COGNITIVE SCIENCES AND HUMAN DEVELOPMENT

Benefits of Physical Exercise on Working Memory Performance: A Systematic Review of Functional MRI Studies

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ABSTRACT

Working memory (WM) is a mental workspace that stores and processes information. A good WM performance has been associated with enhanced cognitive functions. Recent neuroimaging studies show evidence that physical exercises cause functional alterations in specific WM-related brain regions and these neuroplastic changes are presumed to contribute to enhanced WM performance. However, the evidence was based on studies of various types of physical exercise, with each reporting different findings. Furthermore, the effect of the different types of physical exercise on the WM-related brain regions remains elusive as reports are often inconsistent. This paper presents a systematic review of functional magnetic resonance imaging (fMRI) studies that have examined the effect of physical exercise on WM performance and the underlying neural mechanism. Articles were searched in the PubMed and Scopus databases and analysed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Five articles were included, of which three reported only on closed-skill exercises and two reported on open-skill and closed-skill exercises. The main finding is that both open-skill and closed-skill exercises can improve WM performance. For open-skill exercises, the types of physical activity found to improve WM performance were tennis, basketball, badminton, ping-pong, soccer, and dodgeball. On the other hand, the close-skill exercises were running, cycling, swimming, jumping ropes, Wushu, jumping jacks, squats, and planks. However, practising yoga was not associated with improved WM performance. Functional imaging revealed that open-skill exercise evoked more significant brain activity in WM-related brain regions than closed-skill exercises. The review also offers recommendations for future works and underscores the importance of fMRI in sports science.

Keywords: brain activity, fMRI, neuroimaging, physical exercise, working memory

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1 INTRODUCTION

Working memory (WM) is the cognitive ability to temporarily maintain and manipulate information in the mind (Cowan, 2014). Studies have shown that WM plays a crucial role in academic achievement (Maehler & Schuchardt, 2016), attentional control (Oberauer, 2019), decision-making (Del Missier et al., 2013), following instruction (Jaroslawska et al., 2016), and problem-solving (Ellis et al., 2019). Interestingly, recent neuroimaging studies reported that engaging in physical exercises can potentially improve a person's WM performance. For instance, it was found that performing 11 weeks of jump rope, running games, and Wushu significantly improved the WM performance of healthy deaf children (Zhu et al., 2021). Additionally, using functional magnetic resonance imaging (fMRI), the study found that the improved WM performance was accompanied by increased frontal, parietal, and hippocampus activity. A similar positive effect of physical exercise on WM performance was identified in late middle-aged healthy adults who regularly engaged in tennis, badminton, cycling, jogging, and swimming for 12 weeks (Chen et al., 2019). It was further revealed through fMRI scans that the participants who exercised regularly demonstrated increased activity of the prefrontal cortex (PFC), anterior cingulate cortex (ACC), and hippocampus than those who exercised irregularly. The effect of physical exercise on WM performance was also identified in healthy young basketball athletes, where high-scoring basketball players were found to have higher WM performance and better attentional control than their low-scoring counterparts (Vaughan & Laborde, 2020). The authors also observed activations in PFC and ACC, which are responsible for WM and attentional control. Therefore, it can be summarised that various types of physical exercises may benefit WM performance and related brain regions.

Although emerging evidence based on neuroimaging approaches showed the efficacy of physical exercises in improving WM performance across the human lifespan, there are still uncertainties regarding the types of physical exercise to enhance WM performance. For instance, studies showed no positive effect of physical fitness exercise on WM performance (Mora-Gonzalez et al., 2019; van der Fels et al., 2020). Thus, the types of physical exercise to improve WM performance still need to be investigated. Apart from that, though studies have looked into the functional alterations underlying WM improvements, the conclusions that can be drawn with certainty are restricted due to the limited number of available neuroimaging studies and the significant variability in the types of physical exercise, duration, WM assessments, sample size, and population. Therefore, a systematic review providing a comprehensive summary of the types of physical exercises that can improve WM performance and their effects on neuroplastic changes is crucial to answer these uncertainties. Here, we limited our review to recently published neuroimaging studies using fMRI that have investigated the effects of physical exercise and WM performance. We focused only on fMRI because we need more expertise in other neuroimaging modalities. Furthermore, most studies on this topic have mainly incorporated fMRI. This review would provide crucial information for researchers, particularly in cognitive and rehabilitation neurosciences, which search for recent evidence-based approaches to improve cognition in healthy and clinical populations.

