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Title: Physical exercise and motor learning: A scoping review

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Abstract

Physical exercise can enhance motor learning by inducing neurophysiological changes that facilitate this process. This preregistered scoping review aimed to map current knowledge on the effects of physical exercise on motor learning. Experimental studies and review articles examining any form of physical exercise in healthy or clinical populations were included, with outcomes assessing motor skill acquisition and/or retention. A systematic search across eight databases (e.g., MEDLINE, EMBASE, PsychINFO) identified 66 sources, including 62 experimental studies and 4 reviews. Two researchers independently reviewed articles and extracted data using a pretested data extraction table; disagreements at the study selection or data extraction stages were resolved through discussion with a third researcher. Most studies involved healthy populations (83%), with clinical populations underrepresented (17%). Aerobic exercise was most commonly investigated, particularly lower-limb cycling (73%), while resistance exercise was rarely examined (0.6%). Exercise intensity was predominantly high, although 6% of studies reported intensity not reflecting the prescribed method. Motor learning outcomes varied: 55% assessed both skill acquisition and retention, while 45% relied on retention tests alone at short-term or delayed time points, or both. Infrequent use of long-term retention tests limits understanding of lasting effects. Overall, this review highlights gaps in the literature, including the underrepresentation of clinical populations, inconsistent reporting of exercise intensity, scarce research on resistance exercise, and limited assessment of long-term retention, which may affect interpretation of exercise's impact on motor learning.

Keywords: aerobic exercise, resistance exercise, motor skill acquisition, retention test, performance

Highlights

- Clinical populations were underrepresented in the exercise and motor learning field.
- High-intensity lower-limb cycling was the most common exercise studied.
- Resistance exercise was underrepresented in the field.
- Accurate prescription of exercise intensity is essential to ensure reliable results.
- Future research should more frequently use longer-term retention tests.

1. Introduction

Although the terms "physical activity" and "physical exercise" are sometimes used in similar contexts, they refer to different types of physical movements (Caspersen et al., 1985). Physical activity is defined as any body movement produced by skeletal muscles resulting in energy expenditure (Ndahimana & Kim, 2017). In contrast, physical exercise consists of performing planned and structured physical activity to enhance physical fitness or maintain overall health, and can be either chronic or acute (Kenney et al., 2022). There are different types of physical exercise, including aerobic and resistance exercise. Aerobic exercise includes activities such as running, cycling, and swimming, whereas resistance exercise includes weightlifting and bodyweight exercises. These exercise types can involve different modes of muscular contraction, namely concentric, eccentric, and isometric contractions. Aerobic exercise primarily targets the cardiovascular system and metabolic health, leading to improvement in endurance performance. Resistance exercise primarily targets the neuromuscular system and is essential for developing muscular strength and power (ACSM, 2018). Both aerobic and resistance exercise are essential for maintaining independence in activities of daily living, such as walking, climbing stairs, and carrying objects. Moreover, physical exercise intensity may vary (e.g., low, moderate, and high), and the methodology used to prescribe exercise intensity is different among studies. Importantly, physical exercise is not only beneficial for maintaining physical function and overall health, as it has also been shown to exert beneficial effects on brain health (Cotman & Berchtold, 2002; Phillips et al., 2014; Silva et al., 2024).

Numerous studies in the field of exercise science have highlighted how external interventions, such as physical exercise, can enhance nervous system function (Hillman et al., 2008; Tari et al., 2025). More specifically, physical exercise has been shown to induce significant improvements in cognitive function (Erickson et al., 2011; Phillips et al., 2014). Furthermore, physical exercise has been associated with changes in neuroplasticity (Andrews et al., 2020; Neva, 2025; Neva et al., 2017; Singh et al., 2014; Youssef et al., 2024). Neuroplasticity changes, including alterations in motor cortex excitability, occur during motor learning (Cirillo et al., 2011; Coxon et al., 2014; Holland et al., 2015). Motor cortex excitability reflects the responsiveness, or ease, with which neurons in the motor cortex generate action potentials and trigger muscle activity in response to external stimulation, and is influenced by the balance between excitatory and inhibitory signals that contribute to the overall excitability of the motor cortex (Youssef et al., 2024). Changes in motor cortex excitability suggest that physical exercise may act as a priming mechanism for motor learning, potentially by enhancing motor cortex responsiveness and thereby facilitating the acquisition of new motor skills. Consequently, incorporating physical exercise as an adjunct intervention could be an effective strategy to enhance motor learning (Taubert et al., 2015; Wanner et al., 2020).

A motor skill refers to the ability to perform a goal-directed movement that enables an individual to achieve a specific outcome with accuracy and efficiency, using minimal time and effort (Knapp, 1963). Although often used interchangeably, the terms motor performance and motor learning represent distinct concepts. Motor performance refers to the observable execution of a voluntary action, whereas motor learning involves practice-driven processes that lead to relatively lasting improvements in movement ability (Schmidt & Lee, 2011). Motor learning consists of two fundamental aspects: skill acquisition and skill maintenance. Skill acquisition involves developing movement control through practice, and skill maintenance ensures long-term skill retention and adaptability of the learned skill under different contexts (Krakauer et al., 2019). To study these processes, several motor learning categories have been established, including sequence learning, motor adaptation, motor acuity, and associative learning (for more details, see **Figure S1** in supplementary material 1).

Despite the well-established benefits of physical exercise on physical function and cognition (McMorris et al., 2009; Phillips et al., 2014; Yanagisawa et al., 2010), its impact on motor learning remains unclear, with divergent findings contributing to this uncertainty. For example, some studies found that physical exercise improved motor skill acquisition only (Quaney et al., 2009; Statton et al., 2015), whereas other studies showed improvements in both motor acquisition and motor skill retention following physical exercise (Lehmann et al., 2020; Mang et al., 2014; Neva et al., 2019). Another group of studies reported enhancements only in motor skill retention following physical exercise (Ferrer-Uris et al., 2017; Jespersen et al., 2023; Mang et al., 2016; Stavrinos & Coxon, 2017). In contrast, some studies have found no effect on both skill acquisition and retention following an acute bout of aerobic exercise (Baird et al., 2018; Charalambous et al., 2019; James & Wang, 2023; Pixa et al., 2021; Quinlan et al., 2021; Wanner et al., 2020a). Interestingly, the literature includes a wide range of exercise modalities (e.g., continuous and interval training), types (e.g., aerobic and resistance), and intensities (e.g., low, moderate, and high), as well as varied delays in timing of retention tests (i.e., ranging from hours to days), all of which may contribute to the divergent effects of physical exercise on motor learning. Also, within aerobic exercise, multiple forms have been used, including lower-limb cycling, running, walking, and upper-limb cycling. This diversity in exercise types and protocols adds to the variability observed across studies and underscores the need for careful comparison when interpreting results.

Considering these discrepancies, mapping the existing literature is crucial to better understand the effect of physical exercise on motor learning. A scoping review is particularly suited for this purpose, as it allows researchers to organize and summarize the breadth of evidence, identify key concepts, and uncover gaps in current research, which can then inform future systematic reviews (Munn et al., 2018)

Understanding how different types and intensities of physical exercise impact motor learning is essential for developing targeted exercise protocols that address the specific needs of various populations, whether clinical populations in rehabilitation settings or healthy individuals in sport. Because these populations have distinct characteristics and requirements, tailored exercise protocols may be necessary to optimize motor learning outcomes.

This scoping review aims to explore and map the existing literature on the impact of physical exercise on motor learning in humans. Specifically, we addressed the following research questions:

1) What types of populations were investigated?
2) What types of physical exercise were performed to impact motor learning?
3) When was the physical exercise performed relative to motor task practice?
4) Which types of motor learning categories were used?

These research questions provide a clear structure for understanding the current state of the evidence and highlights areas where further research is needed.

2. Methods

This scoping review was i) pre-registered on the Open Science Framework (OSF) Website (https://osf.io/4mv53), ii) conducted according to the JBI scoping review guidelines and recommendations (Peters et al., 2020), and iii) reported according to the PRISMA extension for scoping reviews [PRISMA-ScR, (Tricco et al., 2018)]. The PRISMA-ScR checklist is provided as Supplementary Material 2.

2.1 Search strategy

The database search was conducted by a librarian (DA) in collaboration with LY and consultation with BP and JN. The search strategy included a combination of keywords and terms indexed across various databases, including MEDLINE (Ovid), EMBASE (Ovid), PsycINFO (Ovid), SportDiscus with Full Text (Ebsco), CINAHL Complete (Ebsco), ERIC (ProQuest), Web of Science (Clarivate), and Dissertations & Theses Global (ProQuest). The complete search equations are provided in supplementary material 3. The search process was conducted in February 2024 and updated in March 2025. The second search led to the inclusion of two additional experimental studies. The search was limited to articles in English and French, with no restrictions on the publication year. All identified sources were uploaded in Endnote (Clarivate Analytics, PA, USA) and duplicates were removed. The screening of all sources was then managed using Covidence software (Innovation, 2023) and followed three steps: (1) remaining duplicates removal, (2) title and abstract screening, and (3) full-text evaluation. Two researchers (LY and AOF) independently reviewed articles at each stage, and any disagreements were resolved through discussion with a third researcher (BP). A detailed flowchart outlining the selection process of sources can be found in **Figure 1**.

2.2 Inclusion Criteria

All fully published, peer-reviewed articles evaluating the effect of physical exercise on motor learning were included. Both experimental studies and reviews that incorporated experimental studies were considered. The primary focus was the impact of physical exercise on motor learning, assessed in either laboratory or field settings. Studies were included if they involved clearly defined motor tasks with assessments of skill acquisition, with or without retention tests. However, following the classical definition of motor learning (Schmidt & Lee, 2011), skill maintenance over time was not considered in studies where a retention test was not included. Furthermore, all types of physical exercise interventions

(aerobic or resistance) at any intensity level (low, moderate, high) were included. Finally, the review included studies involving all types of human populations (healthy and clinical) of all ages.

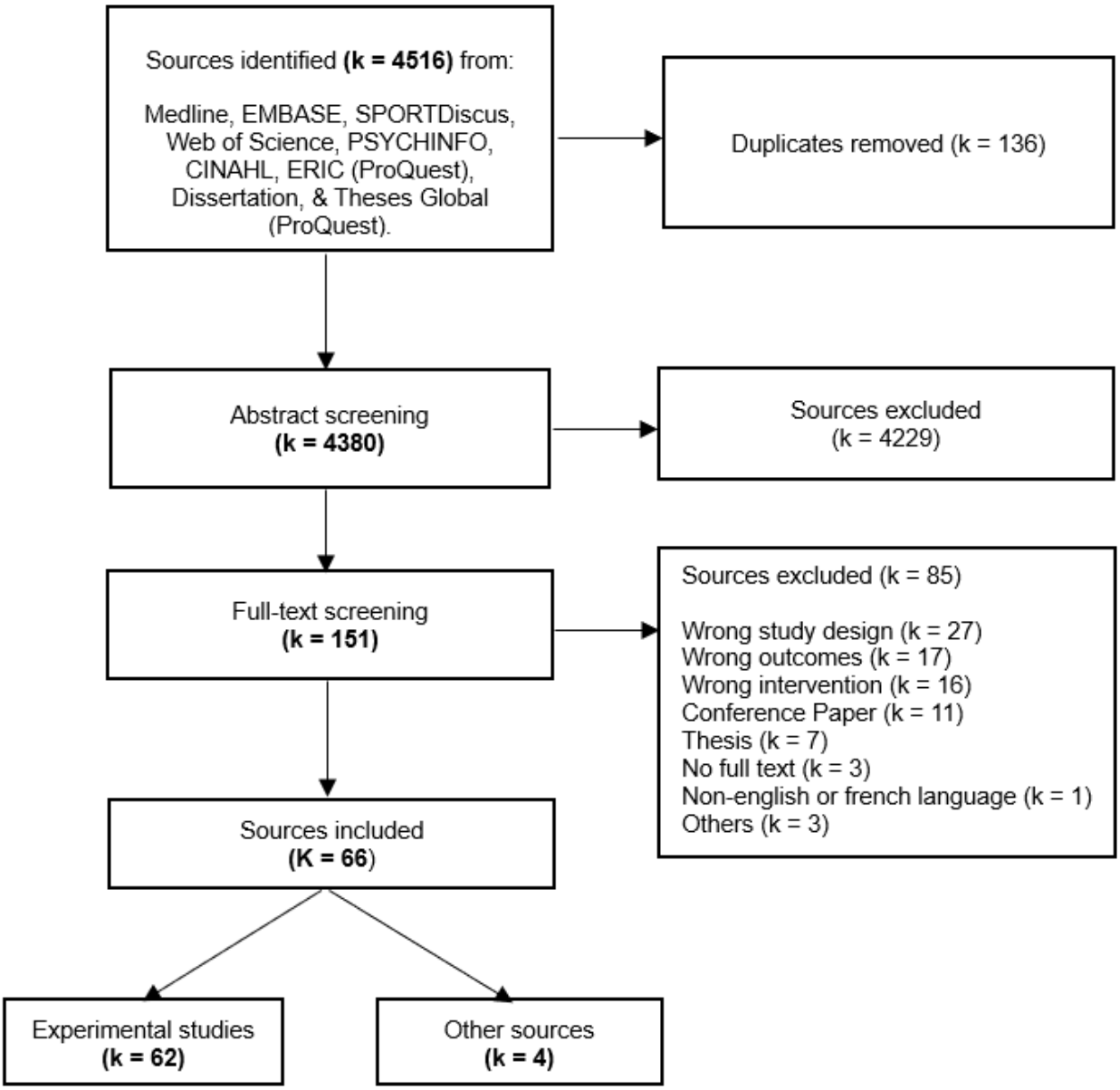

Fig . 1 Flowchart illustrating the selection process of sources.

2.3 Data extraction

The extracted data included details about the evaluated populations, the physical exercise interventions, the motor learning parameters and additional key findings relevant to the objectives of this scoping review. Data extraction was carried out by two independent reviewers (LY and AOF), with any disagreements resolved through discussion. If consensus could not be reached, JN and BP were consulted to provide a final resolution. A data extraction table was used to record the information from the included studies. The initial table was tested on two articles by LY and AOF, then slightly refined before reaching its final version presented in supplementary material 4. For experimental studies, the following data were collected: population characteristics (age and type), details of the physical exercise performed (type, duration, intensity) based on American College of Sports Medicine (ACSM) guidelines (ACSM, 2018), timing of exercise relative to motor task practice (before or after acquisition), motor learning category (sequence, motor acuity, motor adaptation, associative learning) as well as the result as reported in each study (i.e, effect of physical exercise on skill acquisition and/or skill retention). For review articles, data extraction was limited to qualitative information only, specifically the main conclusions and take-home messages related to the effects of physical exercise on motor learning. No quantitative data were extracted from review papers, and primary data reported within these reviews were not re-extracted, thereby avoiding duplication or redundancy with the data extracted in the experimental studies.

Although we followed the pre-registration for the review, two minor deviations were made during the data extraction process to improve methodological clarity. First, we introduced an additional distinction between studies regarding the methodology for exercise prescription. We decided to dissociate prescriptions based on measured versus estimated parameters (e.g., estimated vs measured maximal heart rate). This refinement was not initially planned but was added during data extraction to better capture variability in exercise prescription methods across studies. Second, regarding the motor learning categories (Krakauer et al., 2019), we originally intended to use predefined categories such as sequence learning and adaptation learning. However, after examining the motor tasks used in the included studies, we found that these predefined categories did not fully capture the distinct characteristics of the motor learning constructs investigated. Therefore, we refined our categorization to better reflect the outcomes being evaluated. The categorization used is detailed in **Figure S1** of supplementary material 1.

