementation, research must also address accessibility barriers to exercise mapping technologies and develop more automated, lower-cost and demographically inclusive approaches. Studies should determine best practices for effectively explaining and disseminating precision exercise prescriptions to improve adherence and cognitive gains, especially in underserved communities bearing disproportionate exercise-related health disparities. Focused implementation research will be key to ensure neurocognitive mapping realizes its potential to make personalized, optimized exercise prescriptions to enhance cognition available beyond just highly controlled research environments.

7. Conclusion

Substantial evidence demonstrates that physical exercise improves brain structure, function and cognition; however, considerable interindividual variability exists in these effects due to individual differences in responses to exercise and in cognitive and neural architectures. By addressing interindividual variability in exercise-cognition neuroplasticity, targeted regimens can achieve more pronounced benefits. Recent advances in neuroimaging, electrophysiology, exercise science and cognitive modeling provide an opportunity to map neurocognitive phenotypes and their responsiveness to exercise at an individualized level. Integrating structural and functional brain mapping with cognitive assessments could help identify personalized biomarkers linking exercise-induced neuroplasticity to improvements in specific cognitive abilities for each individual. While precision mapping to inform tailored exercise training is still an emerging concept requiring extensive further development, it represents an innovative future direction with immense potential to advance the exercise-cognition field toward true individualized enhancement of brain health and function.

References

Albinet, C.T., Abou-Dest, A., André, N., Audiffren, M., 2016. Executive functions improvement following a 5-month aquaerobics program in older adults: role of cardiac vagal control in inhibition performance. Biol. Psychol. 115, 69–77.

Alexander, A.L., Lee, J.E., Lazar, M., Field, A.S., 2007. Diffusion tensor imaging of the brain. Neurotherapeutics 4 (3), 316–329.

Alves, C.R., Tessaro, V.H., Teixeira, L.A., Murakava, K., Roschel, H., Gualano, B., Takito, M.Y., 2014. Influence of acute high-intensity aerobic interval exercise bout on selective attention and short-term memory tasks. Percept. Mot. Skills 118 (1), 63–72.

Astin, J.A., Berman, B.M., Bausell, B., Lee, W.L., Hochberg, M., Forys, K.L., 2003. The efficacy of mindfulness meditation plus Qigong movement therapy in the treatment of fibromyalgia: a randomized controlled trial. J. Rheumatol. 30 (10), 2257–2262.

Barha, C.K., Davis, J.C., Falck, R.S., Nagamatsu, L.S., Liu-Ambrose, T., 2017. Sex differences in exercise efficacy to improve cognition: a systematic review and meta-analysis of randomized controlled trials in older humans. Front. Neuroendocrinol. 46, 71–85.

Bashir, S., Mizrahi, I., Weaver, K., Fregni, F., Pascual-Leone, A., 2011. Assessment and modulation of neural plasticity in rehabilitation with transcranial magnetic stimulation. PM&R 2 (12), S253–S268.

Beilock, S.L., Goldin-Meadow, S., 2010. Gesture changes thought by grounding it in action. Psychol. Sci. 21 (11), 1605–1610.

Beilock, S.L., Lyons, I.M., Mattarella-Micke, A., Nusbaum, H.C., Small, S.L., 2008. Sports experience changes the neural processing of action language. Proc. Natl. Acad. Sci. U.S.A. 105 (36), 13269–13273.

Berchtold, N.C., Kesslak, J.P., Pike, C.J., Adlard, P.A., Cotman, C.W., 2001. Estrogen and exercise interact to regulate brain-derived neurotrophic factor mRNA and protein expression in the hippocampus. Eur. J. Neurosci. 14 (12), 1992–2002.

Best, J.R., Chiu, B.K., Liang Hsu, C., Nagamatsu, L.S., Liu-Ambrose, T., 2015. Long-term effects of resistance exercise training on cognition and brain volume in older women: results from a randomized controlled trial. J. Int. Neuropsychol. Soc. 21 (10), 745–756.

Bird, S.R., Hawley, J.A., 2016. Update on the effects of physical activity on insulin sensitivity in humans. BMJ Open Sport Exerc. Med. 2 (1), e000143.