2 METHODOLOGY

2.1 Search Strategy

The article search was performed to identify studies reporting physical exercise and WM performance using fMRI. The search was performed in the PubMed and Scopus databases using the search terms outlined in Table 1. We searched for articles in these two databases that cover most scientific publications, particularly in medicine and biomedical sciences (AlRyalat et al., 2019; Gusenbauer et al., 2019).

Table 1. Search terms used in PubMed and Scopus databases.

PubMed	Scopus
(((((((physical exercise) OR (physical activity)) AND (working memory)) AND (brain activity)) AND (fMRI)) NOT (review)) NOT (EEG)	TITLE-ABS-KEY ("physical exercise" OR "physical activity" AND "working memory" AND "brain activity" AND "fMRI" AND NOT "review" AND NOT "EEG") AND (LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022))

2.2 Study Selection

A systematic search method was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. It is an established standard for reporting evidence in systematic reviews (Moher et al., 2009) and was used in the present study to ensure the selected studies were critical analyses and syntheses. Initially, 57 articles were identified, of which 52 articles were from the PubMed database and five articles from the Scopus database. After removing two duplicates, only 55 articles remained. Out of 55 articles, 37 were excluded based on titles and abstracts, leaving 18 articles. These articles were excluded because they were irrelevant to the study's objectives. A full-text review of 18 articles was assessed to see whether they met the eligibility criteria. The assessment was done by two independent reviewers to prevent selection bias and consensus for eligibility was reached through discussion. Thirteen articles were removed with reasons and only five articles were included in this review. The search process is detailed in the PRISMA flow diagram (Figure 1).