In this scoping review, the number of experimental conditions exceeds the number of studies, as several studies included multiple experimental conditions. For example, some studies involved different

exercise intensities or different populations. As a result, the mapping of the literature was also conducted based on the number of experimental conditions relevant to each research question. In the manuscript, *n* refers to a subtotal of the number of participants, *k* refers to a subtotal of the number of studies, *g* refers to a subtotal of the number of groups, and *e* refers to a subtotal of the number of experimental conditions. When these letters are capitalized, it refers to the grand total (e.g., N = the total number of participants including all studies and all experimental conditions).

Motor learning categorization and results

To classify the motor learning categories used across studies, we identified four main categories based on task characteristics and learning objectives (Krakauer et al., 2019). *Sequence learning*, often referred to as sequence-specific learning, was defined for motor tasks that involve comparing performance on a repeated sequence or sequences with that of random sequences (e.g., serial reaction time task). This comparison is necessary to identify learning that is specific to the practiced sequence rather than general improvements in other aspects of the motor skill. However, if only a repeated sequence or sequences were practiced without including random sequences for comparison, the motor task was categorized as motor acuity. *Motor acuity* refers to improvements in the accuracy and/or precision of performing a particular movement or sequence of movements through practice (e.g., Rho task). In this case, the focus is on refining the ability to execute the motor task more precisely and/or accurately. *Motor adaptation* included tasks in which participants adjusted their movements in response to external perturbation (e.g., visuomotor rotation task). Finally, *associative learning* referred to tasks requiring participants to form arbitrary associations between stimuli and responses (e.g., conditional learning task). The primary objective of each category is shown in **Figure S1** of supplementary material 1. This classification provides a clear view of the distribution of motor learning categories across the included studies and the identification of gaps in literature.

To provide a comprehensive understanding of the effect of physical exercise on motor learning, we examined skill acquisition and skill retention separately based on when physical exercise was performed relative to the motor task. The results for both skill acquisition and skill retention were reported in studies that performed physical exercise prior to the motor task, while only results from retention tests were reported in studies that conducted physical exercise after the motor task. Furthermore, the timing of retention tests varied across studies. To address this potential challenge in the synthesis of findings, we categorized the reported results from retention tests into three time windows: before 24 hours, at 24 hours, and after 24 hours. Consequently, findings from some studies appear in multiple retention time windows. Results were categorized based on exercise intensity and separated

247 according to population type. However, due to the complexity of intervention types and timing, all forms
248 of physical exercise were grouped together in the outcome of this scoping review, regardless of when the
249 exercise was performed. To accurately assess the effects of physical exercise on motor learning, a
250 comparison with a control condition (i.e., without physical exercise) is essential and was included in the
251 majority of the studies. Based on the results reported by the authors in the experimental studies, motor
252 learning effects were categorized as enhanced, no difference, or attenuated performance. Although
253 studies without a control condition were included in the scoping review and their data were extracted,
254 their findings were not considered in the outcome of this scoping review.

255

256 3. Results

257 *3.1 Included studies*

258 Following the systematic search in various databases, 66 sources were included (see **Figure 1**).
259 Following the JBI guidelines for categorization, 62 primary sources were experimental studies and 4
260 secondary sources were review articles [1 narrative review (Taubert et al., 2015), 2 systematic reviews
261 (Bonuzzi & Torriani-Pasin, 2022; Hubner & Voelcker-Rehage, 2017), and 1 systematic review with
262 meta-analysis (Wanner et al., 2020)]. A timeline of the included sources is presented in **Figure 2a**. The
263 research interest on the effect of physical exercise on motor learning first appeared as early as 1970, but
264 after a long gap, studies in this area began to emerge more consistently starting in 2009, reaching a peak
265 in 2023 with 13 studies published that year. A world map illustrating the geographical distribution of the
266 included studies is presented in **Figure 2b**. This scoping review revealed a worldwide interest in the
267 effects of physical exercise on motor learning, with most studies conducted in Canada (k = 16), the United
268 States (k = 11), Germany (k = 10) and Denmark (k = 6).

269 We extracted data from 62 experimental studies to address our specific research questions. The
270 following sections address our review questions, detailing the populations studied, the types of physical
271 exercise implemented, the motor learning parameters investigated, and the timing of physical exercise in
272 relation to motor task practice. An overview of the main characteristics of all experimental studies is
273 presented in **Table 1**. Detailed characteristics of all included experimental studies are provided in **Table**
274 **S1** (Supplementary Material 1), which offers comprehensive study-level information (e.g., population
275 characteristics, exercise protocols, and outcomes). This table is intended for readers interested in
276 exploring individual studies in greater detail.

Table 1. Characteristics of the included studies related to the review questions.

Study	(1) What types of population were investigated?	(2) What types of physical exercise were performed to impact motor learning? (Type, Intensity)		(3) What types of motor learning categories were used?	(4) When was the physical exercise performed relative to motor task practice?
Andrews et al. (2023)	Huntington's diseases	Lower-limb cycling	Moderate	Motor acuity	Before
Andrushko et al. (2023)	Stroke	Lower-limb cycling	High	Sequence	Before
Angulo-Barroso et al. (2019)	Healthy children	Running	High	Motor adaptation	Before
Baird et al. (2018)	Healthy adults	Lower-limb cycling	Low and high	Sequence	Before
Bartz and Smith (1970)	Healthy adults	Walking	Moderate	Motor adaptation	Before
Bonuzzi et al. (2023)	Stroke and healthy adults	Lower-limb cycling	Moderate	Sequence	Before and after
Bosch et al. (2020)	Healthy adults	Lower-limb cycling	Moderate and high	Sequence	After
Chan et al. (2023)	Parkinson's disease	Lower-limb cycling	High	Sequence	After
Charalambous et al. (2018)	Stroke	Treadmill walking and total body exercise	High	Motor adaptation	Before and after
Charalambous et al. (2019)	Healthy adults	Whole-body cycling	High	Motor adaptation	Before
Chen et al. (2023)	Healthy adults	Treadmill running	Moderate	Motor acuity	Before
Coco et al. (2016)	Healthy adults	Lower-limb cycling	High	Motor acuity	After
Cristini et al. (2023)	Healthy adults	Lower-limb cycling	High	Sequence	After
Dal Maso et al. (2018)	Healthy adults	Lower-limb cycling	High	Motor acuity	After
Duchesne et al. (2016)	Parkinson's disease and healthy older adults	Lower-limb cycling	High	Sequence	After
Ferrer-Uris et al. (2017)	Healthy adults	Shuttle run	High	Motor adaptation	Before and after
Ferrer-Uris et al. (2018)	Healthy children	Shuttle run	High	Motor adaptation	Before and after
Greeley et al. (2021)	Healthy older adults	Lower-limb cycling	High	Sequence	Before
Helm et al. (2017)	Healthy adults	Upper-limb cycling	High	Motor adaptation	Before
Holman and Staines (2021)	Healthy adults	Lower-limb cycling	High	Motor adaptation	After
Hubner et al. (2018)	Healthy older adults	Lower-limb cycling	Moderate	Motor acuity	Before
Hung et al. (2021)	Healthy adults	Lower-limb cycling	High	Motor acuity	After
James and Wang (2023)	Healthy adults	Lower-limb cycling	Moderate	Motor adaptation	Before
Jespersen et al. (2023)	Healthy adults	Lower-limb cycling	Moderate and high	Sequence	Before and after
Khan et al. (2022)	Healthy adults	Lower-limb cycling	High	Motor acuity	After
Kuo, Hsieh, Lin, Kuo, et al. (2023)	Healthy adults	Lower-limb cycling	Low, moderate and high	Sequence	After
Kuo, Hsieh, Lin and Nitsche (2023)	Healthy adults	Lower-limb cycling	Moderate	Sequence	After
Lehmann et al. (2020)	Healthy adults	Lower-limb cycling	High	Motor adaptation	Before
Loras et al. (2020)	Healthy adults	Lower-limb cycling	Low and moderate	Motor acuity	Before
Lundbye-Jensen et al. (2017)	Healthy children	Floorball and running	High	Motor acuity	After
Mang et al. (2014)	Healthy adults	Lower-limb cycling	High	Sequence	Before
Mang et al. (2016)	Healthy adults	Lower-limb cycling	High	Sequence	Before
Munz et al. (2021)	Healthy children	Lower-limb cycling	High	Motor acuity	After
Nepveu et al. (2017)	Stroke	Lower-limb cycling	High	Motor acuity	After

Table 1. *Continued*

Study	(1) What types of population were investigated?	(2) What types of physical exercise were performed to impact motor learning? (Type, Intensity)		(3) What types of motor learning categories were used?	(4) When was the physical exercise performed relative to motor task practice?
Neva et al. (2019)	Healthy adults	Lower-limb cycling	Moderate	Motor adaptation	Before
Ostadan et al. (2016)	Healthy adults	Lower-limb cycling	High	Sequence	After
Opie and Semmler (2019)	Healthy adults	Lower-limb cycling	Moderate and high	Motor acuity	Before
Perini et al. (2016)	Healthy adults	Lower-limb cycling	Moderate	Motor acuity	Before
Pixa et al. (2021)	Healthy adults	Lower-limb cycling	Low and high	Motor acuity	Before
Quaney et al. (2009)	Stroke	Lower-limb cycling	Moderate	Sequence	Before
Quinlan et al. (2021)	Healthy adults	Lower-limb cycling	High	Motor acuity	Before
Rhee et al. (2016)	Healthy adults	Lower-limb cycling	High	Motor acuity	After
Roig et al. (2012)	Healthy adults	Lower-limb cycling	High	Motor acuity	Before and after
Roig-Hierro and Batalla (2023)	Healthy adults	Shuttle run	High	Motor acuity	After
Singh et al. (2016)	Healthy adults	Lower-limb cycling	Moderate	Motor adaptation	Before
Skriver et al. (2014)	Healthy adults	Lower-limb cycling	High	Motor acuity	Before
Snow et al. (2016)	Healthy adults	Lower-limb cycling	Moderate	Motor acuity	Before
Statton et al. (2015)	Healthy adults	Running	High	Motor acuity	Before
Stavrinos and Coxon (2017)	Healthy adults	Lower-limb cycling	High	Motor acuity	Before
Steib et al. (2018)	Parkinson's disease	Lower-limb cycling	Moderate	Motor adaptation	Before
Stranda et al. (2019)	Healthy adults	Lower-limb cycling	Moderate	Motor acuity	Before
Swarbrick et al. (2020)	Healthy adults	Lower-limb cycling	Low and high	Motor acuity	Before
Taylor et al. (2024)	Healthy older adults	Lower-limb cycling	High	Motor acuity	Before
Thomas et al. (2016)	Healthy adults	Lower-limb cycling	Low and high	Motor acuity	After
Thomas et al. (2017)	Healthy adults	Strength training, Circuit training and Hockey training	High	Motor acuity	After
Thompson et al. (2023)	Stroke	Whole-body cycling	High	Motor adaptation	After
Tomporowski and Pendleton (2018)	Healthy adults	Dancing	Moderate	Motor acuity	Before and after
Wanga et al. (2023)	Healthy adults	Lower-limb cycling	Low and high	Sequence	After
Wanner et al. (2020a)	Healthy adults	Lower-limb cycling	Low, moderate, and high	Motor adaptation	Before
Wanner et al. (2021)	Parkinson's disease	Lower-limb cycling	Moderate	Motor adaptation	Before
Williams et al. (1985)	Healthy adults	Upper-limb cycling	Low and high	Motor acuity	Before
Yildirim et al. (2024)	Healthy adults	Running	Low and moderate	Motor acuity	Before and after

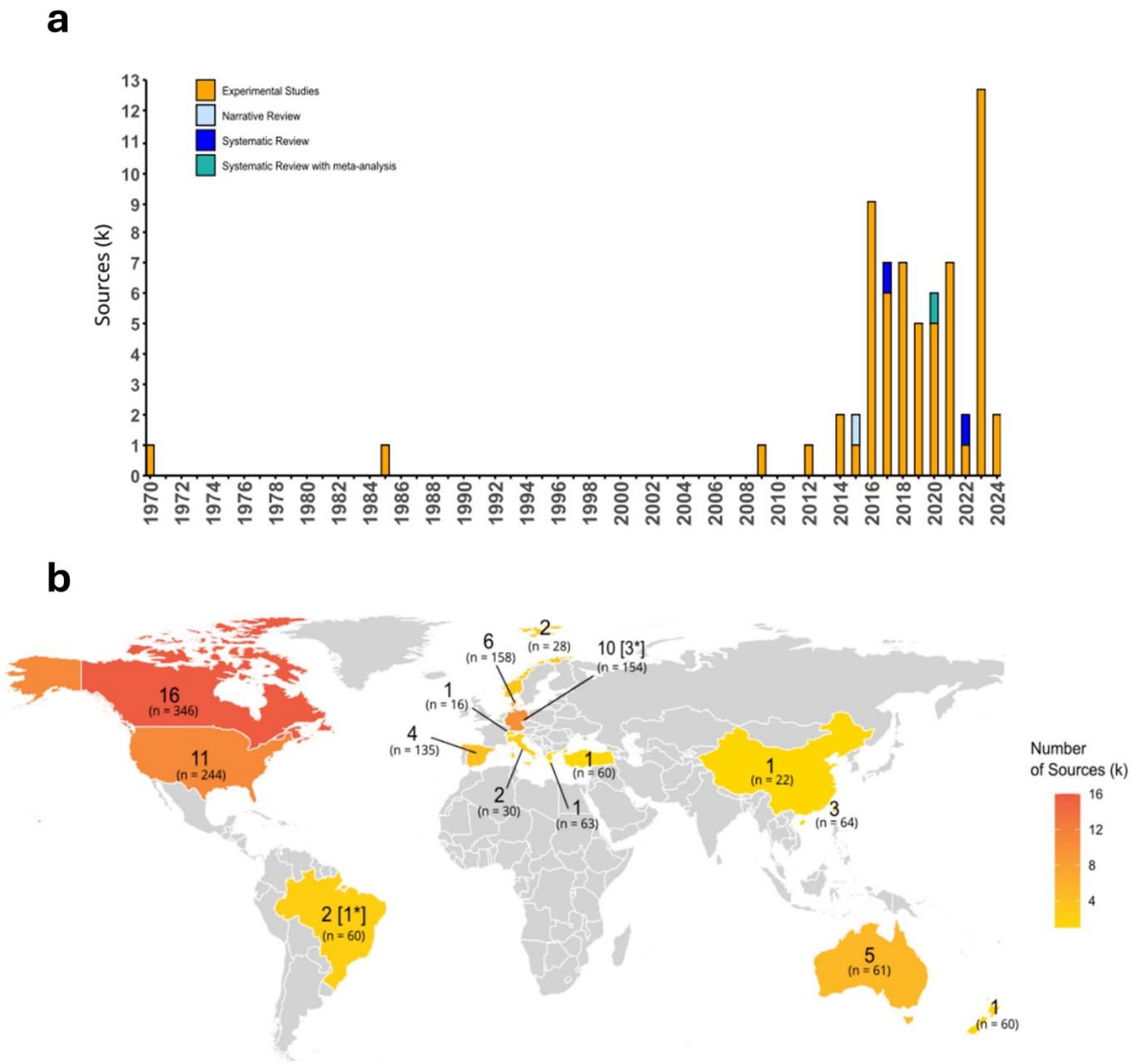

Fig. 2 Temporal and geographical distribution of included sources.
(Panel a) Temporal distribution of all included sources. Orange bars represent experimental studies, while blue gradient bars represent other types of sources (narrative review; systematic review; systematic review with meta-analysis). (Panel b) Geographical distribution of all included sources. The format used is the following: total number [other types of sources*]. The total number of sources is shown first; when sources other than experimental studies are included, their number is indicated in brackets. Darker colors indicate a higher number of sources reported from each country. n refers to the number of participants reported from experimental studies conducted in that country.

