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UnnMindFlex: A prototype mobile application and case study on HRV-guided cognitive enhancement

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Abstract: In today's demanding world, cognitive fitness plays a vital role in academic success and overall well-being, particularly for students facing academic challenges. Essential cognitive abilities such as memory, attention, and problem-solving are crucial for personal and academic development. This paper introduces innovative research on the creation of a prototype mobile application designed to foster individualized cognitive enhancement through aerobic exercise. The UnnMindFlex prototype integrates principles from exercise science, cognitive psychology, and technology to provide personalized interventions. The application features customized exercise programs, real-time heart rate variability (HRV) monitoring, and cognitive assessment tools. By leveraging the cognitive benefits of aerobic exercise, UnnMindFlex aims to enhance cognitive performance and support neuroplasticity. This study outlines the theoretical framework, design principles, and implementation strategies underlying the development of UnnMindFlex. Additionally, it presents preliminary findings from a case study evaluating the application's effectiveness in improving working memory performance. The results highlight significant associations between HRV metrics and cognitive improvements post-aerobic exercise, further validating the potential of UnnMindFlex as a tool for cognitive enhancement. This research provides an initial step toward creating scalable and accessible solutions for cognitive development, especially in high-demand academic environments.

Keywords: Cognitive Growth, Mobile Application, Prototype, Aerobic Exercise, Heart Rate Variability, Working Memory

1 Introduction

In today's fast-paced and high-pressure environment, optimizing cognitive function has become increasingly essential, especially for university students striving to maintain peak mental performance while managing academic challenges. The importance of cognitive fitness in promoting both academic success and personal growth is now widely acknowledged. Key cognitive abilities such as memory, attention, and problem-solving are fundamental to academic achievement, career progression, and overall well-being [Chang *et al.*, 2012].

Research indicates that aerobic exercise is a powerful tool for enhancing cognitive performance[Babei and Azari, 2021] [Takehara *et al.*, 2021]. It not only facilitates neurogenesis in brain regions associated with memory and learning but also strengthens existing neural connections [Voss *et al.*, 2013]. Furthermore, aerobic exercise has been linked to improved heart rate variability (HRV), a key indicator of autonomic nervous system function that plays a crucial role in cognitive processes and emotional regulation [Borresen and Lambert, 2008].

Building on these insights, we introduce UnnMindFlex—a prototype mobile application designed to support individualized cognitive development through aerobic exercise. UnnMindFlex aims to enhance cognitive abilities, boost academic performance, and encourage long-term commitment to cognitive health and overall well-being.

What sets UnnMindFlex apart is its integration of personalized exercise programs, real-time HRV monitoring, and cognitive assessment tools. By combining these features into a single platform, the application provides a comprehensive and tailored approach to cognitive fitness and mental well-being.

2 Related works

The revolution in modern smart fitness and cognitive applications has taken a leap further in how people approach their physical and mental health. Angosto *et al.* [2023] suggest that personalization, ease of use, and perceived usefulness are the key factors influencing users' intentions to use fitness apps. Yang and Koenigstorfer [2021] extend this by suggesting that gamification and motivational functions create a greater influence on physical activity and fitness engagement. Many of these apps record more than just step or calorie counts, instead using data analytics to offer personalized suggestions for sustained behavioral change. Gordon *et al.* [2019] posit that some fitness apps, such as MyFitnessPal, incorporate goal-setting features that promote accountability and, consequently, better weight loss outcomes. The COVID-19 pandemic increased the stakes for virtual fitness solutions. Liu *et al.* [2022] explore how live streaming and virtual reality workouts could facilitate physical activity during lockdowns.

Equally transformative are cognitive apps. Bang *et al.* [2023] reviewed several cognitive training applications and found that many assessed apps are proving to be beneficial by offering relevant and efficient support to improve skills in memory, attention, and problem-solving. Bonnechère *et al.* [2021] confirmed this view and presented findings showing that brain training exercises using technology provide enhanced cognitive tasks, especially for aging adults. Examples include CogniFit, which utilizes adaptive algorithms and automatic level adjustments to increase user engagement and effectiveness, benefiting both personal and clinical use. However, Hu *et al.* [2023] caution that the psychological benefits of exercise and cognitive training apps greatly rely on continuous user engagement and thoughtful application design. These findings emphasize that while modern applications offer a comprehensive approach to physical and cognitive health, they require commitment from users and careful integration into daily activities.