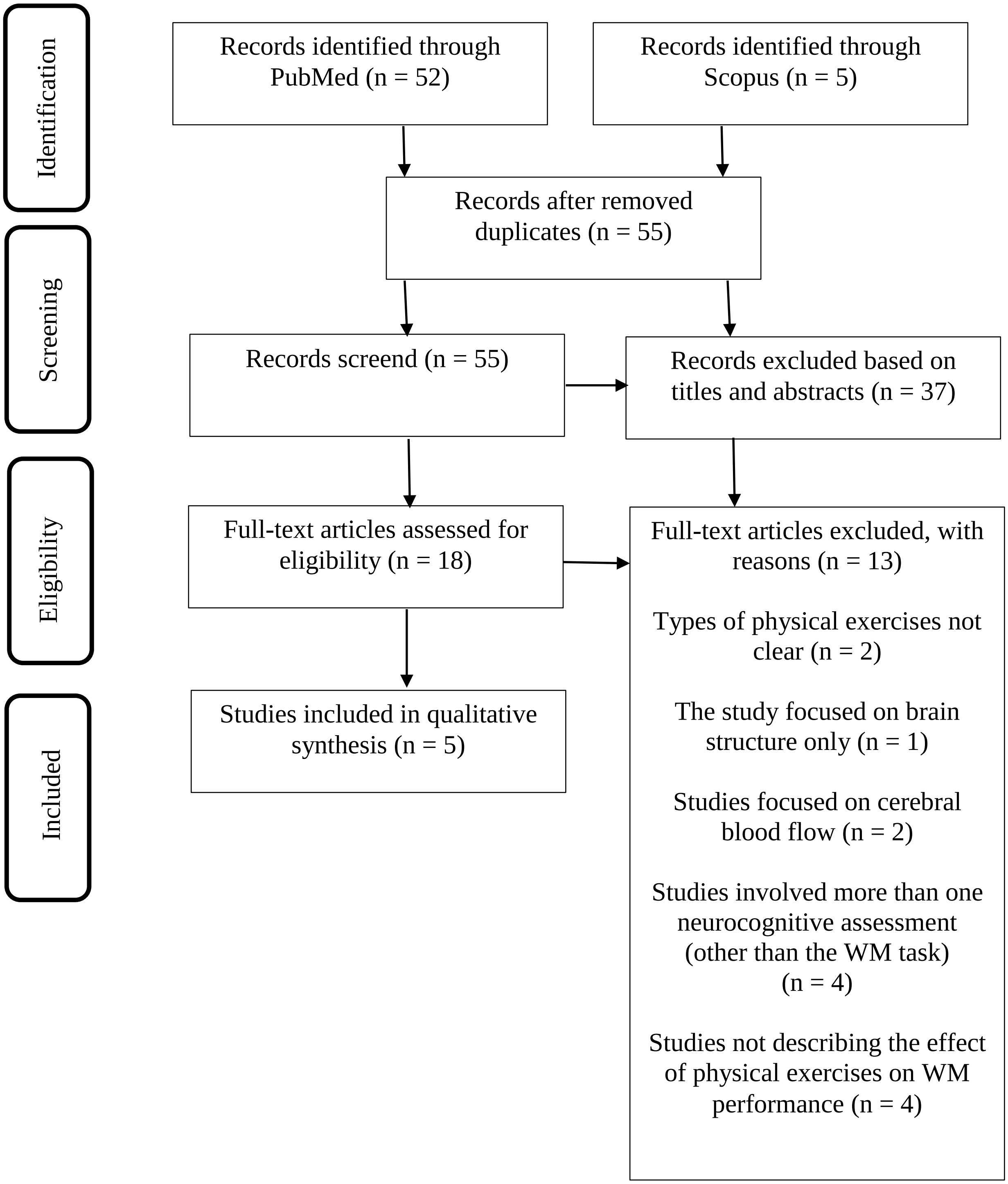

Figure 1. Summary of data collection in accordance with PRISMA guidelines.

2.3 Inclusion and exclusion criteria

The inclusion and exclusion criteria are tabulated in Table 2. This review focused on fMRI studies investigating the effect of physical exercises only on WM performance. To ensure this review provides a comprehensive summary of recent findings, we confined the search to articles published between 2018 and 2023.

Table 2. Inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Study on the effect of physical exercise on WM performance	Review articles
Studies involving functional magnetic resonance imaging (fMRI) to measure brain activity after physical exercise	Animal studies
Articles published in peer-reviewed journals between 2018 to 2022	Studies involving electroencephalogram (EEG) to measure brain electrical activity after physical exercise
Articles written in English	Studies with more than one cognitive assessment

2.4 Data extraction and analysis

Several variables were extracted including the year of publication, study author(s), study design, total participants, participant's age, gender, participant's condition, type of physical exercise, time duration of physical exercise, exercise intensity, name of WM task, WM performance after physical exercise, and changes in brain activity after physical exercise. The data were analysed based on their similarities and differences to achieve summarisation findings. The variability between the data was critically appraised by identifying the inhomogeneities between the different study protocols.

3 RESULTS

Out of the five studies, three were on adult participants (Chen et al., 2019; Gothe et al., 2018; Voss et al., 2020), whereas the other two were on children (de Bruijn et al., 2021; Zhu et al., 2021). Three studies investigated closed-skill exercises (Gothe et al., 2018; Voss et al., 2020; Zhu et al., 2021), while two studies investigated open-skill and closed-skill exercises (Chen et al., 2019; de Bruijn et al., 2021). The characteristics of the five studies are shown in Table 2.

Table 2. Summary of studies reporting the effect of physical exercises on WM performance.