3.2 What types of populations were investigated?

The majority of included studies investigated healthy populations (g = 53), while only a small portion of studies (g = 11) focused on clinical populations (see **Figure 3**). Among the studies including healthy populations, 45 studies involved young healthy adults (studies are listed in **Table 1**). Research involving other age groups was limited, with only 4 studies investigating healthy children (Angulo-Barroso et al., 2019; Ferrer-Uris et al., 2018; Lundbye-Jensen et al., 2017; Munz et al., 2021) and 4 studies focusing on healthy older adults (Duchesne et al., 2015; Greeley et al., 2021; Hubner et al., 2018; Taylor et al., 2024). Within the studies investigating clinical populations, three neurological conditions were identified with 6 studies investigating individuals with stroke (Andrushko et al., 2023; Bonuzzi et al., 2023; Charalambous et al., 2018; Nepveu et al., 2017; Quaney et al., 2009; Thompson et al., 2023), followed by 4 studies investigating individuals with Parkinson's disease (Chan et al., 2023; Duchesne et al., 2015; Steib et al., 2018; Wanner et al., 2021). Additionally, a single study focused on individuals with Huntington's disease (Andrews et al., 2023).

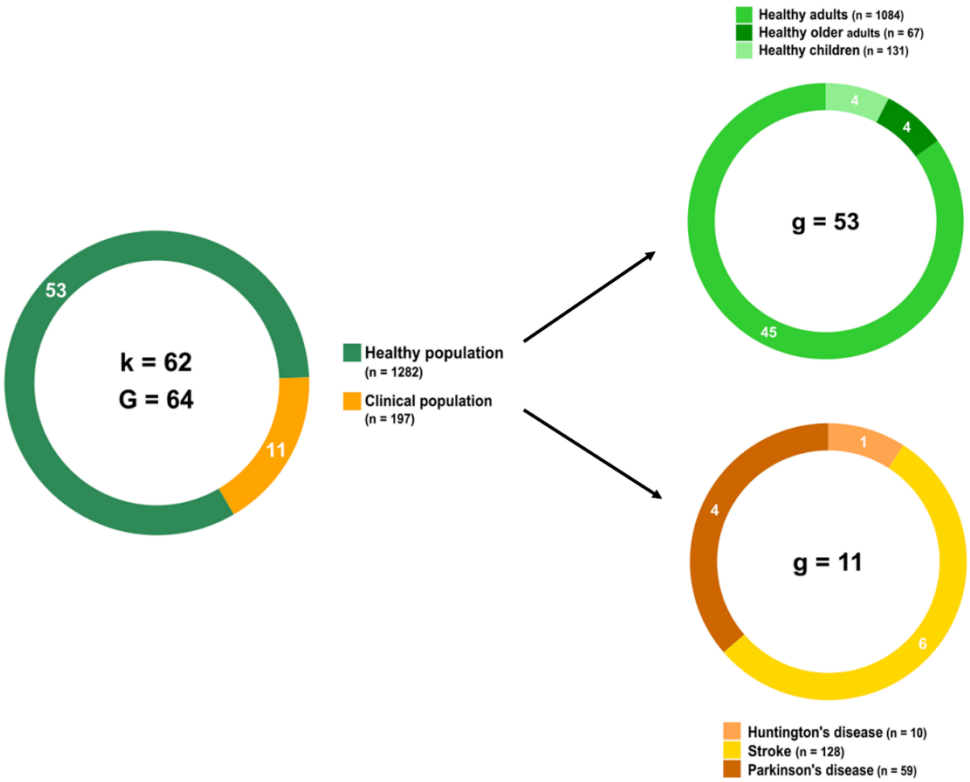

Fig. 3 Types of populations evaluated across all included experimental studies.
Distribution of the 1,479 participants reported across the 62 experimental studies. Participants were categorized as either healthy or clinical populations, with each category further divided into subcategories. Green gradients represent healthy populations, and orange gradients represent clinical populations. k refers to the number of experimental studies, G refers to the overall number of reported groups, g refers to the number of reported subgroups.

3.3 What types and intensities of physical exercise were used?

Among the 62 experimental studies, a total of 81 experimental conditions were conducted (E = 81). The vast majority involved aerobic exercise (e = 79), while only a small number focused on resistance exercise (e = 2) (see **Figure 4a**). Of the aerobic exercise conditions, lower-limb cycling was the main type of exercise used (e = 59). Other aerobic exercise modalities included running (Angulo-Barroso et al., 2019; Chen et al., 2023; Ferrer-Uris et al., 2018; Ferrer-Uris et al., 2017; Lundbye-Jensen et al., 2017; Roig-Hierro & Batalla, 2023; Statton et al., 2015; Yildirim et al., 2024), walking (Bartz & Smith, 1970; Charalambous et al., 2018), upper-limb cycling (Helm et al., 2017; Williams et al., 1985), combined upper and lower-limb cycling (whole-body cycling) (Charalambous et al., 2019; Thompson et al., 2023), and whole-body aerobic exercise (Charalambous et al., 2018). Additionally, a small number of studies employed less common physical exercise, including floorball (Lundbye-Jensen et al., 2017), dancing (Tomporowski & Pendleton, 2018), and hockey (Thomas et al., 2017).

Of the 62 experimental studies included, 34 prescribed exercise intensity based on measured physiological parameters reflecting individual capacity while 28 relied on estimated parameters (see **Figure 4b**). No study used the perception of effort or other perceptual responses to prescribe the exercise intensity. According to ACSM guidelines, the 81 experimental conditions were further classified as high intensity (e = 48), moderate intensity (e = 23), and low intensity (e = 10) (see **Figure 4c**). When combining exercise type and intensity, lower-limb cycling at high intensity was the most commonly used combination, followed by lower-limb cycling at moderate intensity (see **Figure 4d**).

Among the 81 experimental conditions, five showed discrepancies between the reported and actual exercise intensities, as defined by the ACSM guidelines. Specifically, two conditions were reported as moderate intensity, but the prescribed workloads—70% age-predicted heart rate reserve (Holman & Staines, 2021) and 65-85% age-predicted maximal heart rate with a reported average of 84% maximal heart rate (Statton et al., 2015)—fall within the high-intensity range. In another study, two conditions were labeled as moderate and high intensity, but the prescriptions of 50% age-predicted maximal heart rate and 75% age-predicted maximal heart rate respectively, actually correspond to low and moderate intensity based on ACSM guidelines (Loras et al., 2020). Also, one condition was described as low intensity, although the exercise was performed at 50% age-predicted heart rate reserve, which is interpreted as moderate intensity (Opie & Semmler, 2019).

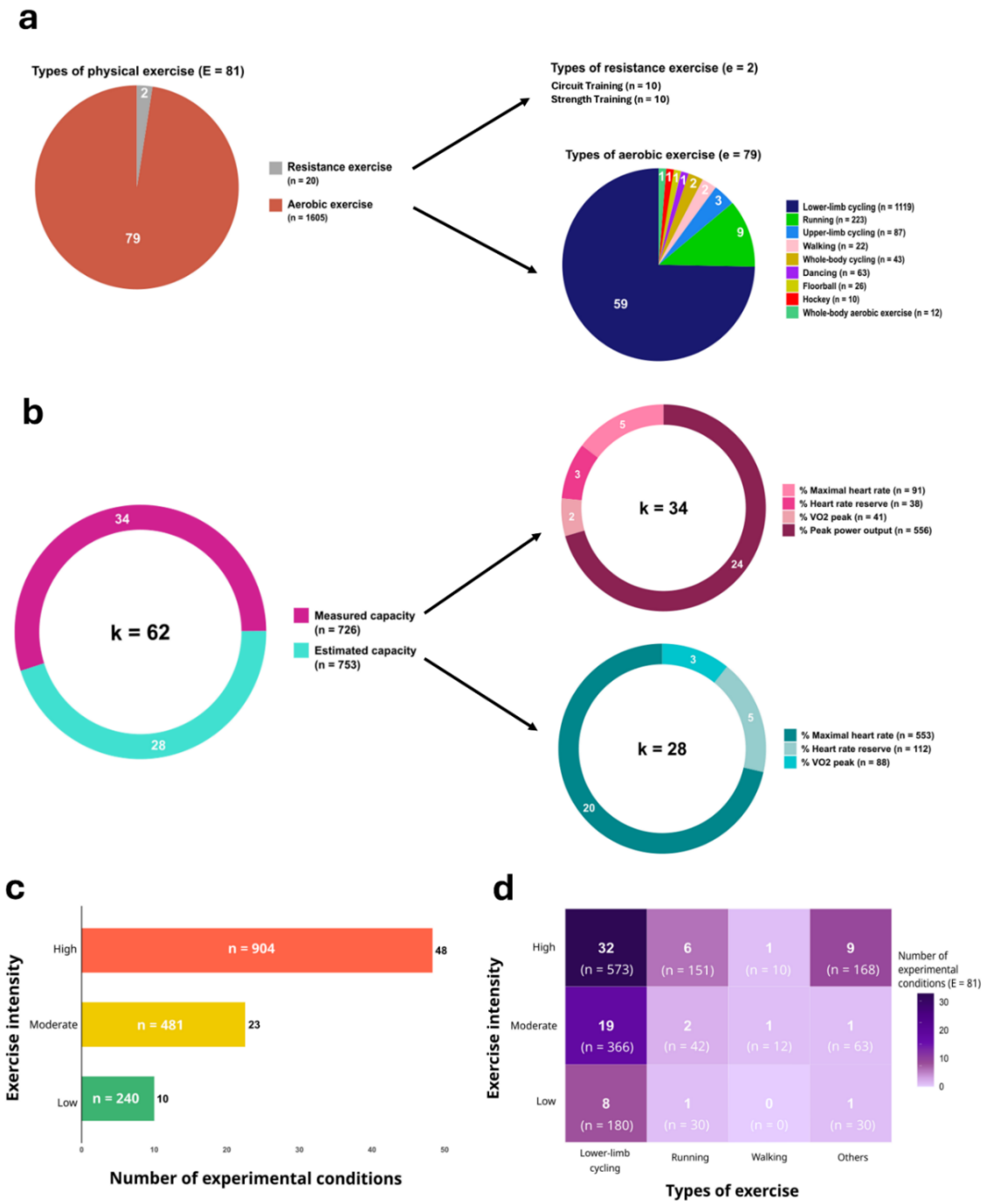

Fig. 4 Types and intensities of physical exercise reported across all included experimental studies. (Panel a) Distribution of the 81 experimental conditions according to exercise type, categorized as aerobic or resistance. Aerobic exercise is further subcategorized by specific types. (Panel b) Prescription of exercise intensities across the experimental studies, pink refers to measured capacity and turquoise refers to estimated capacity. Pink and turquoise gradients refer to measured and estimated exercise parameters respectively. (Panel c) Exercise intensities used across all experiments where red refers to high intensity, yellow refers to moderate intensity and green refers to low intensity. (Panel d) Heatmap showing the combination of exercise type and intensity where darker purple indicates a higher number of experimental conditions using the specific combination. Others refers to all exercise types different from lower-limb cycling, running and walking. E refers to the total number of experimental conditions reported across the 62 included experimental studies, e refers to the number of experimental conditions per exercise type category and n refers to the number of participants.

3.4 Which categories of motor learning were investigated, and when was physical exercise performed relative to motor task practice?

Three motor learning categories were used across the 62 included experimental studies (see **Figure 5a**): 30 involved motor acuity, 16 focused on sequence learning, and 16 addressed motor adaptation; no study investigated associative learning (studies are listed in **Table 1**).

Among the 73 experimental conditions related to the timing of the exercise performed (E = 73), 42 involved physical exercise performed before motor task practice and 31 after (see **Figure 5b**). In healthy adults (e = 51), 30 conditions implemented exercise before motor task practice and 21 after. Among older healthy adults (e = 4), three conditions performed exercise before and one after motor task practice. In healthy children (e = 6), two conditions included exercise before and four after motor task practice. In individuals with stroke (e = 7), four conditions involved exercise before and three after motor task practice. In individuals with Parkinson's disease (e = 4), two conditions implemented exercise before and two after motor task practice. Finally, the single condition involving individuals with Huntington's disease (e = 1) performed exercise before motor task practice (see **Figure 5c**).

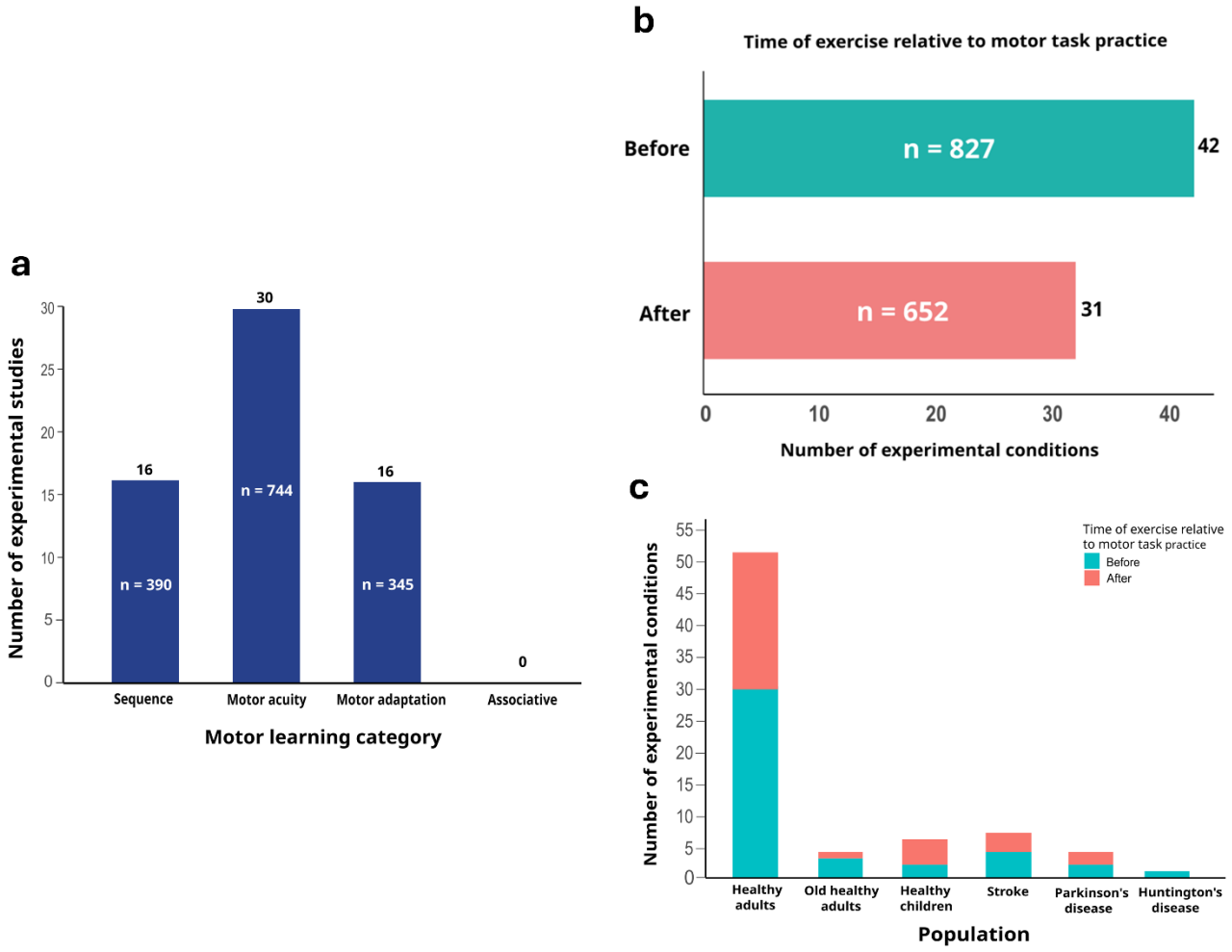

Fig. 5 Motor learning categories and timing of exercise relative to motor task practice.
(Panel a) Distribution of motor learning categories evaluated across the 62 experimental studies. (Panel b) Timing of exercise in relation to motor task practice across the 73 experimental conditions, (Panel c) Timing of exercise in relation to motor task practice across the 73 experimental conditions shown by population type. Light blue indicates exercise performed before the motor task practice, and light red indicates exercise performed after the motor task practice. Before = exercise performed prior to motor task practice; After = exercise performed after the motor task practice; n refers to the number of participants.