Smart fitness applications are revolutionizing health and wellness. While already mainstream due to wearable data integration, the addition of AI-driven personalized recommendations has enabled simultaneous training for both the brain and the body. Many innovative features bridge physical activity with mental wellness, though these technologies are still evolving. Combining fitness with cognitive enhancement is a crucial step forward. Aerobic exercise, in particular, is a valuable tool to integrate into such apps.

Numerous studies have shown that aerobic exercise improves cognitive functioning at all stages of life. Research demonstrates that aerobic exercise—defined as prolonged physical activity that raises heart rate and oxygen consumption—positively impacts cognitive domains, including processing speed, executive functions, attention, and memory [Chang *et al.*, 2012][Babei and Azari, 2021][Ferrer-Uris *et al.*, 2022]. For example, a longitudinal study found that older adults engaged in a 1-year aerobic exercise program had significantly higher hippocampus volumes, leading to improved memory function [Babei and Azari, 2021]. Similarly, a meta-analysis revealed that aerobic exercise interventions benefit cognition by improving synaptic activity, blood flow, brain irrigation, and neuronal plasticity [Ferrer-Uris *et al.*, 2022].

Younger populations, such as children and college students, also benefit from aerobic exercise's cognitive advantages. A meta-analysis of 29 studies found that acute aerobic exercise sessions significantly enhanced cognitive functioning in memory, processing speed, and attention across all age groups [Chang *et al.*, 2012]. A randomized controlled trial showed that preadolescent children's academic achievement improved following a 10-week exercise intervention [Takehara *et al.*, 2021]. Neurobiological, physiological, and psychological mechanisms underpin aerobic exercise's effects on cognitive performance. For instance, aerobic exercise increases the synthesis of neurotrophic factors like brain-derived neurotrophic factor (BDNF), which supports the growth and survival of neurons involved in learning and memory [Voss *et al.*, 2013]. It also improves cerebral blood flow, reduces inflammation, and enhances synaptic connectivity—all contributing to better cognitive functioning [Hötting and Röder, 2013][Stillman *et al.*, 2016].

A recent systematic review and meta-analysis by Ahn and Kim [2023] examined the effects of aerobic exercise on cognitive function and sleep among older adults with mild cognitive impairment. It revealed not only improved cognitive performance but also better sleep quality, pointing to a dual beneficial effect that enhances overall well-being. These findings align with studies by Lu *et al.* [2023] and Mandolesi *et al.* [2018] showing that physical exercise serves as a potent gene modulator for structural and functional brain changes, positively influencing cognitive functioning.

Boere *et al.* [2023] and Kimura *et al.* [2023] conducted studies comparing outdoor and indoor aerobic exercise. Their findings indicate that participants who engaged in aerobic exercise outdoors in natural environments outperformed their indoor counterparts, suggesting that exercise context matters. Natural views appear to improve mood and reduce stress, further enhancing cognitive benefits. Quan *et al.* [2024] reviewed aerobic exercise interventions among adults with neurological disorders, showing gains in executive ability, memory, and attention. These findings encourage the use of aerobic physical activities as a non-invasive neuropsychological intervention.

Sudo *et al.* [2022] examined the effects of acute high-intensity aerobic exercise on cognitive performance. While moderate-intensity exercise consistently yields superior outcomes for attention and processing speed, high-intensity workouts may also promote cognitive benefits [Sudo *et al.*, 2022][McIlvain *et al.*, 2024]. This evidence highlights the potential for different exercise intensities to yield specific cognitive improvements. However, a question remains: how can we determine the optimal intensity level for an individual at a given time?

Taken together, these studies underscore the strong biological mechanisms underlying aerobic exercise's cognitive benefits, including neurogenesis, enhanced blood flow, mood improvement, and stress reduction. These findings support incorporating aerobic activities into daily life to improve physical health and cognitive function across the lifespan.