No	Author and study design	n[a] and gender	Age[b] and patient's condition	Type of physical exercise	Time	Exercise intensity (% of max heart rate)	Type of WM task	WM performance after physical exercise	Brain activity-related WM after physical exercises
1	Chen et al. (2019) Cross-sectional study	70 30 Females 40 Males	57.17±3.23 (open-skill) 59.08±7.15 (closed-skill) Healthy with no psychiatric disease	Open-skill (tennis, basketball, badminton, ping-pong) Closed-skill (jogging, cycling, swimming)	12 weeks (3 sessions each week and 30 minutes each session)	n/a	Spatial WM	Open-skill and closed-skill improved WM performance compared to the control group	Open-skill showed greater brain activity in the left inferior frontal gyrus (IFG), left anterior cingulate cortex (ACC), left supplementary motor area (SMA), right hippocampus, left thalamus, and left putamen compared to closed-skill
2	Voss et al. (2020) Randomized controlled trial study	34 Females	67.1±4.3 Healthy with no psychiatric disease	Closed-skill (cycling)	Acute (single session) Long-term (12 weeks, 3 sessions per week)	Light intensity (53.1) Moderate intensity (65.7)	N-back task	Closed-skill with moderate intensity acutely improves WM performance compared to light-intensity	Closed-skill with moderate intensity showed similar functional connectivity (fc) in acute and long-term phases. Specifically, fc between the right dorsolateral prefrontal cortex (DLPFC) and right superior temporal gyrus (STG), and fc between the right ventrolateral

									prefrontal cortex (VLPFC) and right postcentral gyrus
3	Zhu et al. (2021) Randomized controlled trial study	17 8 Girls 9 Boys	11.21±1.17 Deaf children with no psychiatric disease	Closed-skill (running, jumping ropes, Wushu)	11 weeks (4 sessions per week)	Moderate intensity (64.95)	N-back task	Closed-skill showed better WM performance compared to the control group	Closed-skill increase brain activities in the left IFG, left middle frontal gyrus (MFG), left STG, right inferior parietal lobe (IPL), left hippocampus, and right middle occipital gyrus (MOG)
4	de Bruijn et al. (2021) Randomized controlled trial study	62 32 Girls 30 Boys	9.20±0.61 n/a	Open-skill (soccer, dodgeball) Closed-skill (running relays, jumping jacks, squats, planks)	14 weeks (4 sessions per week)	n/a	Visuospatial WM	Open-skill and closed-skill showed better VSWM performance after exercise compared to before exercise	Open-skill and closed-skill, showed brain activation in the bilateral superior parietal lobe (SPL), right angular gyrus, and bilateral thalamus Decrease brain activation in middle temporal gyrus (MTG) and inferior temporal gyrus (IFG)
5	Gothe et al. (2018)	26 24 Females 2 Males	35.77±15.43 Healthy with no	Closed-skill (Yoga)	Experienced at least 3 years and continuing	n/a	Sternberg	The control group and closed-skill visualized no significant	Closed-skill decreases brain activity in the left DLPFC

Cross-sectional study	psychiatric disease	regularly (more than 3 sessions per week, 1 hour per session)	difference in Sternberg WM accuracy

[a] Total number of participants (including the control group if present) [b] Age reported as mean ± SD

4 DISCUSSION

4.1 Types of physical exercises to improve WM performance

The main finding is that there are two main types of physical exercises that can improve WM performance: open-skill and closed-skill exercises. An open-skill exercise (e.g. badminton, ping-pong, tennis, basketball) requires high cognitive demand, while closed-skill exercise (e.g. jogging, cycling, swimming) requires less cognitive demands (Chen et al., 2019; Gu et al., 2019). Open-skill exercise requires additional cognitive demand as it necessitates a person to be prepared for unpredictable events (Chen et al., 2019). For instance, a player who adheres to game rules while performing complex motor coordination needs to be vigilant for unpredictable events, such as the unpredictable movement of a shuttlecock in badminton or a ball in basketball. Moreover, open-skill exercises require players to pay attention, increase their level of focus, and have good strategic coordination with other teammates (de Bruijn et al., 2021). As such, an open-skill exercise differs from a closed-skill exercise, which is simpler and requires only repetitive movement in a predictable environment (Chen et al., 2019; de Bruijn et al., 2021). For instance, de Bruijn et al. (2021) compared the effects of open-skill exercises (i.e. dodgeball and soccer) and closed-skill exercises (i.e. running relays, jumping jacks, planks, and squats) with standard physical exercise in 62 children. It was discovered that the children showed increased WM performance after performing open-skill exercises, closed-skill exercises, and standard physical activity groups compared to before exercise interventions. However, the increase in WM performance was not significant between the three exercise interventions. Chen et al. (2019) found both open and closed-skill exercises can improve WM performance in healthy older adults. Additionally, they found that healthy older adults who constantly engaged in open and closed-skill exercises had higher cardiovascular fitness compared to those who exercised irregularly. This finding is supported by later studies demonstrating that cardiovascular fitness is positively associated with WM performance (Ishihara et al., 2020; van der Fels et al., 2020). Particularly, Ishihara et al. (2020) found that high-hand dexterity is associated with high WM performance, whereas van der Fels et al. (2020) discovered a significant, positive, and fair correlation between gross motor skills and WM performance.