3.5 Effects of physical exercise on motor learning

The effects of physical exercise on motor learning, as reported by the authors in each included experimental study, were categorized based on acquisition and retention tests (enhanced, no difference, or attenuated) relative to a control condition. Results for the retention tests were separated into three time windows: less than 24 hours, at 24 hours, and more than 24 hours. These results were categorized by exercise intensity (high, moderate and low) and by population type (see **Figure 6**). Detailed results for each study are also provided in **Table S1** of supplementary material 1.

3.5.1 Skill acquisition

A total of 49 experimental conditions (E = 49) assessed the effects of physical exercise on motor skill acquisition (see **Figure 6a**). In healthy children (e = 3; all high intensity), no significant effects were observed. In healthy adults (e = 35), the majority of experimental conditions showed no effect (e = 28; across low, moderate, and high intensities), while six conditions reported enhancement (e = 6; three with high intensity, three with moderate intensity), and one moderate-intensity condition led to attenuated performance. In healthy older adults (e = 3), two conditions showed no effect (high and moderate intensity), and one high-intensity condition led to attenuated performance. Among individuals with stroke (e = 4), one moderate-intensity condition enhanced acquisition, while the others (two high intensity and one moderate intensity) showed no effect. In individuals with Parkinson's disease, three conditions (e = 3; 2 moderate and 1 high intensity) reported no difference. Finally, the single experimental condition involving individuals with Huntington's disease (e = 1) reported improvement following a moderate-intensity exercise.

3.5.2 Retention tests less than 24h

A total of 28 experimental conditions (E = 28) assessed the effects of physical exercise on performance within 24 hours following the exercise intervention (see **Figure 6b**). In healthy children (e = 3), two experimental conditions showed enhanced performance (both at high intensity), and one condition at high intensity showed no difference. In healthy adults (e = 23), five conditions demonstrated enhanced performance (three at high intensity, two at moderate intensity), 17 showed no difference (across all three intensities), and one high-intensity condition showed attenuated performance at retention. In healthy older adults (e = 2), one condition showed enhanced performance (high intensity) and one showed no difference (moderate intensity). Notably, no experimental conditions involving clinical populations were reported in this retention time category.

3.5.3 Retention tests at 24h

A total of 49 experimental conditions (E = 49) assessed the effects of physical exercise on performance at 24 hours following the exercise intervention (see Figure 6c). In healthy children (e = 4), three conditions showed enhanced performance (all at high intensity), and one condition showed attenuated performance (high intensity). In healthy adults (e = 36), 12 conditions demonstrated enhanced performance (nine at high intensity, two at moderate intensity, and one at low intensity), while 24 conditions showed no difference (across all intensities). In healthy older adults (e = 2), both conditions showed no difference (one at high intensity and one at moderate intensity). Among individuals with stroke (e = 4), one condition showed enhanced performance (high intensity), and three conditions showed no difference (all at high intensity). In individuals with Parkinson's disease (e = 3), one condition showed enhanced performance (moderate intensity), and two conditions showed no difference (one at high intensity and one at moderate intensity).

3.5.4 Retention tests more than 24h

A total of 31 experimental conditions (E = 31) assessed the effects of physical exercise on performance beyond 24 hours following the exercise intervention (see **Figure 6d**). In healthy children (e = 3), all conditions showed enhanced performance (all at high intensity). In healthy adults (e = 21), fourteen conditions showed enhanced performance (ten at high intensity, two at moderate intensity, and two at low intensity), and seven conditions showed no difference (three at high intensity, three at moderate intensity, and one at low intensity). In healthy older adults one condition showed no difference (high intensity). Among individuals with stroke (e = 2), one condition showed no difference (moderate intensity), and one condition showed attenuated performance (moderate intensity). In individuals with Parkinson's disease (e = 3), all conditions showed enhanced performance (two at high intensity and one at moderate intensity).

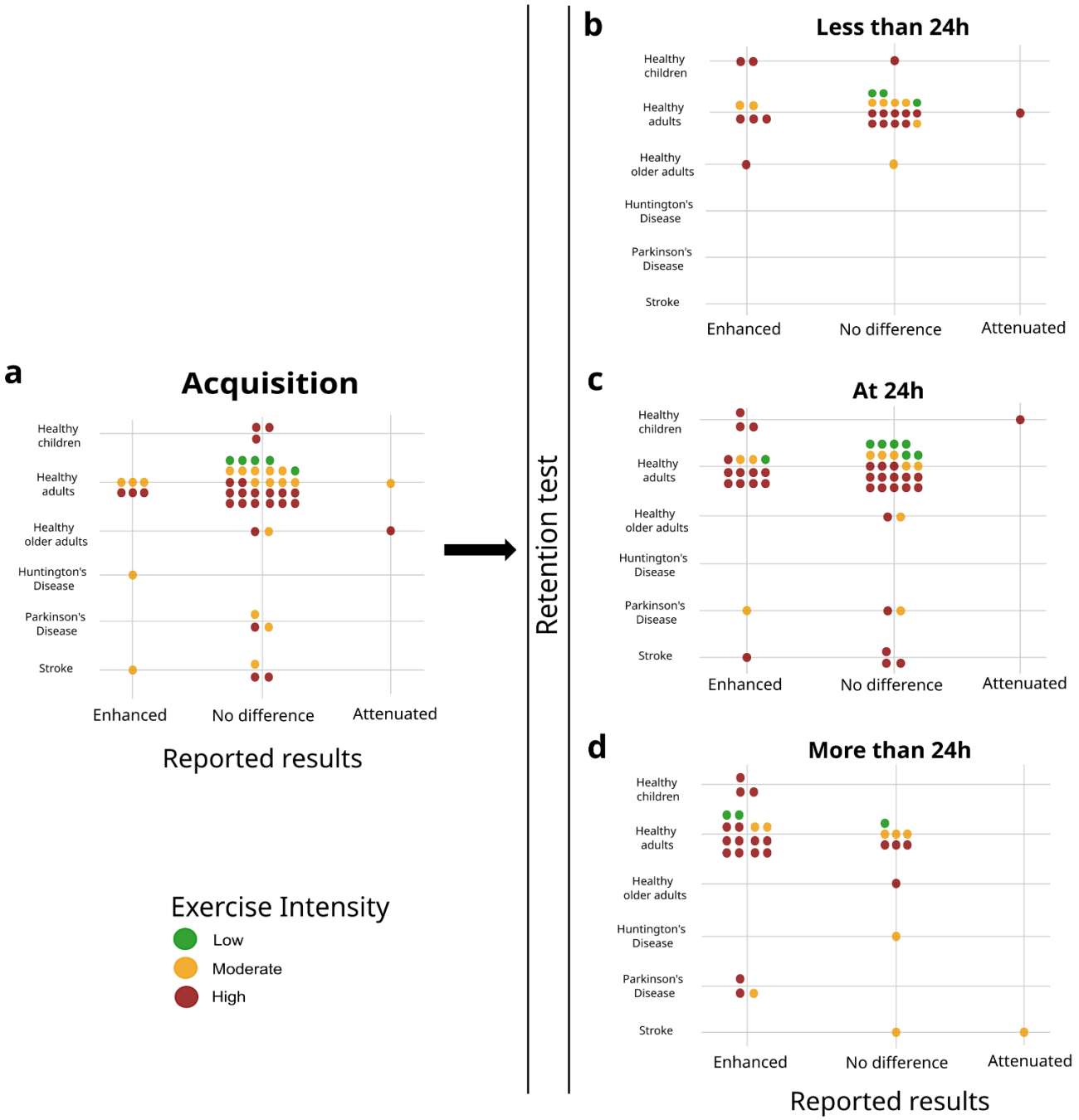

Fig. 6 Effects of physical exercise interventions on motor learning.
Colored dots represent individual experimental conditions, with their position indicating whether motor learning was enhanced, not different, or attenuated compared to a control condition. Only experiments including a control condition were considered. All population types investigated are represented. Reported results related to acquisition are shown only for experiments in which exercise was performed before motor task practice. Reported retention test results are shown regardless of whether exercise was performed before or after motor task practice. (Panel a) Reported results from acquisition. (Panel b) Reported results on motor learning from retention tests conducted within 24 hours following exercise, (Panel c) Reported results on motor learning from retention tests conducted at 24 hours following exercise (Panel d) Reported results on motor learning from retention tests conducted after 24 hours following exercise. Green dots indicate low-intensity exercise, orange dots indicate moderate-intensity exercise, and red dots indicate high-intensity exercise.

3.6 Review articles previously published

Among the included sources, 4 secondary sources were review articles. Bonuzzi and colleagues conducted a systematic review on aerobic exercise and motor learning in healthy individuals, highlighting that exercise performed before or after motor task practice can improve motor learning (Bonuzzi & Torriani-Pasin, 2022). Hubner and colleagues conducted a systematic review examining the effects of physical activity level and acute bouts of physical exercise on motor performance and motor learning of upper limb tasks in older people. This systematic review highlighted the benefits of a high physical activity level in the early phases of motor learning (Hubner & Voelcker-Rehage, 2017). Taubert and colleagues performed a narrative review and discussed behavioral and neurobiological evidence in favor of aerobic exercise as a neuromodulator strategy to promote motor learning and neuroplasticity (Taubert et al., 2015). Wanner and colleagues performed a systematic review and meta-analysis and evaluated how acute aerobic exercise affects the encoding and consolidation of motor memory, highlighting the importance of timing and intensity (Wanner et al., 2020b).

4. Discussion

To the best of our knowledge, this is the first scoping review to explore and map the existing literature on the use of physical exercise to prime motor learning. We included studies involving any population type, any form of physical exercise, and whether the physical exercise was performed before or after any motor learning task. Although our scoping review focuses largely on experimental studies (62 included studies), it should be noted that four previous reviews have explored specific aspects of the topic (1 narrative review, 2 systematic reviews and 1 systematic review with meta-analysis). These focused reviews each addressed important aspects of the topic, and our scoping review synthesis builds on and integrates these contributions by examining a broader range of populations, exercise types, motor learning categories and exercise timing in a single comprehensive framework.

The main outcomes of this scoping review were the following: (1) the evaluated population consisted primarily of healthy individuals, with limited focus on clinical populations and children; (2) the predominant type of physical exercise used was lower-limb cycling, potentially due to its ease of implementation; (3) resistance exercise was rarely used, highlighting a significant gap in the literature regarding its potential role in the promotion of motor learning; (4) in several studies, the prescribed exercise intensity did not align accurately with ACSM guidelines, which may limit the ability to draw accurate conclusions about the effects of specific exercise intensities on motor learning; (5) many studies conducted a single retention test on the same day as the practice session; however, according to the classical definition of motor learning, demonstrating maintenance in motor skill improvement over time via delayed retention tests is essential (Schmidt et al., 2018), and hence these findings may not truly reflect motor learning.

4.1 Limited representation of clinical populations

Most of the included studies involved healthy individuals, with children and clinical populations being significantly less evaluated. One reason could be due to practical limitations, as recruiting healthy adult participants is usually less complicated and requires less time and resources. Yet, in order to determine whether the results obtained in healthy individuals are transferable to children and individuals living with specific health-related conditions, it is essential to replicate the interventions in children and clinical populations. This is particularly of interest for children as this population is crucially developing motor skills needed for their adult life. It is also crucial for clinical populations given that many interventions improving motor learning are designed for rehabilitation purposes (Krakauer, 2006), and the clinical relevance of these interventions should be tested within the clinical populations of interest.

Furthermore, given the limited number of studies involving clinical populations, the division across three distinct conditions (stroke, Parkinson's disease, and Huntington's disease) further limits the applicability of the findings to specific clinical settings, as each subgroup is represented by only a small number of studies.

Importantly, the underlying mechanisms of motor learning may differ between healthy individuals and clinical populations due to different factors including impaired neuroplasticity, altered sensory feedback, or compensatory motor strategies (Boyd & Winstein, 2006; Buma et al., 2010). For instance, in individuals with stroke, cortical reorganization and the recruitment of alternative neural pathways may affect how motor skills are re-acquired (Nudo, 2006). Similarly, in Parkinson's disease, basal ganglia and sensorimotor-related dysfunction may alter feedback-based learning mechanisms (Boyd et al., 2004). These differences imply that exercise interventions that are effective in healthy individuals may not produce the same effects in the context of clinical conditions, making it essential to investigate tailored strategies specific to each clinical population. Therefore, prioritizing research in populations with motor dysfunction and rehabilitation needs including individuals with stroke, or other populations living with neurodegenerative disorders, would be particularly valuable. These population groups could benefit the most from interventions that can enhance motor learning, recovery and maintenance of functional independence. By targeting clinical populations, we can develop more effective, evidence-based interventions that address their specific motor learning profiles.

4.2 Types of aerobic exercise: a focus on lower-limb cycling and the need for diversity

Among the included studies, the predominant form of aerobic exercise was lower-limb cycling. This type of aerobic exercise is likely favored due to its ease of implementation, low risk of injury, and practicality in experimental settings. Particularly, lower-limb cycling effectively induces an aerobic response by engaging the leg muscles, the largest muscle group in the body, resulting in a substantial cardiovascular activation (Poole & Richardson, 1997; Scott et al., 2021). Also, lower-limb cycling allows the upper limbs to remain at rest, which helps prevent the development of neuromuscular fatigue that could negatively impact motor learning when upper-limb motor tasks are used (Ranieri & Di Lazzaro, 2012).

Other types of aerobic exercise such as running, walking, dancing and upper-limb cycling were considerably less represented. Including these diverse forms of aerobic exercise in future research is important for several reasons. Different types may activate distinct neuromuscular and cardiovascular responses, influencing task-specific adaptations, and offer practical alternatives for various populations.

For example, running engages more complex coordination, while upper-limb cycling may be particularly suitable for individuals with lower-limb limitations. Dancing, which is often practiced in groups and especially popular among older adults also deserves attention, as it not only combines demands on the aerobic system and coordination (Keogh et al., 2009; Limanskaya et al., 2021), but has also been associated with enhanced cognitive function (Hewston et al., 2021; Karpati et al., 2015). Dancing also may boost motivation and adherence to regular engagement in physical activity through social interaction (Brustio et al., 2018). In addition, music, which is an integral part of most dance interventions, has itself been linked to improved cognitive function (Schellenberg, 2005) and positive affect (Campion & Levita, 2014), further supporting the potential of dance-based activities in promoting motor learning. Such variety of physical exercise could help reveal how the specific demands of different types of exercise might affect motor learning.

Importantly, all of these reported aerobic types of physical exercise primarily relied on concentric muscle contractions, where the muscles shorten while producing a force. None of the included studies investigated aerobic exercise involving primarily eccentric contractions, like eccentric cycling, in which muscles lengthen while producing a force.