To integrate the concept of smart fitness, aerobic exercise, and cognitive growth, it is essential to identify a reliable physiological metric that can provide insights into the body's resource state for applications aimed at smart cognitive enhancement. Heart rate variability (HRV) stands out as a key indicator of cardiovascular health and autonomic nervous system (ANS) function. Consequently, the relationship between HRV and aerobic exercise has garnered significant attention in recent studies [Borresen and Lambert, 2008]. The dynamic interaction between the sympathetic and parasympathetic branches of the ANS is reflected in the variation of time intervals between successive heartbeats, or HRV [Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996]. According to Thayer *et al.* [2009], a model of neurovisceral integration links a set of neural structures involved in cognitive, affective, and autonomic regulation to HRV and cognitive performance. Their research suggests that individual differences in HRV are related to performance on tasks that engage executive functions and prefrontal cortical activity. Studies have demonstrated that manipulating resting HRV levels can lead to changes in performance on executive-function tasks, reinforcing the idea that HRV is not only a measure of cardiovascular health but also an important indicator of cognitive performance.

According to Michael *et al.* [2017], aerobic exercise has consistently been associated with changes in HRV patterns, suggesting improved cardiac autonomic regulation and vagal tone. Longitudinal studies have demonstrated that regular aerobic exercise increases HRV parameters, including total power, which reflects overall HRV, and high-frequency (HF) power, which indicates parasympathetic activity [Stanley *et al.*, 2013]. These findings suggest that aerobic exercise enhances cardiovascular regulation and promotes a shift toward greater parasympathetic dominance by improving ANS function.

The relationship between HRV and aerobic exercise involves several mechanisms, both acute and long-term. Acute aerobic exercise causes a temporary shift in heart rate during and immediately after exercise, as it activates the baroreflex and increases cardiac output [Borresen and Lambert, 2008]. In contrast, sustained improvements in HRV parameters are driven by structural and functional changes that occur in the heart and autonomic nervous system as a result of chronic aerobic exercise [Michael *et al.*, 2017].

Additionally, research indicates a dose-dependent relationship between aerobic exercise and HRV, with higher exercise volumes and intensities being linked to more significant increases in HRV [Borresen and Lambert, 2008]. However, individual differences in response to aerobic exercise training should be considered, as the extent of HRV adaptations may vary based on factors such as age, fitness level, and genetic makeup [Michael *et al.*, 2017]. The literature supports a strong correlation between aerobic exercise and HRV, with consistent aerobic exercise training improving HRV parameters and cardiac autonomic modulation. As a modifiable lifestyle factor that promotes cardiovascular health and autonomic balance, these findings underscore the importance of aerobic exercise.

An emerging field focused on maximizing cognitive function and performance is the development of systems and platforms for cognitive enhancement through biofeedback. These systems encompass a variety of techniques, including wearable technologies, digital apps, and web-based platforms, all designed to target cognitive domains and offer individualized interventions [Lumsden *et al.*, 2016a]. Wearable technology, which shows promise as an effective tool for cognitive improvement, provides real-time tracking and analysis of behavioral and physiological parameters linked to cognitive function. Devices such as smartwatches, fitness trackers, and EEG headbands enable users to monitor factors like stress levels, physical activity, and sleep quality, all of which can influence cognitive function [Welsh *et al.*, 2023]. By integrating data from multiple sensors and providing personalized insights, wearable technology helps users make informed lifestyle choices that promote cognitive health and well-being.

In addition, digital health interventions and online platforms have been developed to make evidence-based methods for improving cognitive function accessible to a broader audience. These platforms often combine elements of lifestyle interventions, mindfulness practices, and cognitive-behavioral therapy to address factors such as stress management, sleep hygiene, and nutrition, all of which impact cognitive performance [Li *et al.*, 2021]. Online platforms offer scalable and easily accessible interventions, reaching people from diverse demographic and geographic backgrounds. This decentralizes access to cognitive enhancement resources, making them more widely available. Through these platforms and systems, users can explore various methods for enhancing cognitive function and well-being. With the support of these technologies, individuals can maximize their cognitive potential and enjoy longer, healthier lives. These technologies include wearables, online platforms, and digital brain training apps.