Black, J.E., Isaacs, K.R., Anderson, B.J., Alcantara, A.A., Greenough, W.T., 1990. Learning causes synaptogenesis, whereas motor activity causes angiogenesis, in cerebellar cortex of adult rats. Proc. Natl. Acad. Sci. U.S.A. 87 (14), 5568–5572.

Blair, S.N., 1995. Exercise and health: new research on an old relationship. In: Current Issues and Controversies in Prevention, pp. 80–87.

Blumenthal, J.A., Emery, C.F., Madden, D.J., George, L.K., Coleman, R.E., Riddle, M.W., Williams, R.S., 1991. Cardiovascular and behavioral effects of aerobic exercise training in healthy older men and women. J. Gerontol. 46 (5), M147–M157.

Broadhouse, K.M., Singh, M.F., Suo, C., Gates, N., Wen, W., Brodaty, H., Valenzuela, M.J., 2020. Hippocampal plasticity underpins long-term cognitive gains from resistance exercise in MCI. NeuroImage: Clinical 25, 102182.

Cancela Carral, J.M., Ayán Pérez, C., 2007. Effects of high-intensity combined training on women over 65. Gerontology 53 (6), 340–346.

Castellanos, F.X., Di Martino, A., Craddock, R.C., Mehta, A.D., Milham, M.P., 2013. Clinical applications of the functional connectome. Neuroimage 80, 527–540.

Castelli, D.M., Hillman, C.H., Buck, S.M., Erwin, H.E., 2007. Physical fitness and academic achievement in third-and fifth-grade students. J. Sport Exerc. Psychol. 29 (2), 239–252.

Chaddock-Heyman, L., Erickson, K.I., Voss, M.W., Knecht, A.M., Pontifex, M.B., Castelli, D.M., Kramer, A.F., 2013. The effects of physical activity on functional MRI activation associated with cognitive control in children: a randomized controlled intervention. Front. Hum. Neurosci. 7, 72.

Chaddock-Heyman, L., Erickson, K.I., Holtrop, J.L., Voss, M.W., Pontifex, M.B., Raine, L.B., Kramer, A.F., 2014. Aerobic fitness is associated with greater white matter integrity in children. Front. Hum. Neurosci. 8, 584.

Chaddock-Heyman, L., Hillman, C.H., Cohen, N.J., Kramer, A.F., 2018. III. The importance of physical activity and aerobic fitness for cognitive control and memory in children. Monogr. Soc. Res. Child Dev. 79 (4), 25–50.

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 Res. 1453, 87–101.

Chou, C.C., Kao, S.C., Pan, C.C., McCullick, B., Fu, H.L., Wang, C.H., 2023. Cognitively engaging movement games improve interference control and academic performance in overweight children: a randomized control trial. Scand. J. Med. Sci. Sports 33 (4), 521–534.

Coe, D.P., Pivarnik, J.M., Womack, C.J., Reeves, M.J., Malina, R.M., 2006. Effect of physical education and activity levels on academic achievement in children. Med. Sci. Sports Exerc. 38 (8), 1515.

Colcombe, S., Kramer, A.F., 2003. Fitness effects on the cognitive function of older adults: a meta-analytic study. Psychol. Sci. 14 (2), 125–130.

Colcombe, S.J., Kramer, A.F., Erickson, K.I., Scalf, P., McAuley, E., Cohen, N.J., Webb, A., Jerome, G.J., Marquez, D.X., Elavsky, S., 2004. Cardiovascular fitness, cortical plasticity, and aging. Proc. Natl. Acad. Sci. U.S.A. 101 (9), 3316–3321.

Colcombe, S.J., Erickson, K.I., Scalf, P.E., Kim, J.S., Prakash, R., McAuley, E., Kramer, A.F., 2006. Aerobic exercise training increases brain volume in aging humans. J. Gerontol. A Biol. Sci. Med. Sci. 61 (11), 1166–1170.

Cook, S.W., Mitchell, Z., Goldin-Meadow, S., 2008. Gesturing makes learning last. Cognition 106 (2), 1047–1058.

Crova, C., Struzzolino, I., Marchetti, R., Masci, I., Vannozzi, G., Forte, R., Pesce, C., 2014. Cognitively challenging physical activity benefits executive function in overweight children. J. Sports Sci. 32 (3), 201–211.