4.3 Eccentric and resistance exercise: underexplored avenues in motor learning research

Interestingly, none of the included studies investigated the effects of physical exercise primarily involving eccentric muscle contractions on motor learning. Eccentric contractions, which involve muscle lengthening while resisting a workload, are known to induce distinct neural adaptations compared to concentric contractions (Fang et al., 2001; Latella et al., 2019). Despite this, research focusing specifically on eccentric-based physical exercise remains limited, representing a notable gap in the literature. Specifically, eccentric contractions have been associated with a prolonged decrease in intracortical inhibition (Latella et al., 2019), a neurophysiological marker of altered motor cortex excitability. Also, it has been shown that eccentric cycling elicits greater activation in sensorimotor-related cortical areas of the frontal and parietal lobes during movement planning and execution (Fang et al., 2001), as well as increased activation in cognitive-related brain regions (Borot et al., 2024). Given the involvement of these brain regions in motor learning, eccentric cycling could induce potential benefits to motor learning.

In fact, recent preliminary evidence from our laboratory (Youssef et al., 2025) supports this idea. This study, which was not included in the present scoping review due to its preprint status at the time of

submission, suggests that eccentric cycling enhances motor learning more than concentric cycling in healthy young adults. These findings suggest that compared to concentric cycling, eccentric cycling may offer specific advantages that promote motor learning. Beyond its potential effects on motor learning, eccentric cycling also provides physiological advantages. For a similar workload, eccentric cycling results in a lower cardiovascular, respiratory, and metabolic cost compared to concentric cycling (Clos et al., 2019; Isner-Horobeti et al., 2013; Peñailillo et al., 2013; Peñailillo et al., 2015). Eccentric cycling is therefore a particularly appealing exercise modality for clinical populations with reduced cardiorespiratory capacity [e.g., (Pageaux et al., 2020)], as well as for older adults [(e.g., (Gault & Willems, 2013)]. Since lower-limb cycling is already the most employed exercise type in the reviewed literature, integrating eccentric cycling could allow researchers to build on already established protocols while expanding the range of muscular contractions studied. Finally, other eccentric-focused exercise types like downhill walking or running also deserve attention. These exercise types involve distinct neuromuscular demands (Garnier et al., 2018) and a lower energy cost (Vernillo et al., 2017), which could be beneficial in rehabilitation. Given the potential benefits of eccentric exercise on motor learning, its integration into future studies evaluating the effects of physical exercise on motor learning appears both feasible and promising (LaStayo et al., 2014).

Beyond eccentric-focused types of exercise, our findings also raise important considerations about resistance exercise, which often incorporates eccentric contractions and shares similar physiological mechanisms (Douglas et al., 2017). These findings also highlight a significant gap in the motor learning literature, which is the underrepresentation of resistance exercise as priming exercise. Of the 81 experimental conditions included, only two involved resistance exercise, despite the fact that this exercise type is widely used in rehabilitation and training. Resistance exercise may influence motor learning through several neural mechanisms. It has been shown that resistance exercise increases muscle activation and neural drive to muscles, leading to improved force production capacity (Aagaard et al., 2002). Resistance exercise can also modulate corticospinal excitability, with evidence indicating that resistance training induces neuroplastic changes within the motor cortex and corticospinal tract (Carroll et al., 2002; Kidgell & Pearce, 2010). Furthermore, resistance exercise may enhance proprioceptive input, increasing sensory feedback, which is an essential component of motor control and learning (Proske & Gandevia, 2012). Supporting these observations, cerebral blood flow during force exertion has been shown to correlate with activity in brain areas such as the primary motor cortex, and the supplementary motor area (Dettmers et al., 1995). These regions are also integral to motor learning processes, suggesting a neuroanatomical overlap between areas recruited during resistance exercise and those underlying motor

learning. However, the direct role of the effects of resistance exercise on motor learning remains largely unexplored. Investigating how resistance exercise influences motor learning represents a promising avenue for future research. Taken together, these observations highlight the need for future studies to incorporate both eccentric and resistance exercise types to better understand their potential roles in enhancing motor learning across various populations.

4.4 Prescription of exercise intensities

Although all studies reported the exercise intensity used, we standardized intensity categorization based on the exercise prescription details provided using the ACSM guidelines (ACSM, 2018). In 5 experimental conditions, discrepancies were observed between the prescribed intensity and the actual workload performed by participants. Some exercise appeared either lighter or more intense than prescribed. For instance, Holman et al. (2021) and Statton et al. (2015) reported using moderate-intensity exercise, yet the prescribed workloads correspond to high-intensity levels according to ACSM guidelines (Holman & Staines, 2021; Statton et al., 2015). Similarly, Opie and Semmler (2019) described their exercise protocol as low-intensity, although it aligns with moderate-intensity based on ACSM classifications (Opie & Semmler, 2019). In contrast, Loras et al. (2020) referred to their two exercise conditions as moderate and high intensity exercise, but these would correspond to low and moderate intensity, respectively, under ACSM classifications (Loras et al., 2020). First, this inconsistency suggests that following established exercise guidelines is essential for drawing accurate conclusions about the effects of specific exercise intensities on motor learning. Second, it allows replicability across studies which is an essential factor for building a consistent and reliable body of evidence. Additionally, while many studies relied on predicted values (e.g., age-predicted maximal heart rate, age-predicted heart rate reserve, estimated VO2max), and although we recognize the practicality of using predicted values in certain research settings, prescribing intensities based on measured capacities are preferable to ensure that the targeted intensity is truly achieved for each participant. Interestingly, none of the studies included in this review employed self-paced exercise protocols. This is notable, as self-paced exercise, for example prescribed with the intensity of perceptual responses such as effort (Beaume et al., 2025; Pageaux, 2016), when matched for workload with externally prescribed intensities (Ekkekakis et al., 2008), has been proposed to enhance affective responses, which can be beneficial for promoting adherence to rehabilitation programs (Ekkekakis et al., 2011).

4.5 Uneven representation of motor learning categories

While the studies included in this review examined various motor learning categories such as sequence learning, motor acuity, and motor adaptation, none investigated the effects of physical exercise on associative learning, which is a fundamental form of motor learning involving stimulus-response associations. Given its relevance in real-world contexts and rehabilitation settings (Le Pelley et al., 2016), investigating how physical exercise influences associative learning could offer valuable insights. For instance, tasks such as learning to respond appropriately to traffic signals while driving rely heavily on stimulus-response associations.

Additionally, the field would benefit from more balanced research across motor learning categories. The current emphasis on motor acuity (n = 30) contrasts with the limited number of studies evaluating sequence learning and motor adaptation (both n = 16). Sequence learning, for example, is highly relevant for activities like playing a musical instrument or typing on a keyboard, while motor adaptation is crucial in situations such as adjusting movements to a new sports technique or learning to walk on uneven surfaces. More research in these underrepresented categories could allow for more robust meta-analyses and potentially clarify whether the effects of physical exercise vary depending on the motor learning type.

4.6 Timing of retention tests

When measuring skill retention, different time points were reported across the studies falling in our defined time windows: less than 24 hours, at 24 hours, and more than 24 hours following motor task practice. Some studies included two time points (Chan et al., 2023; Charalambous et al., 2019; Dal Maso et al., 2018; Hubner et al., 2018; Jespersen et al., 2023; Khan et al., 2022; Pixa et al., 2021; Thomas et al., 2017; Thomas et al., 2016; Wanga et al., 2023; Wanner et al., 2021; Yildirim et al., 2024) or all three time points (Angulo-Barroso et al., 2019; Ferrer-Uris et al., 2018; Ferrer-Uris et al., 2017; Holman & Staines, 2021; Lundbye-Jensen et al., 2017; Roig et al., 2012; Skriver et al., 2014; Swarbrick et al., 2020; Tomporowski & Pendleton, 2018), which provides a clearer understanding of the effects on motor learning. Other studies only assessed short-term retention at less than 24 hours (Bartz & Smith, 1970; Bosch et al., 2020; Coco et al., 2016; James & Wang, 2023; Kuo et al., 2023a; Kuo et al., 2023b; Ostadan et al., 2016; Stavrinos & Coxon, 2017; Taylor et al., 2024). However, measuring skill retention only in the short term (e.g., same day as initial practice) may not be sufficient to assess motor learning, as this may primarily reflect temporary rather sustained performance improvements (Schmidt et al., 2018). According to Schmidt et al. (2018), observing performance after a sufficient delay provides stronger

evidence of stable and relatively permanent changes in the learner's capability, which is the hallmark of motor learning (Schmidt et al., 2018).

Ideally, studies could include both short-term and longer-term retention tests, with the 24-hour time point used as a standard. This would help determine whether performance improvements due to practice are maintained over time, facilitate comparisons across studies, and provide insight into the evolution of motor skill consolidation, which is the process by which newly acquired motor skills become stable and resistant to interference. Using consistent methods to measure skill retention would also help improve the quality of future studies in the field of physical exercise and motor learning.

4.7 Limitations

This scoping review has several limitations, particularly regarding the reported results of motor learning, due to the complexity of categorization. First, for retention tests, all studies were grouped together regardless of whether physical exercise was performed before or after skill acquisition, as the heterogeneity in study designs made it difficult to establish clear subcategories for the reported results on motor learning. Second, no differentiation was made based on the type of exercise for the reported results on motor learning, which limits the ability to attribute specific effects to a particular type of exercise. Third, because we examine the effects of physical exercise in general and as reported by the authors, exercise frequency was not considered, and no distinction was made between acute and chronic interventions. Future studies with more data may allow for a more refined mapping of the literature addressing these aspects.

4.8 Perspectives for future studies

This scoping review highlighted several key areas for future research on the effects of physical exercise on motor learning. First, accurately prescribing exercise intensity is essential. Many studies showed inconsistencies between the reported and the actual prescribed intensity, which can affect the reliability of findings. Using measured values rather than predicted ones, and adhering to established guidelines like the ACSM, would improve consistency and accuracy across studies. As self-paced exercise are proposed to enhance affective responses (Beaume et al., 2025; Pageaux, 2016) and have positive effect on exercise adherence, future studies should consider testing the possibility to prime motor learning with exercise prescribed based on perceptual responses, with particular interest on the perception

of effort (Beaume et al., 2025; Pageaux, 2016). Furthermore, although most studies have concentrated on concentric lower-limb cycling, it is essential to explore the impact of other types of exercise, such as eccentric cycling, on motor learning. Additionally, resistance exercise was rarely used. Integrating resistance exercise modalities will enable us to better understand its potential role in enhancing motor learning across various populations. Moreover, measuring skill retention in motor learning studies in exercise science is another area to improve. Studies testing retention only within a few hours may not fully capture the achievement and maintenance of motor learning. Therefore, including longer retention time points, particularly at 24 hours and more, might help in providing a more comprehensive understanding of the effects of physical exercise on motor learning. Finally, more studies are needed where children, older adults and clinical populations are involved. Increasing research on clinical populations is especially important as motor learning can play a critical role in rehabilitation and recovery.

5. Conclusion

In conclusion, while the field of physical exercise and motor learning is growing, there are several key areas that require improvement. Future research should prioritize accurate and consistent reporting of exercise intensity and consider longer retention intervals to better capture lasting motor learning effects and, consequently, better understand the impact of physical exercise on motor learning. Additionally, greater inclusion of children, older adults and clinical populations is essential, as these population groups may benefit most from motor learning interventions but remain underrepresented in the current literature. Expanding the range of exercise modalities, more particularly types of exercise involving eccentric contractions and resistance-based exercise, may also reveal unique advantages relevant to motor learning in both healthy and clinical populations. Addressing these gaps will help in building a more robust and applicable body of evidence to inform both clinical and non-clinical practice.

List of Abbreviations

- n = subtotal number of participants
- k = subtotal number of studies
- g = subtotal number of groups
- e = subtotal number of experimental conditions
- N = total number of participants (grand total)
- K = total number of studies (grand total)
- G = total number of groups (grand total)
- E = total number of experimental conditions (grand total)

Author contributions

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Disclosure statement

The authors report there are no competing interests to declare.

References

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *93*(4), 1318-1326. https://doi.org/10.1152/japplphysiol.00283.2002

ACSM. (2018). *Amercian College of Sports Medecine's Guidelines for Exercise Testing and Prescription* (10th ed.). https://doi.org/https://www.acsm.org/education-resources/books/guidelines-exercise-testing-prescription

Andrews, S. C., Curtin, D., Hawi, Z., Wongtrakun, J., Stout, J. C., & Coxon, J. P. (2020, Jan 10). Intensity Matters: High-intensity Interval Exercise Enhances Motor Cortex Plasticity More Than Moderate Exercise. *Cereb Cortex, 30*(1), 101-112. https://doi.org/10.1093/cercor/bhz075

Andrews, S. C., Kämpf, L., Curtin, D., Hinder, M., Wenderoth, N., Stout, J. C., & Coxon, J. P. (2023). A single bout of moderate-intensity aerobic exercise improves motor learning in premanifest and early Huntington's disease. *Frontiers in Psychology, 14*, 9. https://doi.org/10.3389/fpsyg.2023.1089333

Andrushko, J. W., Rinat, S., Greeley, B., Larssen, B. C., Jones, C. B., Rubino, C., Denyer, R., Ferris, J. K., Campbell, K. L., Neva, J. L., & Boyd, L. A. (2023). Improved processing speed and decreased functional connectivity in individuals with chronic stroke after paired exercise and motor training. *Scientific Reports, 13*(1), 14. https://doi.org/10.1038/s41598-023-40605-8

Angulo-Barroso, R., Ferrer-Uris, B., & Busquets, A. (2019, Aug). Enhancing children's motor memory retention through acute intense exercise: Effects of different exercise durations [Empirical Study; Quantitative Study]. *Frontiers in Psychology Vol 10 2019, ArtID 2000, 10*. https://doi.org/http://dx.doi.org/10.3389/fpsyg.2019.02000

Baird, J. F., Gaughan, M. E., Saffer, H. M., Sarzynski, M. A., Herter, T. M., Fritz, S. L., den Ouden, D. B., & Stewart, J. C. (2018, Dec). The effect of energy-matched exercise intensity on brain-derived neurotrophic factor and motor learning [Empirical Study; Quantitative Study]. *Neurobiology of Learning and Memory, 156*, 33-44. https://doi.org/http://dx.doi.org/10.1016/j.nlm.2018.10.008

Bartz, D. W., & Smith, L. E. (1970, Aug). Effect of moderate exercise on the performance and learning of a gross motor skill. *Perceptual and Motor Skills, 31*(1), 187-190. https://doi.org/http://dx.doi.org/10.2466/pms.1970.31.1.187

Beaume, J.-B., Di Domenico, H., Bowen, M., Hintzy, F., Millet, G. Y., Pageaux, B., Debevec, T., & Rupp, T. (2025). Neuromuscular Fatigue Induced by Cycling at a Fixed Level of Perceived Effort: Effects of Different Purported Hypoxic Methods. *35*(2), e70021. https://doi.org/https://doi.org/10.1111/sms.70021

Bonuzzi, G. M. G., Bastos, F. H., Schweighofer, N., Wade, E., Winstein, C. J., & Torriani-Pasin, C. (2023). Moderate-intensity cardiovascular exercise performed before motor practice attenuates offline implicit motor learning in stroke survivors but not age-matched neurotypical adults. *Experimental Brain Research, 241*(8), 2019-2032. https://doi.org/10.1007/s00221-023-06659-w

Bonuzzi, G. M. G., & Torriani-Pasin, C. (2022). Cardiovascular exercise and motor learning in non-disabled individuals: A systematic review with a behavioral emphasis. *Motriz-Revista De Educacao Fisica, Revista de Educacao Fisica. 28(no pagination)*(e1022005221). https://doi.org/https://dx.doi.org/10.1590/S1980-65742022005221

Borot, L., Pageaux, B., Laroche, D., Vergotte, G., Lepers, R., & Perrey, S. (2024). Eccentric cycling involves greater mental demand and cortical activation of the frontoparietal network. *34*(1), e14517. https://doi.org/https://doi.org/10.1111/sms.14517

Bosch, B., Bringard, A., Logrieco, M. G., Lauer, E., Imobersteg, N., Thomas, A., Ferretti, G., Schwartz, S., & Igloi, K. (2020, 09 18). Effect of acute physical exercise on motor sequence memory [Research Support, Non-U.S. Gov't]. *Scientific Reports, 10*(1), 15322. https://doi.org/https://dx.doi.org/10.1038/s41598-020-72108-1

Boyd, L. A., & Winstein, C. J. (2006). Explicit Information Interferes with Implicit Motor Learning of Both Continuous and Discrete Movement Tasks After Stroke. *30*(2), 46-57. https://doi.org/10.1097/01.NPT.0000282566.48050.9b

Boyd, L. A., Winstein, C. J. J. L., & memory. (2004). Providing explicit information disrupts implicit motor learning after basal ganglia stroke. *11*(4), 388-396.