Therefore, modern fitness and cognitive applications represent a powerful fusion of technology and health science, offering innovative solutions to enhance both physical and cognitive well-being. Aerobic exercise, as a cornerstone of these advancements, provides a robust framework for improving cognitive function through neurobiological and physiological mechanisms. Combined with wearable technology and personalized digital platforms, these innovations hold immense potential to promote healthier, longer lives through integrated physical and cognitive health strategies.

Despite technological advancements and the rise of cognitive enhancement platforms, there remain several gaps in the current body of knowledge. One major gap is the lack of individualized methods for cognitive enhancement and a limited understanding of how individual variability affects cognitive responses to interventions [Anguera *et al.*, 2013]. Although many platforms offer standardized training courses or interventions, they often overlook the diverse cognitive profiles and needs of users, which can result in suboptimal outcomes for some individuals [Owen *et al.*, 2010]. Another gap lies in the failure to incorporate contextual and lifestyle factors into cognitive enhancement programs. Some platforms focus solely on cognitive exercises, neglecting other controllable factors that have been shown to impact cognitive function [Li *et al.*, 2021]. To optimize cognitive health and performance, a holistic approach is needed that accounts for the interplay between cognitive, physiological, and environmental factors.

Furthermore, the development and evaluation of cognitive enhancement platforms need to be more transparent and scientifically rigorous. Many existing interventions rely on marketing claims or anecdotal testimonials rather than empirical evidence to support their safety and effectiveness [Simons *et al.*, 2016]. Additionally, most research on cognitive enhancement technologies suffers from small sample sizes, short follow-up periods, and methodological flaws, limiting the generalizability and reliability of the findings [Lumsden *et al.*, 2016a].

To address these gaps, there is a need for customized platforms that account for individual differences in lifestyle, cognitive function, and environmental context [Owen *et al.*, 2010]. By leveraging advances in digital health technologies, artificial intelligence, and personalized medicine, researchers and developers can create interventions that dynamically adapt to users' needs and preferences, maximiz-

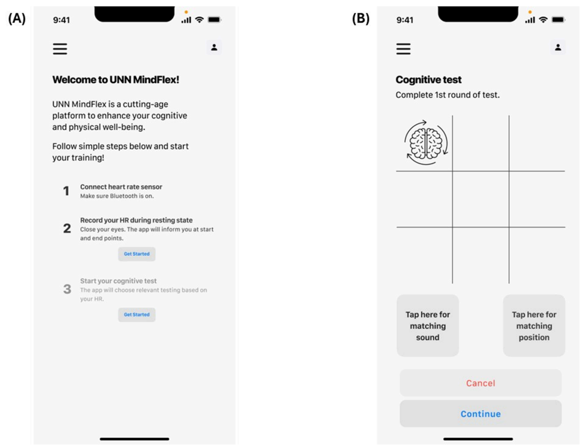

Figure 1. Screen shots of UnnMindFlex prototype: (A) – welcome screen, (B) – cognitive test.

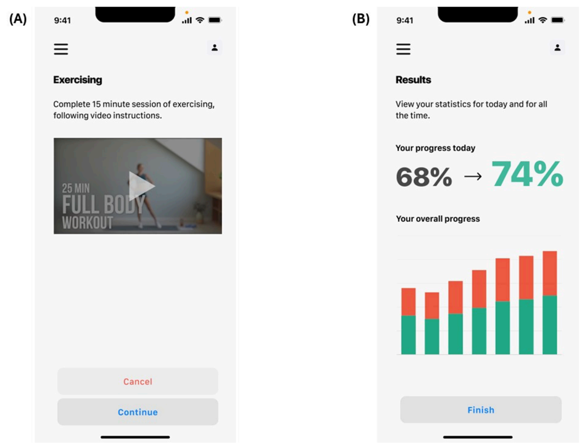

Figure 2. Screen shots of UnnMindFlex prototype: (A) – exercising, (B) – results.

ing both effectiveness and user engagement [Anguera *et al.*, 2013]. The gaps in our current understanding underscore the importance of moving towards individualized cognitive enhancement systems that are context-sensitive, adaptable, and supported by empirical evidence.