Cuddy, T.F., Ramos, J.S., Dalleck, L.C., 2019. Reduced exertion high-intensity interval training is more effective at improving cardiorespiratory fitness and Cardiometabolic health than traditional moderate-intensity continuous training. Int. J. Environ. Res. Public Health 16 (3), 483.

Curlik II, D.M., Shors, T.J., 2013. Training your brain: do mental and physical (MAP) training enhance cognition through the process of neurogenesis in the hippocampus? Neuropharmacology 64, 506–514.

Davis, C.L., Tomporowski, P.D., McDowell, J.E., Austin, B.P., Miller, P.H., Yanasak, N.E., Naglieri, J.A., 2011. Exercise improves executive function and achievement and alters brain activation in overweight children: a randomized, controlled trial. Health Psychol. 30 (1), 91.

DiNicola, L.M., Braga, R.M., Buckner, R.L., 2020. Parallel distributed networks dissociate episodic and social functions within the individual. J. Neurophysiol. 123, 1144–1179.

Ditye, T., Jacobson, L., Walsh, V., Lavidor, M., 2012. Modulating behavioral inhibition by tDCS combined with cognitive training. Exp. Brain Res. 219 (3), 363–368.

Dubois, J., Adolphs, R., 2016. Building a science of individual differences from fMRI. Trends Cogn. Sci. 20 (6), 425–443.

Erickson, K.I., Kim, J.S., Suever, B.L., Voss, M.W., Francis, B.M., Kramer, A.F., 2008. Genetic contributions to age-related decline in executive function: a 10-year longitudinal study of COMT and BDNF polymorphisms. Front. Hum. Neurosci. 2, 11.

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. Proc. Natl. Acad. Sci. U.S.A. 108 (7), 3017–3022.

Erickson, K.I., Miller, D.L., Weinstein, A.M., Akl, S.L., Banducci, S., 2012. Physical activity and brain plasticity in late adulthood: a conceptual and comprehensive review. Ageing Res. 3, 34–47.

Falk, E.B., Berkman, E.T., Lieberman, M.D., 2013. From neural responses to population behavior: neural focus group predicts population-level media effects. Psychol. Sci. 23 (5), 439–445.

Fisher, A.J., Medaglia, J.D., Jeronimus, B.F., 2018. Lack of group-to-individual generalizability is a threat to human subjects research. Proc. Natl. Acad. Sci. U.S.A. 115 (27), E6106–E6115.

Gabrieli, J.D., Ghosh, S.S., Whitfield-Gabrieli, S., 2015. Prediction as a humanitarian and pragmatic contribution from human cognitive neuroscience. Neuron 85 (1), 11–26.

Galinsky, V.L., Frank, L.R., 2023. Critically synchronized brain waves form an effective, robust and flexible basis for human memory and learning. Sci. Rep. 13, 434. https://doi.org/10.1038/s41598-023-31365-6.

Gayda, M., Ribeiro, P.A., Juneau, M., Nigam, A., 2016. Comparison of different forms of exercise training in patients with cardiac disease: where does high-intensity interval training fit? Can. J. Cardiol. 32 (4), 485–494.

Gilmore, A.W., Nelson, S.M., McDermott, K.B., 2021. Precision functional mapping of human memory systems. Curr. Opin. Behav. Sci. 40, 52–57.

Gordon, E.M., Nelson, S.M., 2021. Three types of individual variation in brain networks revealed by single-subject functional connectivity analyses. Curr. Opin. Behav. Sci. 40, 79–86.

Gordon, E.M., et al., 2017. Individual-specific features of brain systems identified with resting-state functional correlations. Neuroimage 146, 918–939.

Gratton, C., Laumann, T.O., Nielsen, A.N., Greene, D.J., Gordon, E.M., Gilmore, A.W., Petersen, S.E., 2019. Functional brain networks are dominated by stable group and individual factors, not cognitive or daily variation. Neuron 98 (2), 439–452.

Gustavsson, A., Weinryb, R.M., Göransson, S., Pedersen, N.L., Åsberg, M., 1997. Stability and predictive ability of personality traits across 9 years. Personal. Individ. Differ. 22 (6), 783–791.

Hillman, C.H., Erickson, K.I., Kramer, A.F., 2008. Be smart, exercise your heart: exercise effects on brain and cognition. Nat. Rev. Neurosci. 9 (1), 58–65.