4.2 Effects of open-skill and closed-skill exercises on WM-related brain regions

Physical exercises may also facilitate WM performance by increasing brain activity in WM-related brain regions. As compared to closed-skill exercises, open-skill exercises evoked greater brain activity in the left inferior frontal gyrus (IFG), left anterior cingulate cortex (ACC), left supplementary motor area (SMA), right hippocampus, left thalamus, and left putamen in healthy older adults (Chen et al., 2019). These brain regions are known to be involved in auditory WM — a cognitive system that helps a person understand verbal communication (Othman et al., 2020). For instance, the posterior part of the left IFG, which forms Broca’s area, plays a role in syntactic processing. Meanwhile, the anterior part of the left IFG is crucial for semantic processing (Ishkhanyan et al., 2020). Besides, SMA plays a role in motor speech production as it connects to Broca’s area (Canas et al., 2018). On the contrary, the right hippocampus maintains spatial memory information that allows a person to identify locations and aid in navigation (Bonner-Jackson et al., 2015; Chen et al., 2019; Ezzati et al., 2016; Nedelska et al., 2012). ACC plays a vital role in attentional control in emotional regulation (Feurer et al., 2022). Emotional regulation is the ability to manage and respond to emotion. Individuals with emotional dysregulation showed difficulty in accepting the emotional response which led to depression, anger, anxiety, shame, and self-harm. Fox et al. (2015) described that a deficit in attentional control may lead to an inability to suppress negative thinking. Jasielska et al. (2015) found that individuals with high WM use emotional regulation strategies (e.g. positive reappraisal) more frequently compared to individuals with low WM. Lastly, left putamen plays a crucial role in minimizing irrelevant information from entering WM (Baier et al., 2010).

4.3 Closed-skill exercises with moderate intensity improves WM performance

Interestingly, Zhu et al. (2021) compared the exercise group and the control group in deaf children. The exercise group underwent closed-skill exercises with moderate intensity while there was no intervention exercise in the control group. It was revealed that WM performance was better in the exercise group compared to the control group. Additionally, participants who performed moderate intensity showed increased brain activity in the left IFG, left superior temporal gyrus (STG), left middle frontal gyrus (MFG), left hippocampus, and right inferior parietal lobe (IPL). STG consists of Wernicke's area that contributes to auditory WM performance (Othman et al., 2019). In addition, Gohel et al. (2019) found that left IFG (i.e. the Broca's area) and left MFG showed left lateralisation that is dominant in language comprehension**.** On the other hand, the left hippocampus is involved in the verbal episodic memory process (Ezzati et al., 2016). Besides, de Bruijn et al. (2021) found that open-skill exercises (i.e., soccer, dodgeball) and closed-skill exercises (i.e., jumping jacks, squats, and planks) evoked higher brain activation in the superior parietal lobe (SPL) and right angular gyrus (located at IPL), but decreased activation in the middle temporal gyrus (MTG) and inferior temporal gyrus (ITG). This may be due to the right posterior parietal cortex (PPC), which includes SPL and IPL, playing a crucial role in visuospatial WM as compared to MTG and ITG (Abdul Wahab et al., 2022; Pisella, 2017).