Building on these insights and challenges in creating complex cognitive enhancement systems, we present UnnMindFlex, a prototype application designed to provide easy access to cognitive skills enhancement. Our approach is grounded in several key principles: First, the system should operate automatically to minimize human error. Second, it must be based on solid scientific data. Third, it should be sensitive to users' physical and mental states, as many individuals may not be aware of underlying health issues. Fourth, it should be scalable, accessible, and easy to use, with clear mechanisms for tracking progress.

3 Description of UnnMindFlex prototype

Based on the principles outlined earlier, we propose a prototype for a mobile application (screens created using Figma, a browser-based web design tool), as mobile platforms offer accessibility, scalability, and seamless connectivity, such as Bluetooth. To ensure safety, the app is built on biological feedback, incorporating real-time data derived from HRV. To accurately assess the user's fitness level, the system requires connection to a wearable heart rate sensor (e.g., Polar H10) – see Figure 1 (A). Depending on the user's goals and physical condition, the app will recommend a cognitive training program tailored to the appropriate type and intensity.

UnnMindFlex includes cognitive assessment tasks to evaluate users' performance across several domains, including memory, attention, and others. For example, it may recommend a mixed n-back test, as shown in Figure 1 (B), to accurately assess the current state of cognitive skills. For attention, the app can offer tasks such as the go/no-go test, visual reaction test, and others. The selection of cognitive tests in UnnMindFlex is grounded in established cognitive neuroscience principles and psychological research, with a focus on tests that have demonstrated validity and reliability in measuring key cognitive abilities, such as memory, attention, executive functions, processing speed, and problem-solving skills.

To enhance the targeted cognitive domains, the app will recommend an appropriate aerobic workout session, as shown in Figure 2 (A). During the exercise, HRV is monitored to track the user's condition and ensure that physical load remains within safe limits.

After physical activity, the app will recommend a second round of cognitive testing, which is based on an analysis of the results from both the previous physical and cognitive assessments. The app collects data from each stage of testing, allowing users to track both their immediate and overall progress, as shown in Figure 2 (B). The cognitive tests may also be adjusted based on the user's progress.

The entire process flow is outlined in Figure 3.

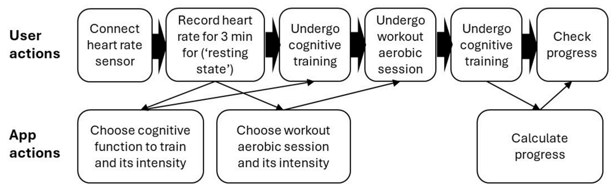

Figure 3. General pipeline of UnnMindFlex app.

The presented pipeline highlights how all stages work together seamlessly to create a comprehensive and individualized system for cognitive development through aerobic exercise.

Thus, the developed prototype application for individualized cognitive growth addresses several gaps identified in the Related Works section. Firstly, the application follows an individualized approach—cognitive training and aerobic exercise regimens are tailored to the user's current physical state, which is assessed during the Resting State stage. This helps address the issue of the lack of individualized methods for cognitive enhancement [Anguera *et al.*, 2013]. Secondly, the app considers certain controllable factors linked to altered cognitive function [Li *et al.*, 2021], with physical activity being the primary factor integrated at this stage. This approach acknowledges the close interactions between cognitive, physiological, and environmental factors.

To close the gap associated with the insufficient scientific evidence supporting proposed solutions for cognitive growth [Simons *et al.*, 2016], we are conducting laboratory experiments to clarify the impact of aerobic exercises on cognitive functions - see Case study section.

Taken together, the prototype application, UnnMindFlex, adheres to the principles outlined earlier. It is automatic, with pre-programmed stages that minimize human-factor errors. While fundamental scientific evidence is still being developed, preliminary results indicate that cognitive performance improves following aerobic exercise. UnnMindFlex takes the user's physical state into account when recommending cognitive and aerobic training, while also providing tracking of progress. Additionally, the prototype is scalable and can easily be further developed.

Implementation strategies for UnnMindFlex include the following:

- Conducting user research, gathering feedback, and iteratively refining the application based on user input.
- Collecting big data on cognitive function, physical activity levels, and other relevant metrics to update personalized recommendations through AI. AI data analysis will be implemented using advanced machine learning algorithms trained on collected data.
- Ensuring that UnnMindFlex is accessible to a wide range of users, including those with disabilities or special needs.
- Implementing robust security measures to protect user data and privacy.
- Collecting user feedback, conducting regular performance reviews, and updating the application with new features and optimizations as needed.
- Forming partnerships with healthcare providers, fitness professionals, and academic institutions to validate UnnMindFlex's effectiveness and leverage expertise in cognitive science, exercise physiology, and technology development.