Hillman, C.H., Pontifex, M.B., Castelli, D.M., Khan, N.A., Raine, L.B., Scudder, M.R., Kamijo, K., 2014. Effects of the FITKids randomized controlled trial on executive control and brain function. Pediatrics 134 (4), e1063–e1071.

Hu, J., Liu, M., Yang, R., et al., 2022. Effects of high-intensity interval training on improving arterial stiffness in Chinese female university students with normal weight obese: a pilot randomized controlled trial. J. Transl. Med. 20, 60.

Illes, J., Bird, S.J., 2006. Neuroethics: a modern context for ethics in neuroscience. Trends Neurosci. 29 (9), 511–517.

Jameson, J.L., Longo, D.L., 2015. Precision medicine—personalized, problematic, and promising. Obstet. Gynecol. Surv. 70 (10), 612–614.

Jeannerod, M., 2001. Neural simulation of action: a unifying mechanism for motor cognition. Neuroimage 14 (1), S103–S109.

Jeannerod, M., Decety, J., 1995. Mental motor imagery: a window into the representational stages of action. Curr. Opin. Neurobiol. 5 (6), 727–732.

Jordan, K., Heinze, H.J., Lutz, K., Kanowski, M., Jäncke, L., 2001. Cortical activations during the mental rotation of different visual objects. Neuroimage 13 (1), 143–152.

Kamijo, K., Pontifex, M.B., O'Leary, K.C., Scudder, M.R., Wu, C.T., Castelli, D.M., Hillman, C.H., 2011. The effects of an afterschool physical activity program on working memory in preadolescent children. Dev. Sci. 14 (5), 1046–1058.

Kandola, A., Hendrikse, J., Lucassen, P.J., Yücel, M., 2016. Aerobic exercise as a tool to improve hippocampal plasticity and function in humans: practical implications for mental health treatment. Front. Hum. Neurosci. 10, 373.

Kao, S.C., Baumgartner, N.W., Pritt, T., Wu, S., Schmitt, S., Ullrich-French, S., Wang, C.H., 2023a. Acute effects of mindful interval exercise on cognitive performance in a higher education setting. Psychol. Sport Exerc. 64, 102326.

Kao, S.C., Chen, F.T., Moreau, D., Drollette, E.S., Amireault, S., Chu, C.H., Chang, Y.K., 2023b. Acute effects of exercise engagement on neurocognitive function: a systematic review and meta-analysis on P3 amplitude and latency. Int. Rev. Sport Exerc. Psychol.

Keeley, T.J., Fox, K.R., 2009. The impact of physical activity and fitness on academic achievement and cognitive performance in children. Int. Rev. Sport Exerc. Psychol. 2 (2), 198–214.

Kelly, M.E., Loughrey, D., Lawlor, B.A., Robertson, I.H., Walsh, C., Brennan, S., 2014. The impact of exercise on the cognitive functioning of healthy older adults: a systematic review and meta-analysis. Ageing Res. Rev. 16, 12–31.

Khodadadi, F., Bagheri, R., Negaresh, R., Moradi, S., Nordvall, M., Camera, D.M., Wong, A., Suzuki, K., 2023. The effect of high-intensity interval training type on body fat percentage, fat, and fat-free mass: a systematic review and meta-analysis of randomized clinical trials. J. Clin. Med. 12 (6), 2291.

Kinnafick, F.-E., Thøgersen-Ntoumani, C., Duda, J.L., 2018. The effect of need supportive text messages on motivation and physical activity behaviour. J. Behav. Med. 41 (4), 574–586.

Knaepen, K., Goekint, M., Heyman, E.M., Meeusen, R., 2010. Neuroplasticity—exercise-induced response of peripheral brain-derived neurotrophic factor. Sports Med. 40 (9), 765–801.

Kosslyn, S.M., DiGirolamo, G.J., Thompson, W.L., Alpert, N.M., 1998. Mental rotation of objects versus hands: neural mechanisms revealed by positron emission tomography. Psychophysiology 35 (2), 151–161.