Brustio, P. R., Liubicich, M. E., Chiabrero, M., & Rabaglietti, E. J. G. N. (2018). Dancing in the golden age: a study on physical function, quality of life, and social engagement. *39*(6), 635-639.

Buma, F. E., Lindeman, E., Ramsey, N. F., Kwakkel, G. J. N., & repair, n. (2010). Functional neuroimaging studies of early upper limb recovery after stroke: a systematic review of the literature. *24*(7), 589-608.

Campion, M., & Levita, L. J. T. J. o. P. P. (2014). Enhancing positive affect and divergent thinking abilities: Play some music and dance. *9*(2), 137-145.

Carroll, T. J., Riek, S., & Carson, R. G. (2002). The sites of neural adaptation induced by resistance training in humans. *544*(2), 641-652. https://doi.org/https://doi.org/10.1113/jphysiol.2002.024463

Caspersen, C. J., Powell, K. E., & Christenson, G. M. (1985, Mar-Apr). Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. *Public Health Rep, 100*(2), 126-131.

Chan, S. T., Tai, C. H., Wang, L. Y., Luh, J. J., & Lee, Y. Y. (2023). Influences of Aerobic Exercise on Motor Sequence Learning and Corticomotor Excitability in People With Parkinson's Disease. *Neurorehabilitation and Neural Repair, 37*(1), 37-45. https://doi.org/10.1177/15459683221147006

Charalambous, C. C., Alcantara, C. C., French, M. A., Li, X., Matt, K. S., Kim, H. E., Morton, S. M., & Reisman, D. S. (2018, 05 15). A single exercise bout and locomotor learning after stroke: physiological, behavioural, and computational outcomes [Research Support, N.I.H., Extramural

Research Support, Non-U.S. Gov't]. *Journal of Physiology, 596*(10), 1999-2016. https://doi.org/https://dx.doi.org/10.1113/JP275881

Charalambous, C. C., French, M. A., Morton, S. M., & Reisman, D. S. (2019, Nov). A single high-intensity exercise bout during early consolidation does not influence retention or relearning of sensorimotor locomotor long-term memories [Empirical Study; Quantitative Study]. *Experimental Brain Research, 237*(11), 2799-2810. https://doi.org/http://dx.doi.org/10.1007/s00221-019-05635-7

Chen, C., Ryuh, Y. J., Tomporowski, P. P., Lamberth, J., Pan, Z., & Conners, D. A. (2023). Acute Effect of Skill Random Practice Versus Cardiovascular Exercise on Motor Learning of a Golf Putting Task. *International Journal of Sport Psychology, 54*(2), 140-151. https://doi.org/10.7352/ijsp.2023.54.140

Cirillo, J., Todd, G., & Semmler, J. G. (2011, Dec). Corticomotor excitability and plasticity following complex visuomotor training in young and old adults. *Eur J Neurosci, 34*(11), 1847-1856. https://doi.org/10.1111/j.1460-9568.2011.07870.x

Clos, P., Laroche, D., Stapley, P. J., & Lepers, R. (2019). Neuromuscular and Perceptual Responses to Sub-Maximal Eccentric Cycling. *Front Physiol, 10*, 354. https://doi.org/10.3389/fphys.2019.00354

Coco, M., Perciavalle, V., Cavallari, P., & Perciavalle, V. (2016, Mar). Effects of an Exhaustive Exercise on Motor Skill Learning and on the Excitability of Primary Motor Cortex and Supplementary Motor Area [Observational Study]. *Medicine, 95*(11), e2978. https://doi.org/https://dx.doi.org/10.1097/MD.0000000000002978

Cotman, C. W., & Berchtold, N. C. (2002). Exercise: a behavioral intervention to enhance brain health and plasticity. *Trends in Neurosciences, 25*(6), 295-301. https://doi.org/10.1016/S0166-2236(02)02143-4

Coxon, J. P., Peat, N. M., & Byblow, W. D. (2014, Jul 1). Primary motor cortex disinhibition during motor skill learning. *J Neurophysiol, 112*(1), 156-164. https://doi.org/10.1152/jn.00893.2013

Dal Maso, F., Desormeau, B., Boudrias, M.-H., & Roig, M. (2018, Jul). Acute cardiovascular exercise promotes functional changes in cortico-motor networks during the early stages of motor memory consolidation [Empirical Study; Quantitative Study]. *NeuroImage, 174*, 380-392. https://doi.org/http://dx.doi.org/10.1016/j.neuroimage.2018.03.029

Dettmers, C., Fink, G. R., Lemon, R. N., Stephan, K. M., Passingham, R. E., Silbersweig, D., Holmes, A., Ridding, M. C., Brooks, D. J., & Frackowiak, R. J. J. o. n. (1995). Relation between cerebral activity and force in the motor areas of the human brain. *74*(2), 802-815.

Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2017, 2017/04/01). Eccentric Exercise: Physiological Characteristics and Acute Responses. *Sports Medicine, 47*(4), 663-675. https://doi.org/10.1007/s40279-016-0624-8

Duchesne, C., Lungu, O., Nadeau, A., Robillard, M. E., Boré, A., Bobeuf, F., Lafontaine, A. L., Gheysen, F., Bherer, L., & Doyon, J. (2015, Oct). Enhancing both motor and cognitive functioning in

Parkinson's disease: Aerobic exercise as a rehabilitative intervention. *Brain Cogn, 99*, 68-77. https://doi.org/10.1016/j.bandc.2015.07.005

Ekkekakis, P., Hall, E. E., & Petruzzello, S. J. (2008, Apr). The relationship between exercise intensity and affective responses demystified: to crack the 40-year-old nut, replace the 40-year-old nutcracker! *Ann Behav Med, 35*(2), 136-149. https://doi.org/10.1007/s12160-008-9025-z

Ekkekakis, P., Parfitt, G., & Petruzzello, S. J. (2011, Aug 1). The pleasure and displeasure people feel when they exercise at different intensities: decennial update and progress towards a tripartite rationale for exercise intensity prescription. *Sports Med, 41*(8), 641-671. https://doi.org/10.2165/11590680-000000000-00000

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, Feb 15). Exercise training increases size of hippocampus and improves memory. *Proc Natl Acad Sci U S A, 108*(7), 3017-3022. https://doi.org/10.1073/pnas.1015950108

Fang, Y., Siemionow, V., Sahgal, V., Xiong, F., & Yue, G. H. (2001, Oct). Greater movement-related cortical potential during human eccentric versus concentric muscle contractions. *J Neurophysiol, 86*(4), 1764-1772. https://doi.org/10.1152/jn.2001.86.4.1764

Ferrer-Uris, B., Busquets, A., & Angulo-Barroso, R. (2018, Feb). Adaptation and retention of a perceptual-motor task in children: Effects of a single bout of intense endurance exercise [Empirical Study; Quantitative Study]. *Journal of Sport & Exercise Psychology, 40*(1), 1-9. https://doi.org/http://dx.doi.org/10.1123/jsep.2017-0044

Ferrer-Uris, B., Busquets, A., Lopez-Alonso, V., Fernandez-Del-Olmo, M., & Angulo-Barroso, R. (2017). Enhancing consolidation of a rotational visuomotor adaptation task through acute exercise. *PLoS ONE [Electronic Resource], 12*(4), e0175296. https://doi.org/10.1371/journal.pone.0175296

Garnier, Y. M., Lepers, R., Dubau, Q., Pageaux, B., & Paizis, C. (2018, Oct). Neuromuscular and perceptual responses to moderate-intensity incline, level and decline treadmill exercise. *European Journal of Applied Physiology, 118*(10), 2039-2053. https://doi.org/10.1007/s00421-018-3934-8

Gault, M. L., & Willems, M. E. (2013, Sep 25). Aging, functional capacity and eccentric exercise training. *Aging Dis, 4*(6), 351-363. https://doi.org/10.14336/ad.2013.0400351

Greeley, B., Chau, B., Jones, C. B., Neva, J. L., Kraeutner, S. N., Campbell, K. L., & Boyd, L. A. (2021, 08 24). Multiple bouts of high-intensity interval exercise reverse age-related functional connectivity disruptions without affecting motor learning in older adults [Randomized Controlled Trial

Research Support, Non-U.S. Gov't]. *Scientific Reports, 11*(1), 17108. https://doi.org/https://dx.doi.org/10.1038/s41598-021-96333-4

Helm, E. E., Matt, K. S., Kirschner, K. F., Pohlig, R. T., Kohl, D., & Reisman, D. S. (2017, Oct). The influence of high intensity exercise and the Val66Met polymorphism on circulating BDNF and locomotor learning [Empirical Study; Quantitative Study]. *Neurobiology of Learning and Memory, 144*, 77-85. https://doi.org/http://dx.doi.org/10.1016/j.nlm.2017.06.003

Hewston, P., Kennedy, C. C., Borhan, S., Merom, D., Santaguida, P., Ioannidis, G., Marr, S., Santesso, N., Thabane, L., Bray, S. J. A., & ageing. (2021). Effects of dance on cognitive function in older adults: a systematic review and meta-analysis. *50*(4), 1084-1092.

Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008, Jan). Be smart, exercise your heart: exercise effects on brain and cognition. *Nat Rev Neurosci, 9*(1), 58-65. https://doi.org/10.1038/nrn2298

Holland, L., Murphy, B., Passmore, S., & Yielder, P. (2015, Mar 30). Time course of corticospinal excitability changes following a novel motor training task. *Neuroscience Letters, 591*, 81-85. https://doi.org/10.1016/j.neulet.2015.02.022

Holman, S. R., & Staines, W. R. (2021, Aug). The effect of acute aerobic exercise on the consolidation of motor memories. *Experimental Brain Research, 239*(8), 2461-2475. https://doi.org/https://dx.doi.org/10.1007/s00221-021-06148-y

Hubner, L., Godde, B., & Voelcker-Rehage, C. (2018). Acute Exercise as an Intervention to Trigger Motor Performance and EEG Beta Activity in Older Adults [Research Support, Non-U.S. Gov't]. *Neural Plasticity, 2018*, 4756785. https://doi.org/https://dx.doi.org/10.1155/2018/4756785

Hubner, L., & Voelcker-Rehage, C. (2017, Sep). Does physical activity benefit motor performance and learning of upper extremity tasks in older adults? - A systematic review [Review]. *European*

Review of Aging and Physical Activity, 14, 19, Article 15. https://doi.org/10.1186/s11556-017-0181-7

Innovation, V. H. (2023). Covidence systematic review software. https://www.covidence.org

Isner-Horobeti, M. E., Dufour, S. P., Vautravers, P., Geny, B., Coudeyre, E., & Richard, R. (2013, Jun). Eccentric exercise training: modalities, applications and perspectives. *Sports Med, 43*(6), 483-512. https://doi.org/10.1007/s40279-013-0052-y

James, R., & Wang, J. S. (2023). The effects of a single bout of moderate-intensity aerobic exercise on visuomotor adaptation and its savings. *Neurobiology of Learning and Memory, 204*, 7. https://doi.org/10.1016/j.nlm.2023.107801

Jespersen, L., Maes, K. M., Ardenkjær-Skinnerup, N., Roig, M., Bjorndal, J. R., Beck, M. M., & Lundbye-Jensen, J. (2023). Acute exercise performed before and after motor practice enhances the positive effects on motor memory consolidation. *Neurobiology of Learning and Memory, 205*, 10. https://doi.org/10.1016/j.nlm.2023.107830

Karpati, F. J., Giacosa, C., Foster, N. E. V., Penhune, V. B., & Hyde, K. L. (2015). Dance and the brain: a review. *1337*(1), 140-146. https://doi.org/https://doi.org/10.1111/nyas.12632

Kenney, W. L., Wilmore, J. H., & Costill, D. L. (2022). *Physiology of sport and exercise*. Human kinetics.

Keogh, J. W., Kilding, A., Pidgeon, P., Ashley, L., Gillis, D. J. J. o. a., & activity, p. (2009). Physical benefits of dancing for healthy older adults: a review. *17*(4), 479-500.

Khan, A., Singh, J., Neary, J. P., & Mang, C. S. (2022). Exercise Effects on Motor Skill Consolidation and Intermuscular Coherence Depend on Practice Schedule. *Brain Sciences, 12*(4), 17. https://doi.org/10.3390/brainsci12040436

Kidgell, D. J., & Pearce, A. J. (2010, October). Corticospinal properties following short-term strength training of an intrinsic hand muscle. *Human Movement Science, 29*(5), 631-641. https://doi.org/http://dx.doi.org/10.1016/j.humov.2010.01.004

Knapp, B. (1963). *Skill in Sport: The Attainment of Proficiency*. Routledge & K. Paul. https://books.google.ca/books?id=LEcW9JcXup8C

Krakauer, J. W. (2006, Feb). Motor learning: its relevance to stroke recovery and neurorehabilitation. *Current Opinion in Neurology, 19*(1), 84-90. https://doi.org/10.1097/01.wco.0000200544.29915.cc

Krakauer, J. W., Hadjiosif, A. M., Xu, J., Wong, A. L., & Haith, A. M. (2019, Mar 14). Motor Learning. *Comprehensive Physiology, 9*(2), 613-663. https://doi.org/10.1002/cphy.c170043

Kuo, H. I., Hsieh, M. H., Lin, Y. T., Kuo, M. F., & Nitsche, M. A. (2023a, Jan-Apr). A single bout of aerobic exercise modulates motor learning performance and cortical excitability in humans. *Int J Clin Health Psychol, 23*(1), 100333. https://doi.org/10.1016/j.ijchp.2022.100333

Kuo, H. I., Hsieh, M. H., Lin, Y. T., & Nitsche, M. A. (2023b, Nov). Acute Aerobic Exercise at Different Intensities Modulates Motor Learning Performance and Cortical Excitability in Sedentary Individuals. *Eneuro, 10*(11). https://doi.org/10.1523/eneuro.0182-23.2023

LaStayo, P., Marcus, R., Dibble, L., Frajacomo, F., & Lindstedt, S. J. J. o. A. P. (2014). Eccentric exercise in rehabilitation: safety, feasibility, and application. *116*(11), 1426-1434.

Latella, C., Goodwill, A. M., Muthalib, M., Hendy, A. M., Major, B., Nosaka, K., & Teo, W. P. (2019, Mar). Effects of eccentric versus concentric contractions of the biceps brachii on intracortical inhibition and facilitation. *Scand J Med Sci Sports, 29*(3), 369-379. https://doi.org/10.1111/sms.13334

Le Pelley, M. E., Mitchell, C. J., Beesley, T., George, D. N., & Wills, A. J. J. P. b. (2016). Attention and associative learning in humans: An integrative review. *142*(10), 1111.

Lehmann, N., Villringer, A., & Taubert, M. (2020, Mar). Colocalized white matter plasticity and increased cerebral blood flow mediate the beneficial effect of cardiovascular exercise on long-term motor learning [Brain Imaging; Empirical Study; Quantitative Study]. *The Journal of Neuroscience, 40*(12), 2416-2429. https://doi.org/http://dx.doi.org/10.1523/JNEUROSCI.2310-19.2020

Limanskaya, O. V., Yefimova, O. V., Kriventsova, I. V., Wnorowski, K., & Bensbaa, A. J. P. e. o. s. (2021). The coordination abilities development in female students based on dance exercises. *25*(4), 249-256.