To ensure data security, all physiological and cognitive data are stored locally on the user's device with optional secure cloud synchronization via end-to-end encryption. Future versions of UnnMindFlex will incorporate machine learning algorithms trained on anonymized aggregated data to generate adaptive recommendations based on HRV trends and user performance clusters. No personally identifiable information is processed by the app server.

4 Case study

4.1 Participants and procedure

Fifteen healthy volunteers (aged 19–23 years, 7 males), all students from the Faculty of Social Sciences at Lobachevsky University, participated in the pilot study. Each session was conducted individually. After providing written informed consent, participants were equipped with a Polar H10 chest strap sensor to continuously record heart rate and heart rate variability (HRV).

The procedure consisted of three main stages. First, a three-minute Resting State baseline was recorded to assess each participant's initial physiological state. Next, participants completed a working memory (WM) task — a dual 1-back paradigm with mixed modality (spatial and verbal), implemented using Brain Workshop software (v4.8.4). The test included 60 trials and lasted approximately 4 minutes, requiring a button press if the current stimulus matched the one presented one step earlier either spatially or in content.

Immediately after the cognitive assessment, participants engaged in a video-guided 15-minute aerobic exercise routine. The moderate-intensity session (e.g., bodyweight squats, arm raises, brisk stepping) was displayed on a 55-inch screen and designed to elevate heart rate to 60–70% of age-predicted maximum. HRV was recorded throughout the exercise.

Following the workout, participants repeated the same WM task to assess potential cognitive changes post-exercise.

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the Faculty of Social Sciences at Lobachevsky University (Protocol No. 8, dated February 20, 2024).

4.2 Data Processing and Analysis

Data analysis was performed using Jupyter Notebook. At the initial preprocessing stage, RR-intervals (time intervals between consecutive heartbeats) were filtered to exclude artifacts: intervals shorter than 300 ms or longer than 1400 ms were removed. Additionally, RR-intervals deviating by more than 70% from the median of the previous five intervals were discarded to minimize noise.

HRV metrics were computed using the NeuroKit2 library. The following time-domain HRV measures were analyzed:

- MEAN – The mean of RR intervals.
- SDNN – The standard deviation of RR intervals.
- RMSSD – The square root of the mean of the squared successive differences between adjacent RR intervals.
- SDSD – The standard deviation of the successive differences between RR intervals.
- CVNN – The coefficient of variation of RR intervals (SDNN divided by MEAN).
- CVSD – The coefficient of variation of successive differences (RMSSD divided by MEAN).

Statistical analysis was performed using the Mann–Whitney U test for independent samples to compare HRV features between groups.

4.3 Results

One participant was excluded from the final analysis due to a 100% performance score on the n-back test before and after aerobic exercise, making it impossible to assess changes in WM. For the remaining 14 participants, a criterion for WM improvement was defined as at least a 5% increase in n-back accuracy following aerobic exercise. Based on this criterion, 8 participants demonstrated enhanced working memory performance after exercise.

To further investigate individual differences in HRV at the Resting State, we conducted a statistical comparison using the Mann–Whitney U test. Significant differences in HRV metrics between participants who exhibited WM improvement and those who did not are summarized in Table 1.

The results indicate that participants who demonstrated WM improvement after aerobic exercise had lower baseline values for specific HRV metrics, including CVSD, RMSSD, and SDSD, compared to those who did not show cognitive enhancement. These findings suggest that HRV patterns at rest can serve as predictors of cognitive responsiveness to aerobic exercise, particularly in the domain of WM.

Lower RMSSD and SDSD values at rest reflect reduced vagal tone, indicating a predominance of sympathetic over parasympathetic regulation in these individuals. This autonomic profile may be associated with higher cognitive effort allocation and increased sensitivity to physiological changes induced by exercise. Following aerobic activity, participants with these baseline characteristics exhibited a more pronounced HRV shift toward sympathetic dominance, aligning with the neurovisceral integration model [Thayer *et al.*, 2009]. According to this model, autonomic flexibility supports cognitive control, suggesting that individuals with a more reactive autonomic system may experience greater cognitive facilitation after aerobic exercise.