Krafft, C.E., Schaeffer, D.J., Schwarz, N.F., Chi, L., Weinberger, A.L., Pierce, J.E., McDowell, J.E., 2014. Improved frontoparietal white matter integrity in overweight children is associated with attendance at an after-school exercise program. Dev. Neurosci. 36 (1), 1–9.

Lambourne, K., Tomporowski, P., 2010. The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. Brain Res. 1341, 12–24.

Laumann, T.O., Snyder, A.Z., Mitra, A., Gordon, E.M., Gratton, C., Adeyemo, B., Gilmore, A.W., Nelson, S.M., Berg, J.J., Greene, D.J., McCarthy, J.E., Tagliazucchi, E., Laufs, H., Schlaggar, B.L., Dosenbach, N.U.F., Petersen, S.E., 2017. On the stability of BOLD fMRI correlations. Cereb. Cortex 27 (10), 4719–4732.

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. Neurobiol. Aging 33 (8), 1690–1698.

Lynch, C.J., Elbau, I.G., Zhu, S., Ayaz, A., Bukhari, H., Power, J.D., Liston, C., 2023. Precision mapping and transcranial magnetic stimulation of individual-specific functional brain networks in humans. STAR Protocols 4 (1), 102118.

Maddock, R.J., Casazza, G.A., Fernandez, D.H., Maddock, M.I., 2016. Acute modulation of cortical glutamate and GABA content by physical activity. J. Neurosci. 36 (8), 2449–2457.

Madhavan, S., Shah, B., 2012. Enhancing motor skill learning with transcranial direct current stimulation—a concise review with applications to stroke. Front. Psych. 3, 66.

Mahalakshmi, B., Maurya, N., Lee, S.D., Bharath Kumar, V., 2020. Possible neuroprotective mechanisms of physical exercise in neurodegeneration. Int. J. Mol. Sci. 21 (16), 5895.

Mann, T.N., Lamberts, R.P., Lambert, M.I., 2014. High responders and low responders: factors associated with individual variation in response to standardized training. Sports Med. 44 (8), 1113–1124.

Marek, S., Dosenbach, N.U., 2018. The frontoparietal network: function, electrophysiology, and importance of individual precision mapping. Dialogues Clin. Neurosci. 20 (2), 133.

Marek, S., Greene, D.J., 2021. Precision functional mapping of the subcortex and cerebellum. Curr. Opin. Behav. Sci. 40, 12–18.

Martin, D.M., Liu, R., Alonzo, A., Green, M., Player, M.J., Sachdev, P., Loo, C.K., 2013. Can transcranial direct current stimulation enhance outcomes from cognitive training? A randomized controlled trial in healthy participants. Int. J. Neuropsychopharmacol. 16 (9), 1927–1936.

McDermott, K.B., Buckner, R.L., Petersen, S.E., Kelley, W.M., Sanders, A.L., 1999. Set-and code-specific activation in frontal cortex: an fMRI study of encoding and retrieval of faces and words. J. Cogn. Neurosci. 11 (6), 631–640.

Milanović, Z., Sporiš, G., Weston, M., 2015. Effectiveness of high-intensity interval training (HIT) and continuous endurance training for VO 2max improvements: a systematic review and meta-analysis of controlled trials. Sports Med. 45 (10), 1469–1481.

Mora, F., Segovia, G., del Arco, A., 2007. Aging, plasticity and environmental enrichment: structural changes and neurotransmitter dynamics in several areas of the brain. Brain Res. Rev. 55 (1), 78–88.

Moreau, D., 2013a. Constraining movement alters the recruitment of motor processes in mental rotation. Exp. Brain Res. 224 (3), 447–454.

Moreau, D., 2013b. Motor expertise modulates movement processing in working memory. Acta Psychol. (Amst) 142 (3), 356–361.

Moreau, D., 2015. Brains and brawn: complex motor activities to maximize cognitive enhancement. Educ. Psychol. Rev. 27 (3), 475–482.

Moreau, D., 2018a. Beyond exercise: designing physical activities for cognitive enhancement. In: Handbook of Sport Neuroscience and Psychophysiology. Routledge, pp. 373–384.

Moreau, D., 2018b. Physical exercise and cognitive enhancement. In: The Exercise Effect on Mental Health: Neurobiological Mechanisms. Routledge, pp. 171–187.