Loras, H., Haga, M., & Sigmundsson, H. (2020, Feb). Effect of a Single Bout of Acute Aerobic Exercise at Moderate-to-Vigorous Intensities on Motor Learning, Retention and Transfer [Article]. *Sports, 8*(2), 13, Article 15. https://doi.org/10.3390/sports8020015

Lundbye-Jensen, J., Skriver, K., Nielsen, J. B., & Roig, M. (2017). Acute exercise improves motor memory consolidation in preadolescent children. *Frontiers in Human Neuroscience Vol 11 2017, ArtID 182, 11*. https://ovidsp.ovid.com/ovidweb.cgi?T=JS&CSC=Y&NEWS=N&PAGE=fulltext&D=psyc14&AN=2017-17997-001

Mang, C. S., Snow, N. J., Campbell, K. L., Ross, C. J., & Boyd, L. A. (2014, Dec 1). A single bout of high-intensity aerobic exercise facilitates response to paired associative stimulation and promotes sequence-specific implicit motor learning. *J Appl Physiol (1985), 117*(11), 1325-1336. https://doi.org/10.1152/japplphysiol.00498.2014

Mang, C. S., Snow, N. J., Wadden, K. P., Campbell, K. L., & Boyd, L. A. (2016, 12). High-Intensity Aerobic Exercise Enhances Motor Memory Retrieval. *Medicine & Science in Sports & Exercise, 48*(12), 2477-2486. https://ovidsp.ovid.com/ovidweb.cgi?T=JS&CSC=Y&NEWS=N&PAGE=fulltext&D=med13&AN=27414689

https://libkey.io/libraries/2401/pdfexpress/openurl?genre=article&aulast=Mang&issn=0195-9131&title=Medicine+%26+Science+in+Sports+%26+Exercise&atitle=High-Intensity+Aerobic+Exercise+Enhances+Motor+Memory+Retrieval.&volume=48&issue=12&spage=2477&epage=2486&date=2016&doi=10.1249%2FMSS.0000000000001040&pmid=27414689&sid=OVID:medline

McMorris, T., Tomporowski, P., & Audiffren, M. (2009). *Exercise and cognitive function*. John Wiley & Sons.

Munn, Z., Peters, M. D., Stern, C., Tufanaru, C., McArthur, A., & Aromataris, E. J. B. m. r. m. (2018). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *18*(1), 143.

Munz, M., Baving, L., & Prehn-Kristensen, A. (2021, Mar). Sleep following intense physical exercise stabilizes motor learning in typically developing boys [Empirical Study; Quantitative Study]. *Mental Health and Physical Activity Vol 20 2021, ArtID 100365, 20*. https://doi.org/http://dx.doi.org/10.1016/j.mhpa.2020.100365

Ndahimana, D., & Kim, E.-K. J. C. n. r. (2017). Measurement methods for physical activity and energy expenditure: a review. *6*(2), 68-80.

Nepveu, J. F., Thiel, A., Tang, A., Fung, J., Lundbye-Jensen, J., Boyd, L. A., & Roig, M. (2017, Aug). A Single Bout of High-Intensity Interval Training Improves Motor Skill Retention in Individuals With Stroke [Randomized Controlled Trial]. *Neurorehabilitation & Neural Repair, 31*(8), 726-735. https://doi.org/https://dx.doi.org/10.1177/1545968317718269

Neva, J. L. (2025). Exercise-induced neuroplasticity. In J. H. Grafman (Ed.), *Encyclopedia of the Human Brain (Second Edition)* (pp. 706-729). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-820480-1.00218-7

Neva, J. L., Brown, K. E., Mang, C. S., Francisco, B. A., & Boyd, L. A. (2017, May). An acute bout of exercise modulates both intracortical and interhemispheric excitability. *Eur J Neurosci, 45*(10), 1343-1355. https://doi.org/10.1111/ejn.13569

Neva, J. L., Ma, J. A., Orsholits, D., Boisgontier, M. P., & Boyd, L. A. (2019, Apr). The effects of acute exercise on visuomotor adaptation, learning, and inter-limb transfer [Empirical Study; Quantitative Study]. *Experimental Brain Research, 237*(4), 1109-1127. https://doi.org/http://dx.doi.org/10.1007/s00221-019-05491-5

Nudo, R. J. J. C. o. i. n. (2006). Mechanisms for recovery of motor function following cortical damage. *16*(6), 638-644.

Opie, G. M., & Semmler, J. G. (2019, Aug 1). Acute Exercise at Different Intensities Influences Corticomotor Excitability and Performance of a Ballistic Thumb Training Task. *Neuroscience, 412*, 29-39. https://doi.org/10.1016/j.neuroscience.2019.05.049

Ostadan, F., Centeno, C., Daloze, J. F., Frenn, M., Lundbye-Jensen, J., & Roig, M. (2016, Dec). Changes in corticospinal excitability during consolidation predict acute exercise-induced off-line gains in

procedural memory. *Neurobiology of Learning & Memory, 136*, 196-203. https://doi.org/10.1016/j.nlm.2016.10.009

Pageaux, B. (2016, Nov). Perception of effort in Exercise Science: Definition, measurement and perspectives. *Eur J Sport Sci, 16*(8), 885-894. https://doi.org/10.1080/17461391.2016.1188992

Pageaux, B., Besson, D., Casillas, J. M., Lepers, R., Gremeaux, V., Ornetti, P., Gouteron, A., & Laroche, D. (2020, May). Progressively increasing the intensity of eccentric cycling over four training sessions: A feasibility study in coronary heart disease patients. *Ann Phys Rehabil Med, 63*(3), 241-244. https://doi.org/10.1016/j.rehab.2019.09.007

Peñailillo, L., Blazevich, A., Numazawa, H., & Nosaka, K. (2013, Sep). Metabolic and muscle damage profiles of concentric versus repeated eccentric cycling. *Med Sci Sports Exerc, 45*(9), 1773-1781. https://doi.org/10.1249/MSS.0b013e31828f8a73

Peñailillo, L., Blazevich, A. J., & Nosaka, K. (2015, Apr). Muscle fascicle behavior during eccentric cycling and its relation to muscle soreness. *Med Sci Sports Exerc, 47*(4), 708-717. https://doi.org/10.1249/mss.0000000000000473

Peters, M. D. J., Marnie, C., Tricco, A. C., Pollock, D., Munn, Z., Alexander, L., McInerney, P., Godfrey, C. M., & Khalil, H. (2020, Oct). Updated methodological guidance for the conduct of scoping reviews. *JBI Evid Synth, 18*(10), 2119-2126. https://doi.org/10.11124/jbies-20-00167

Phillips, C., Baktir, M. A., Srivatsan, M., & Salehi, A. (2014). Neuroprotective effects of physical activity on the brain: a closer look at trophic factor signaling. *Front Cell Neurosci, 8*, 170. https://doi.org/10.3389/fncel.2014.00170

Pixa, N. H., Hubner, L., Kutz, D. F., & Voelcker-Rehage, C. (2021). A Single Bout of High-Intensity Cardiovascular Exercise Does Not Enhance Motor Performance and Learning of a Visuomotor Force Modulation Task, but Triggers Ipsilateral Task-Related EEG Activity. *International Journal of Environmental Research & Public Health [Electronic Resource], 18*(23), 27. https://doi.org/https://dx.doi.org/10.3390/ijerph182312512

Poole, D. C., & Richardson, R. S. J. S. M. (1997). Determinants of oxygen uptake: implications for exercise testing. *24*, 308-320.

Proske, U., & Gandevia, S. C. (2012). The Proprioceptive Senses: Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force. *92*(4), 1651-1697. https://doi.org/10.1152/physrev.00048.2011

Quaney, B. M., Boyd, L. A., McDowd, J. M., Zahner, L. H., Jianghua, H., Mayo, M. S., & Macko, R. F. (2009, Nov-Dec). Aerobic exercise improves cognition and motor function poststroke [Empirical Study; Quantitative Study]. *Neurorehabilitation and Neural Repair, 23*(9), 879-885. https://doi.org/http://dx.doi.org/10.1177/1545968309338193

Quinlan, C., Rattray, B., Pryor, D., Northey, J. M., Coxon, J., Cherbuin, N., & Andrews, S. C. (2021, Jun). A short-term intervention of high-intensity exercise and anodal-tDCS on motor learning in middle-aged adults: An RCT [Empirical Study; Quantitative Study]. *Frontiers in Human Neuroscience Vol 15 2021, ArtID 661079, 15*. https://doi.org/http://dx.doi.org/10.3389/fnhum.2021.661079

Ranieri, F., & Di Lazzaro, V. (2012, Dec). The role of motor neuron drive in muscle fatigue. *Neuromuscul Disord, 22 Suppl 3*, S157-161. https://doi.org/10.1016/j.nmd.2012.10.006

Roig-Hierro, E., & Batalla, A. (2023). Acute exercise on complex motor memory retention: the role of task cognitive demands. *International Journal of Sport and Exercise Psychology*, 15. https://doi.org/10.1080/1612197x.2023.2278522

Roig, M., Skriver, K., Lundbye-Jensen, J., Kiens, B., & Nielsen, J. B. (2012, Sep). A single bout of exercise improves motor memory [Empirical Study; Quantitative Study]. *PLoS ONE Vol 7(9), 2012, ArtID e44594, 7*(9). https://doi.org/http://dx.doi.org/10.1371/journal.pone.0044594

Schellenberg, E. G. J. C. D. i. P. S. (2005). Music and cognitive abilities. *14*(6), 317-320.

Schmidt, R. A., & Lee, T. D. (2011). *Motor control and learning: A behavioral emphasis, 5th ed*. Human Kinetics.

Schmidt, R. A., Lee, T. D., Winstein, C., Wulf, G., & Zelaznik, H. N. (2018). *Motor control and learning: A behavioral emphasis*. Human kinetics.

Scott, K., Howley, E. T., & Quindry, J. (2021). *Exercise physiology: theory and application to fitness and performance*. McGraw-Hill.

Silva, N. C. B. S., Barha, C. K., Erickson, K. I., Kramer, A. F., & Liu-Ambrose, T. J. T. i. n. (2024). Physical exercise, cognition, and brain health in aging. *47*(6), 402-417.

Singh, A. M., Duncan, R. E., Neva, J. L., & Staines, W. R. (2014, 2014/06/21). Aerobic exercise modulates intracortical inhibition and facilitation in a nonexercised upper limb muscle. *BMC Sports Science, Medicine and Rehabilitation, 6*(1), 23. https://doi.org/10.1186/2052-1847-6-23

Skriver, K., Roig, M., Lundbye-Jensen, J., Pingel, J., Helge, J. W., Kiens, B., & Nielsen, J. B. (2014, Dec). Acute exercise improves motor memory: Exploring potential biomarkers [Empirical Study; Quantitative Study]. *Neurobiology of Learning and Memory, 116*, 46-58. https://doi.org/http://dx.doi.org/10.1016/j.nlm.2014.08.004

Statton, M. A., Encarnacion, M., Celnik, P., & Bastian, A. J. (2015, Oct). A single bout of moderate aerobic exercise improves motor skill acquisition [Empirical Study; Quantitative Study]. *PLoS ONE Vol 10(10), 2015, ArtID e0141393, 10*(10). https://doi.org/http://dx.doi.org/10.1371/journal.pone.0141393

Stavrinos, E. L., & Coxon, J. P. (2017, Apr). High-intensity interval exercise promotes motor cortex disinhibition and early motor skill consolidation [Empirical Study; Mathematical Model; Quantitative Study]. *Journal of Cognitive Neuroscience, 29*(4), 593-604. https://doi.org/http://dx.doi.org/10.1162/jocn_a_01078

Steib, S., Wanner, P., Adler, W., Winkler, J., Klucken, J., & Pfeifer, K. (2018, Oct). A single bout of aerobic exercise improves motor skill consolidation in Parkinson's disease [Empirical Study; Quantitative Study]. *Frontiers in Aging Neuroscience Vol 10 2018, ArtID 328, 10*. https://doi.org/http://dx.doi.org/10.3389/fnagi.2018.00328

Swarbrick, D., Kiss, A., Trehub, S., Tremblay, L., Alter, D., & Chen, J. L. (2020). HIIT the Road Jack: An Exploratory Study on the Effects of an Acute Bout of Cardiovascular High-Intensity Interval Training on Piano Learning. *Frontiers in Psychology, 11*, 17. https://doi.org/10.3389/fpsyg.2020.02154

Tari, A. R., Walker, T. L., Huuha, A. M., Sando, S. B., & Wisloff, U. J. T. L. (2025). Neuroprotective mechanisms of exercise and the importance of fitness for healthy brain ageing. *405*(10484), 1093-1118.

Taubert, M., Villringer, A., & Lehmann, N. (2015, Dec). Endurance exercise as an "endogenous" neuro-enhancement strategy to facilitate motor learning. *Frontiers in Human Neuroscience Vol 9 2015, ArtID 692, 9*. https://doi.org/http://dx.doi.org/10.3389/fnhum.2015.00692

Taylor, E. M., Cadwallader, C. J., Curtin, D., Chong, T. T. J., Hendrikse, J. J., & Coxon, J. P. (2024, 2024/02/17). High-intensity acute exercise impacts motor learning in healthy older adults. *npj Science of Learning, 9*(1), 9. https://doi.org/10.1038/s41539-024-00220-2

Thomas, R., Flindtgaard, M., Skriver, K., Geertsen, S. S., Christiansen, L., Korsgaard Johnsen, L., Busk, D. V. P., Bojsen-Moller, E., Madsen, M. J., Ritz, C., Roig, M., & Lundbye-Jensen, J. (2017, Nov). Acute exercise and motor memory consolidation: Does exercise type play a role? [Randomized Controlled Trial]. *Scandinavian Journal of Medicine & Science in Sports, 27*(11), 1523-1532. https://doi.org/https://dx.doi.org/10.1111/sms.12791

Thomas, R., Johnsen, L. K., Geertsen, S. S., Christiansen, L., Ritz, C., Roig, M., & Lundbye-Jensen, J. (2016). Acute exercise and motor memory consolidation: The role of exercise intensity. *PLoS ONE Vol 11(7), 2016, ArtID e0159589, 11*(7). https://doi.org/http://dx.doi.org/10.1371/journal.pone.0159589

Thompson, E. D., Bhat, S., French, M. A., Morton, S., Pohlig, R. T., & Reisman, D. S. (2023). Effects of an Acute High Intensity Exercise Bout on Retention of Explicit, Strategic Locomotor Learning in Individuals With Chronic Stroke. *Neurorehabilitation and Neural Repair, 37*(9), 628-639. https://doi.org/10.1177/15459683231195039

Tomporowski, P. D., & Pendleton, D. M. (2018, Oct). Effects of the timing of acute exercise and movement complexity on young adults' psychomotor learning [Empirical Study; Quantitative Study]. *Journal of Sport & Exercise Psychology, 40*(5), 240-248. https://doi.org/http://dx.doi.org/10.1123/jsep.2017-0289

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., Lewin, S., Godfrey, C. M., Macdonald, M. T., Langlois, E. V., Soares-Weiser, K., Moriarty, J., Clifford, T., Tunçalp, Ö., & Straus, S. E. (2018,

Oct 2). PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Annals of Internal Medicine, 169*(7), 467-473. https://doi.org/10.7326/m18-0850