These preliminary findings highlight the potential of HRV as a biomarker for predicting cognitive enhancement through physical activity. Further research is needed to determine whether similar effects can be observed in other cognitive domains, such as attention, executive functioning, and processing speed. Future studies should explore whether tailoring exercise regimens based on HRV profiles can maximize cognitive benefits across different cognitive functions and whether these effects persist over time.

As this is a pilot feasibility study, the primary aim was to assess the usability of the app and preliminary patterns linking HRV profiles with cognitive responsiveness. The 5% threshold was chosen heuristically, based on observed within-subject variability in n-back performance across sessions in similar cognitive studies (e.g., [Lumsden *et al.*, 2016b]). Future studies will explore more refined classification thresholds and include control groups.

At this stage, the study did not track long-term engagement metrics, as participants used the tools in a supervised laboratory environment. However, future studies will include usage analytics (e.g., frequency, duration, time of day) to better understand engagement patterns and inform personalized prompts to sustain adherence.

Furthermore, emerging research suggests that circadian factors may influence both exercise effectiveness and cognitive performance. Although the current study did not control for time-of-day effects, future protocols will include session timing as a covariate to better isolate the contribution of aerobic activity to cognitive outcomes.

5 Conclusions

The UnnMindFlex prototype introduces a novel approach to cognitive enhancement by integrating aerobic exercise with personalized cognitive training. By leveraging real-time heart rate variability (HRV) monitoring and validated cognitive assessment tools, the application creates an adaptive, data-driven system aimed at improving cognitive function. Preliminary findings suggest that short aerobic exercise sessions can lead to improvements in working memory performance, aligning with the neurovisceral integration model. The observed changes in HRV metrics further support the hypothesis that aerobic exercise induces autonomic modulation, enhancing cognitive readiness and engagement.

These results demonstrate the potential of UnnMindFlex to bridge the gap between cognitive psychology, physiological monitoring, and digital interventions, offering a practical solution for cognitive enhancement in various contexts. Beyond its scientific foundations, UnnMindFlex has been designed with scalability, accessibility, and automation at its core. The platform minimizes human-factor errors by offering a structured, individualized approach that adapts to the user's physical and cognitive state.

Looking ahead, future development will focus on expanding machine learning capabilities to further personalize the experience, improving security measures to protect user data, and ensuring inclusivity for a broad range of user groups. UnnMindFlex has the potential to become a potentially scalable system for cognitive enhancement, particularly in high-demand academic environments.

Additionally, while the current study focused on immediate post-exercise effects, we acknowledge that some cognitive benefits of aerobic exercise—such as those associated with neurogenesis—may manifest only over longer periods. Future longitudinal studies are needed to capture these delayed effects and to determine their contribution to cognitive enhancement.

Declarations

Acknowledgements

This paper is an extended and revised version of Olawuwo *et al.* [2026] (forthcoming).

Authors' Contributions

SO is the main contributor and writer of this manuscript. VV, AD, NN, and CC performed the experiments and wrote original draft. VD contributed to the conception of this study. All authors read and approved the final manuscript.

Competing interests

The authors declare no conflicts of interests.

Availability of data and materials

The datasets analyzed during the current study contain confidential information and cannot be made publicly available due to institutional regulations. Access to the anonymized datasets may be granted by the corresponding author upon request. Applicants will be required to describe the intended purposes of data use. Requests

Table 1. HRV metrics in samples with different results of working memory (WM) enhancement after aerobic exercise (U - Mann-Whitney criterion value).

HRV metric	WM improvement sample (N=8)	No WM improvement sample (N=6)	U	p-value
CVSD	0.04	0.08	5	0.014
RMSSD	29.47	60.27	5	0.014
SDSD	29.60	60.60	5	0.014

will be reviewed by the institutional ethics committee, and applicants will need to justify the use of the dataset within the framework of Open Science and sign a waiver prohibiting its use for commercial purposes.

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