Moreau, D., 2022. How malleable are cognitive abilities? A critical perspective on popular brief interventions. Am. Psychol. 77 (3), 409–423.

Moreau, D., Chou, E., 2019. The acute effect of high-intensity exercise on executive function: a meta-analysis. Perspect. Psychol. Sci. 14 (5), 734–764.

Moreau, D., Conway, A.R.A., 2013. Cognitive enhancement: a comparative review of computerized and athletic training programs. Int. Rev. Sport Exerc. Psychol. 6 (1), 155–183.

Moreau, D., Conway, A.R.A., 2014. The case for an ecological approach to cognitive training. Trends Cogn. Sci. 18 (7), 334–336.

Moreau, D., Wiebels, K., 2021. Assessing change in intervention research: the benefits of composite outcomes. Adv. Methods Pract. Psychol. Sci. 4 (1), 1–14.

Moreau, D., Wiebels, K., 2022. Psychological constructs as local optima. Nat. Rev. Psychol. 1, 188–189.

Moreau, D., Wiebels, K., 2023. Genomics might not be the solution, but epistemic validity remains a challenge in the social sciences. Behav. Brain Sci. 46, e221.

Moreau, D., Wang, C.H., Tseng, P., Juan, C.H., 2015a. Blending transcranial direct current stimulations and physical exercise to maximize cognitive improvement. Front. Psychol. 6, 678.

Moreau, D., Morrison, A.B., Conway, A.R.A., 2015b. An ecological approach to cognitive enhancement: complex motor training. Acta Psychol. (Amst) 157, 44–55.

Moreau, D., Kirk, I.J., Waldie, K.E., 2017. High-intensity training enhances executive function in children in a randomized, placebo-controlled trial. Elife 6, e25062.

Moreau, D., Kao, S.C., Wang, C.H., 2023. Probing brain dynamics correlates of motor expertise with mobile recordings. Sport Exerc. Perform. Psychol.

Mueller, S.G., Schuff, N., Yaffe, K., Madison, C., Miller, B., Weiner, M.W., 2010. Hippocampal atrophy patterns in mild cognitive impairment and Alzheimer's disease. Hum. Brain Mapp. 31 (9), 1339–1347.

Muldoon, S.F., Pasqualetti, F., Gu, S., Cieslak, M., Grafton, S.T., Vettel, J.M., Bassett, D.S., 2016. Stimulation-based control of dynamic brain networks. PLoS Comput. Biol. 12 (9), e1005076.

Mulser, L., Moreau, D., 2023. Effect of acute cardiovascular exercise on cerebral blood flow: a systematic review. Brain Res. 1809, 148355.

Nagel, I.E., Chicherio, C., Li, S.C., von Oertzen, T., Sander, T., Villringer, A., Heekeren, H.R., Bäckman, L., Lindenberger, U., 2008. Human aging magnifies genetic effects on executive functioning and working memory. Front. Hum. Neurosci. 2, 1.

Naselaris, T., Allen, E., Kay, K., 2021. Extensive sampling for complete models of individual brains. Curr. Opin. Behav. Sci. 40, 45–51.

Neeper, S.A., Gómez-Pinilla, F., Choi, J., Cotman, C., 1995. Exercise and brain neurotrophins. Nature 373 (6510), 109.

Neeper, S.A., Gómez-Pinilla, F., Choi, J., Cotman, C.W., 1996. Physical activity increases mRNA for brain-derived neurotrophic factor and nerve growth factor in rat brain. Brain Res. 726 (1–2), 49–56.

Newbold, D.J., Laumann, T.O., Hoyt, C.R., Hampton, J.M., Montez, D.F., Raut, R.V., Dosenbach, N.U., 2020. Plasticity and spontaneous activity pulses in disused human brain circuits. Neuron 107 (3), 580–589.

Okamoto, M., Mizuuchi, D., Omura, K., Lee, M., Oharazawa, A., Yook, J.S., Inoue, K., Soya, H., 2021. High-intensity intermittent training enhances spatial memory and hippocampal neurogenesis associated with BDNF signaling in rats. Cereb. Cortex 31 (9), 4386–4397.

Penedo, F.J., Dahn, J.R., 2005. Exercise and well-being: a review of mental and physical health benefits associated with physical activity. Curr. Opin. Psychiatry 18 (2), 189–193.