Voss et al. (2021) investigated closed-skill exercise (i.e. cycling) in healthy older adults at two different intensities. The authors found that WM performance is better after moderate intensity compared to light intensity. Voss et al. (2021) described that moderate intensity should achieve a heart rate between 64% and 76% of the maximum heart rate an individual can achieve based on age. From the neurological perspective, the study found increased functional connectivity between the right posterior STG and the right DLPFC. According to Ohkuma et al. (2022), high cortical activity of the right STG and right DLPFC enables a person to solve insight problems. The insight problem-solving techniques consist of chunk decomposition and constraint relaxation (Ohkuma et al., 2022). Chunk decomposition is the ability of a person to consciously understand the problem meanwhile constraint relaxation is the technique of properly decomposing the chunks (Ohkuma et al., 2022). Additionally, Voss et al. (2020) found high functional connectivity between the right postcentral gyrus and the right ventrolateral prefrontal cortex (VLPFC). The postcentral gyrus, also called primary somatosensory cortex, is involved in processing somatosensory information (e.g., touch, pain, pressure, vibration, and temperature) (Borich et al., 2015). Meanwhile, the VLPFC receives somatosensory information from the postcentral gyrus (Miller & Cohen, 2001). Thus, the high functional connectivity allows tactile WM processing (Spitzer et al., 2014). From their findings, Voss et al. (2021) concluded that performing a closed-skill exercise (i.e., cycling) at moderate intensity may lead to high WM performance.

4.4 Closed-skill exercises that were not beneficial to WM performance

However, not all physical exercise may be beneficial to the WM. For instance, Gothe et al. (2018) discovered no significant difference in WM performance accuracy between closed-skill (i.e. Yoga practitioners) and the control group. They also found low brain activations in the left DLPFC in participants performing a closed-skill exercise (i.e. Yoga). Of the five studies reviewed, Gothe et al. (2018) was the only study that used the traditional WM task (i.e. Sternberg WM task). The other four studies either use the N-back task, visuospatial WM task, or spatial WM task. Jablonska et al. (2020) described that the traditional WM task (i.e. Sternberg task) did not activate DLPFC because this brain region is activated only when there is a manipulation processing of information. In the Sternberg WM task, no information is manipulated as it only involves the maintenance of information (Jablonska et al., 2020). Another plausible reason is that there was no significant difference in cardiovascular fitness between the Yoga practitioners and the control group.

4.5 Limitations and future recommendations

There are several limitations in literature worthy of discussion. In this study, we proposed that physical exercises are beneficial to WM performance. However, the neural mechanism underlying these differences warrants further investigation. For example, both open-skill and close-skill exercise studies reported heterogeneity in WM performance and functional alterations of the WM networks. The variability of the findings was high due to the different types of physical exercise, duration, WM assessments, sample size, and population. Existing neuroimaging studies on physical exercise are also limited, with most having a small sample size and not controlling for confounders such as gender, handedness, and WM capacity. As such, we would recommend future research to be more comprehensive by including a large number of samples and taking into consideration factors that may influence the outcomes. Apart from that, though it is known that closed-skill exercises require moderate intensity to improve WM performance, the level of intensity for open-skill exercises remains unclear. Therefore, future works may also consider exploring the optimum intensity level to improve WM performance through open-skill exercises.

5 CONCLUSION

In summary, the types of physical exercise that improve WM performance are open-skill and closed-skill exercises. Open-skill exercise needs high cognitive demand to adapt to fast-changing unpredictable stimuli. Meanwhile, closed-skill exercises require less cognitive demand as they involve repetitive movement in a predictable environment. Although studies did not show any significant difference in the outcomes of open-skill and closed-skill exercises on WM performance, studies did demonstrate that open-skill exercises evoked greater brain activity in WM-related brain regions than closed-skill. Surprisingly, closed-skill exercises can increase brain activity in WM-related brain regions when performed at moderate intensity. Taken together, this review highlights that physical exercises, regardless of their types, could provide benefits to WM performance by increasing brain activity in WM-related brain regions.

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