Piper, S.K., Krueger, A., Koch, S.P., Mehnert, J., Habermehl, C., Steinbrink, J., Schmitz, C.H., 2014. A wearable multi-channel fNIRS system for brain imaging in freely moving subjects. Neuroimage 85, 64–71.

Poldrack, R.A., 2017. Precision neuroscience: dense sampling of individual brains. Neuron 95 (4), 727–729.

Ramos, J.S., Dalleck, L.C., Tjonna, A.E., Beetham, K.S., Coombes, J.S., 2015. The impact of high-intensity interval training versus moderate-intensity continuous training on vascular function: a systematic review and meta-analysis. Sports Med. 45 (5), 679–692.

Rognmo, Ø., Hetland, E., Helgerud, J., Hoff, J., Slørdahl, S.A., 2004. High intensity aerobic interval exercise is superior to moderate intensity exercise for increasing aerobic capacity in patients with coronary artery disease. Eur. J. Cardiovasc. Prev. Rehabil. 11 (3), 216–222.

Roig, M., Nordbrandt, S., Geertsen, S.S., Nielsen, J.B., 2013. The effects of cardiovascular exercise on human memory: a review with meta-analysis. Neurosci. Biobehav. Rev. 37 (8), 1645–1666.

Sarnthein, J, Petsche, H, Rappelsberger, P, Shaw, GL, von Stein, A, 1998. Synchronization between prefrontal and posterior association cortex during human working memory. Proc. Natl. Acad. Sci. U S A 95 (12), 7092–7096. https://doi.org/10.1073/pnas.95.12.7092. PMID: 9618544; PMCID: PMC22750.

Schaeffer, D.J., Krafft, C.E., Schwarz, N.F., Chi, L., Rodrigue, A.L., Pierce, J.E., McDowell, J.E., 2014. An 8-month exercise intervention alters frontotemporal white matter integrity in overweight children. Psychophysiology 51 (8), 728–733.

Schmidt, M., Jäger, K., Egger, F., Roebers, C.M., Conzelmann, A., 2015. Cognitively engaging chronic physical activity, but not aerobic exercise, affects executive functions in primary school children: a group-randomized controlled trial. J. Sport Exerc. Psychol. 37 (6), 575–591.

Scott, S.D., Rotter, T., Hartling, L., Chambers, T., Bannar-Martin, K.H., 2019. A protocol for a systematic review of implementation frameworks. Syst. Rev. 8 (1), 1–6.

Shatil, E., 2013. Does combined cognitive training and physical activity training enhance cognitive abilities more than either alone? A four-condition randomized controlled trial among healthy older adults. Front. Aging Neurosci. 5, 8.

Silberzahn, R., Uhlmann, E.L., Martin, D.P., Anselmi, P., Aust, F., Awtrey, E., Carlsson, R., 2018. Many analysts, one data set: making transparent how variations in analytic choices affect results. Adv. Methods Pract. Psychol. Sci. 1 (3), 337–356.

Smith, P.J., Blumenthal, J.A., Hoffman, B.M., Cooper, H., Strauman, T.A., Welsh-Bohmer, K., Browndyke, J.N., Sherwood, A., 2010. Aerobic exercise and neurocognitive performance: a meta-analytic review of randomized controlled trials. Psychosom. Med. 72 (3), 239–252.

Stephen, E.P., Hotan, G.C., Pierce, E.T., et al., 2020. Broadband slow-wave modulation in posterior and anterior cortex tracks distinct states of propofol-induced unconsciousness. Sci. Rep. 10, 13701. https://doi.org/10.1038/s41598-020-68756-y.

Strube, W., Bunse, T., Nitsche, M.A., Nikolaeva, A., Palm, U., Padberg, F., Hasan, A., 2016. Bidirectional variability in motor cortex excitability modulation following 1 mA transcranial direct current stimulation in healthy participants. Physiol. Rep. 4 (15), e12884.

Thomas, A.G., Dennis, A., Rawlings, N.B., Stagg, C.J., Matthews, L., Morris, M., Kolind, S.H., Foxley, S.B., Jenkinson, M., Nichols, T.E., Dawes, H., Bandettini, P.A., Johansen-Berg, H., 2016. Multi-modal characterization of rapid anterior hippocampal volume increase associated with aerobic exercise. Neuroimage 131, 162–170.

Thompson, T., Steffert, T., Ros, T., Leach, J., Gruzelier, J., 2008. EEG applications for sport and performance. Methods 45 (4), 279–288.

Tomporowski, P.D., 2003. Effects of acute bouts of exercise on cognition. Acta Psychol. (Amst) 112 (3), 297–324.

Tsukamoto, H., Suga, T., Takenaka, S., Tanaka, D., Takeuchi, T., Hamaoka, T., Hashimoto, T., 2016. Greater impact of acute high-intensity interval exercise on post-exercise executive function compared to moderate-intensity continuous exercise. Physiol. Behav. 155, 224–230.

van Praag, H., Kempermann, G., Gage, F.H., 1999. Running increases cell proliferation and neurogenesis in the adult mouse dentate gyrus. Nat. Neurosci. 2 (3), 266–270.

Vaynman, S., Ying, Z., Yin, D., Gomez-Pinilla, F., 2006. Exercise differentially regulates synaptic proteins associated to the function of BDNF. Brain Res. 1070 (1), 124–130.

Vladisauskas, M., Belloli, L.M.L., Fernández Slezak, D., Goldin, A.P., 2022. A machine learning approach to personalize computerized cognitive training interventions. Front. Artif. Intell. 5, 788605.

Wang, C.H., Yang, C.T., Moreau, D., Muggleton, N., 2017. Motor expertise modulates neural oscillations and temporal dynamics of cognitive control. Neuroimage 158, 260–270.

Wang, C.H., Moreau, D., Yang, C.T., Tsai, Y.Y., Lin, J.T., Liang, W.K., Tsai, C.H., 2019a. Aerobic exercise modulates transfer and brain signal complexity following cognitive training. Biol. Psychol. 144, 85–98.

Voss, MW, Prakash, RS, Erickson, KI, Basak, C, Chaddock, L, Kim, JS, Alves, H, Heo, S, Szabo, AN, White, SM, Wójcicki, TR, Mailey, EL, Gothe, N, Olson, EA, McAuley, E, Kramer, AF, 2010. Plasticity of brain networks in a randomized intervention trial of exercise training in older adults. Front. Aging Neurosci. 2, 32. https://doi.org/10.3389/fnagi.2010.00032. PMID: 20890449; PMCID: PMC2947936.

Wang, C.H., Moreau, D., Yang, C.T., Lin, J.T., Tsai, Y.Y., Tsai, C.L., 2019b. The influence of aerobic fitness on top-down and bottom-up mechanisms of interference control. Neuropsychology 33 (2), 245–255.

Watson, A., Timperio, A., Brown, H., Best, K., Hesketh, K.D., 2017. Effect of classroom-based physical activity interventions on academic and physical activity outcomes: a systematic review and meta-analysis. Int. J. Behav. Nutr. Phys. Act. 14 (1), 114.

Wexler, M., Kosslyn, S., Berthoz, A., 1998. Motor processes in mental rotation. Cognition 68 (1), 77–94.

Wierenga, L.M., Doucet, G.E., Dima, D., Agartz, I., Aghajani, M., Akudjedu, T.N., et al., 2014. Greater male than female variability in regional brain structure across the lifespan. Hum. Brain Map. 35 (12), 6255–6269.

Wilckens, KA, Ferrarelli, F, Walker, MP, Buysse, DJ, 2018. Slow-wave activity enhancement to improve cognition. Trends Neurosci. 41 (7), 470–482. https://doi.org/10.1016/j.tins.2018.03.003. PMID: 29628198; PMCID: PMC6015540.

Woo, C.W., Chang, L.J., Lindquist, M.A., Wager, T.D., 2017. Building better biomarkers: brain models in translational neuroimaging. Nat. Neurosci. 20 (3), 365–377.

Wraga, M., Thompson, W.L., Alpert, N.M., Kosslyn, S.M., 2003. Implicit transfer of motor strategies in mental rotation. Brain Cogn. 52 (2), 135–143.

Yarkoni, T., Westfall, J., 2017. Choosing prediction over explanation in psychology: lessons from machine learning. Perspect. Psychol. Sci. 12 (6), 1100–1122.