Vernillo, G., Giandolini, M., Edwards, W. B., Morin, J.-B., Samozino, P., Horvais, N., & Millet, G. Y. (2017, 2017/04/01). Biomechanics and Physiology of Uphill and Downhill Running. *Sports Medicine, 47*(4), 615-629. https://doi.org/10.1007/s40279-016-0605-y

Wanga, F., Jiang, Y., & Hou, L. (2023). Effects of different exercise intensities on motor skill learning capability and process. *Science & Sports, 38*(2), 9. https://doi.org/10.1016/j.scispo.2021.09.006

Wanner, P., Cheng, F.-H., & Steib, S. (2020, Sep). Effects of acute cardiovascular exercise on motor memory encoding and consolidation: A systematic review with meta-analysis [Literature Review; Systematic Review; Meta Analysis]. *Neuroscience and Biobehavioral Reviews, 116*, 365-381. https://doi.org/http://dx.doi.org/10.1016/j.neubiorev.2020.06.018

Wanner, P., Cheng, F., & Steib, S. (2020b). Effects of acute cardiovascular exercise on motor memory encoding and consolidation: A systematic review with meta-analysis. *Neuroscience and Biobehavioral Reviews, 116*, 365-381. https://doi.org/http://dx.doi.org/10.1016/j.neubiorev.2020.06.018

Wanner, P., Muller, T., Cristini, J., Pfeifer, K., & Steib, S. (2020a). Exercise Intensity Does not Modulate the Effect of Acute Exercise on Learning a Complex Whole-Body Task. *Neuroscience, 426*, 115-128. https://doi.org/https://dx.doi.org/10.1016/j.neuroscience.2019.11.027

Wanner, P., Winterholler, M., Gasner, H., Winkler, J., Klucken, J., Pfeifer, K., & Steib, S. (2021, Feb). Acute exercise following skill practice promotes motor memory consolidation in Parkinson's disease [Empirical Study; Quantitative Study]. *Neurobiology of Learning and Memory Vol 178 2021, ArtID 107366, 178*. https://doi.org/http://dx.doi.org/10.1016/j.nlm.2020.107366

Williams, L., Pottinger, P., & Shapcott, D. (1985, Feb). Effects of exercise on choice reaction latency and movement speed [Empirical Study]. *Perceptual and Motor Skills, 60*(1), 67-71. https://doi.org/http://dx.doi.org/10.2466/pms.1985.60.1.67

Yanagisawa, H., Dan, I., Tsuzuki, D., Kato, M., Okamoto, M., Kyutoku, Y., & Soya, H. (2010, May 1). Acute moderate exercise elicits increased dorsolateral prefrontal activation and improves

cognitive performance with Stroop test. *NeuroImage, 50*(4), 1702-1710. https://doi.org/10.1016/j.neuroimage.2009.12.023

Yildirim, M. S., Guclu-Gunduz, A., Ozkul, C., & Korkmaz, S. (2024, Sep). Investigating the acute effect of low and moderate intensity aerobic exercise on whole-body task learning and cognition in young adults. *Eur J Neurosci, 60*(6), 5203-5216. https://doi.org/10.1111/ejn.16504

Youssef, L., Harroum, N., Francisco, B. A., Johnson, L., Arvisais, D., Pageaux, B., Romain, A. J., Hayward, K. S., & Neva, J. L. (2024, Jul 18). Neurophysiological effects of acute aerobic exercise in young adults: a systematic review and meta-analysis. *Neuroscience & Biobehavioral Reviews, 164*, 105811. https://doi.org/10.1016/j.neubiorev.2024.105811

Youssef, L., Pageaux, B., & Neva, J. L. (2025). Eccentric cycling improves motor learning more than concentric cycling. 2025.2005.2008.652761. https://doi.org/10.1101/2025.05.08.652761 %J bioRxiv

Figure captions

Figure 1. Flowchart illustrating the selection process of sources.

Figure 2. Temporal and geographical distribution of included sources.
(Panel a) Temporal distribution of all included sources. Orange bars represent experimental studies, while blue gradient bars represent other types of sources (narrative review; systematic review; systematic review with meta-analysis). (Panel b) Geographical distribution of all included sources. The format used is the following: total number [other types of sources*]. The total number of sources is shown first; when sources other than experimental studies are included, their number is indicated in brackets. Darker colors indicate a higher number of sources reported from each country. n refers to the number of participants reported from experimental studies conducted in that country.

Figure 3. Types of populations evaluated across all included experimental studies.
Distribution of the 1,479 participants reported across the 62 experimental studies. Participants were categorized as either healthy or clinical populations, with each category further divided into subcategories. Green gradients represent healthy populations, and orange gradients represent clinical populations. k refers to the number of experimental studies, G refers to the overall number of reported groups, g refers to the number of reported subgroups.

Figure 4. Types and intensities of physical exercise reported across all included experimental studies.
(Panel a) Distribution of the 81 experimental conditions according to exercise type, categorized as aerobic or resistance. Aerobic exercise is further subcategorized by specific types. (Panel b) Prescription of exercise intensities across the experimental studies, pink refers to measured capacity and turquoise refers to estimated capacity. Pink and turquoise gradients refer to measured and estimated exersie parameters respectively. (Panel c) Exercise intensities used across all experiments where red refers to high intensity, yellow refers to moderate intensity and green refers to low intensity. (Panel d) Heatmap showing the combination of exercise type and intensity where darker purple indicates a higher number of experimental conditions using the specific combination. Others refers to all exercise types different from lower-limb cycling, running and walking. E refers to the total number of experimental conditions

reported across the 62 included experimental studies, e refers to the number of experimental conditions per exercise type category and n refers to the number of participants.

Figure 5. Motor learning categories and timing of exercise relative to motor task practice.

(Panel a) Distribution of motor learning categories evaluated across the 62 experimental studies. (Panel b) Timing of exercise in relation to motor task practice across the 73 experimental conditions, (Panel c) Timing of exercise in relation to motor task practice across the 73 experimental conditions shown by population type. Light blue indicates exercise performed before the motor task practice, and light red indicates exercise performed after the motor task practice. Before = exercise performed prior to motor task practice; After = exercise performed after the motor task practice; n refers to the number of participants.

Figure 6. Effects of physical exercise interventions on motor learning.

Colored dots represent individual experimental conditions, with their position indicating whether motor learning was enhanced, not different, or attenuated compared to a control condition. Only experiments including a control condition were considered. All population types investigated are represented. Reported results related to acquisition are shown only for experiments in which exercise was performed before motor task practice. Reported retention test results are shown regardless of whether exercise was performed before or after motor task practice. (Panel a) Reported results from acquisition. (Panel b) Reported results on motor learning from retention tests conducted within 24 hours following exercise, (Panel c) Reported results on motor learning from retention tests conducted at 24 hours following exercise (Panel d) Reported results on motor learning from retention tests conducted after 24 hours following exercise. Green dots indicate low-intensity exercise, orange dots indicate moderate-intensity exercise, and red dots indicate high-intensity exercise.

Supplementary Material 1

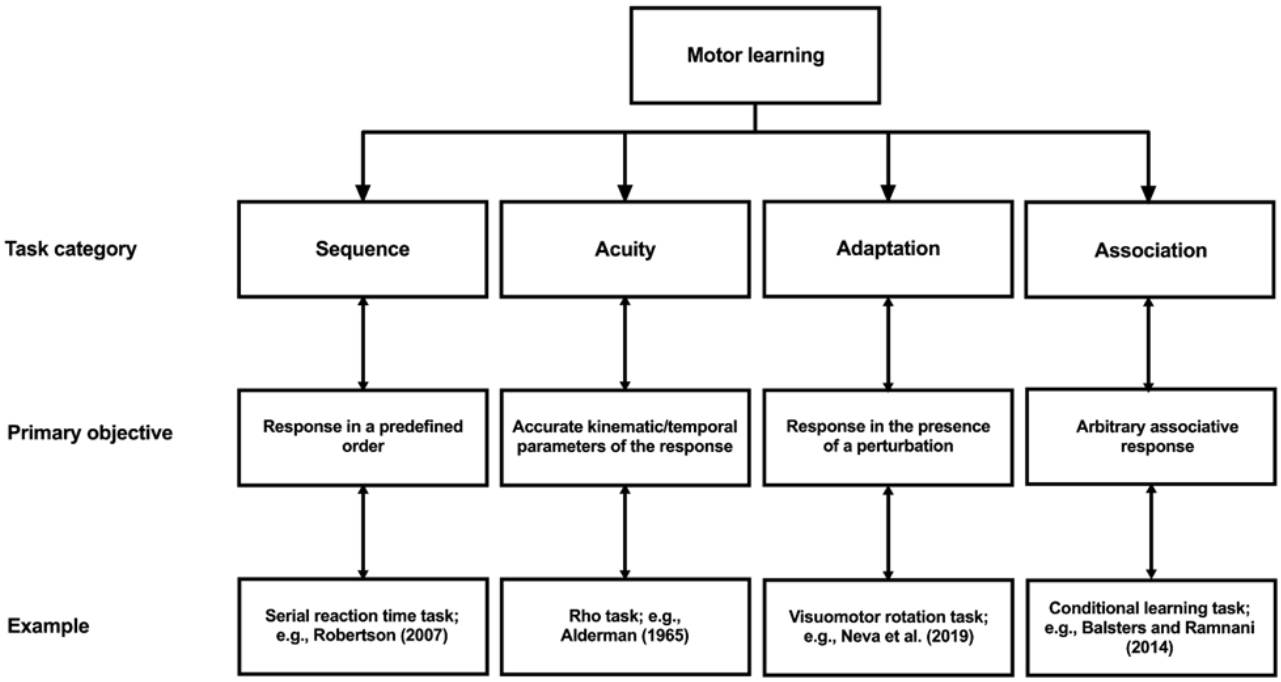

Figure S1. Classification of the task categories investigated to infer motor learning. This figure illustrates four commonly used motor learning task categories, classified according to their primary objective. The examples shown represent typical experimental tasks used within each category to assess motor learning.

Studies cited in Figure S1:

Alderman, R. B. (1965, 1965/05/01). Influence of Local Fatigue on Speed and Accuracy in Motor Learning. Research Quarterly. American Association for Health, Physical Education and Recreation, 36(2), 131-140. https://doi.org/10.1080/10671188.1965.10614670

Balsters, J. H., & Ramnani, N. (2011, Feb 9). Cerebellar plasticity and the automation of first-order rules. Journal of Neuroscience, 31(6), 2305-2312. https://doi.org/10.1523/jneurosci.4358-10.2011

Neva, J. L., Ma, J. A., Orsholits, D., Boisgontier, M. P., & Boyd, L. A. (2019, Apr). The effects of acute exercise on visuomotor adaptation, learning, and inter-limb transfer [Empirical Study; Quantitative Study]. Experimental Brain Research, 237(4), 1109-1127. https://doi.org/http://dx.doi.org/10.1007/s00221-019-05491-5

Robertson, E. M. (2007). The Serial Reaction Time Task: Implicit Motor Skill Learning? , 27(38), 10073-10075. https://doi.org/10.1523/JNEUROSCI.2747-07.2007 %J The Journal of Neuroscience

Table S1: Characteristics of the studies included in the scoping review.

Study	Total N	Type of population (n of exercise groups; age ± SD years)	Physical exercise	Exercise parameters	Motor Learning Category	Exercise Timing to Acquisition	Retention	Exercise effect on motor learning compared to control	
								Acquisition	Retention
Andrews et al., 2023	20	Huntington's disease (n = 10, 48.4 ± 13)	Lower-limb cycling	Moderate 20 min - CONT 50-55% age-predicted HRR	Motor acuity	Before	7d	↗	↔
Andrushko et al., 2023	25	Stroke patients (n = 14, 66 ± 11)	Lower-limb cycling (5 sessions)	High 23 min - HIIT 3min at 75% Wpeak 3 min at 10W	Sequence	Before	24h	↔	↔
Angulo-Barroso et al., 2019	71	Healthy children (n = 46, 9.2 ± 0.9)	Running	High 16 min (LONG) ; 5 min (SHORT) - HIIT LONG: 3 min at 85% estim. VO_2max ; 2 min at 60% estim. VO_2max SHORT: 2 min at 85% estim. VO_2max ; 1 min at 60% estim. VO_2max	Motor adaptation	Before	1h, 24h, 7d	↔	↗ for LONG and SHORT
Baird et al., 2018	48	Healthy adults (n = 32, 23 ± 3.1)	Lower-limb cycling	Low CONT: 40% measured max resistance until 200 kcals were expended (average: 28.67 min) High CONT: 80% measured max resistance until 200kcals were expended (average 16.75 min)	Sequence	Before	24h	↔	↔
Bartz et al., 1970	20	Healthy adults (n = 10, 18-20 yrs)	Walking	Moderate 4 min - CONT HR target: 120-170 bpm	Motor adaptation	Before	<10 min	↔	↔
Bonuzzi et al., 2023	90	Stroke patients (n = 15; 51.6 ± 9.2)	Lower-limb cycling (3 sessions)	Moderate 20 min - CONT 50-70% age-predicted HRR	Sequence	Before	10d	↔	↘
		Stroke patients (n = 15; 49.6 ± 15.9)				After		↔	↔
		Healthy adults (n = 15; 51.6 ± 9.2)				Before		↘	↔
		Healthy adults (n = 15; 49.6 ± 15.9)				After		↔	↔
Bosch et al., 2020	15	Healthy adults (n = 15; 23.7 ± 4.0)	Lower-limb cycling	Moderate 30 min - CONT 70% measured MHR High 15 min - CONT 80% measured MHR	Sequence	After	2.5h	NA	↗ for High ↔ for Moderate
Chan et al., 2023	30	Parkinson's disease (n = 15; 62.4 ± 8.5)	Lower-limb cycling	High 20 min - CONT 60-75% measured HRR	Sequence	After	1d, 7d	↔	↗ at Day 7
Charalambous et al., 2018 (active control)	37	Stroke patients (n=12; 55 ± 16)	Treadmill walking	High 5 min - CONT 70-85% age-predicted MHR	Motor adaptation	Before	24h	↔	↔
		Stroke patients (n=12; 62 ± 10)	Total body exercise			After		↔	↔
Charalambous et al., 2019	26	Healthy adults (n = 13; 21.8 ± 0.5)	Whole-body cycling	High 5 min - CONT 77-94% age-predicted MHR	Motor adaptation	Before	1d, 7d	↔	↔
Chen et al., 2023	24	Healthy adults (n = 12; 20.9 ± 0.7)	Treadmill Running	Moderate 30 min - CONT 65-85% age-predicted MHR (average was 75%)	Motor acuity	Before	24h	↔	↔
Coco et al., 2016 (no control)	28	Healthy adults (n = 28; 37.4 ± 5.8)	Lower-limb cycling	High CONT: 3 minutes of unloaded cycling with 30W increase every 3min until exhaustion	Motor acuity	After	< 1h	NA	↘
Cristini et al., 2023	56	Healthy adults (n = 20; 23.9 ± 3.4)	Lower-limb cycling	High 16 min - HIIT 3 min at 85–90 % of measured PPO 2min at 25 % of PPO.	Sequence	After	24h	NA	↔
Dal Maso et al., 2018	25	Healthy adults (n = 12; 24.3 ± 3.6)	Lower-limb cycling	High 15 min - HIIT 3min at 90% measured HRR 2min at 50W	Motor acuity	After	8h, 24h	NA	↔ for 8h ↗ at 24h
Duchesne et al., 2015	39	Parkinson's disease (n = 19; 59 ± 7.1)	Lower-limb cycling (3x/week for 12 weeks)	High CONT Start: 20 min at 60% measured PPO End: 40 min at 80% measured PPO	Sequence	After	12 weeks	NA	↗
		Healthy older adults (n = 20; 64 ± 8.2)				After			↗

CONT = continuous; HRR = Heart rate reserve; W = Watts; HIIT = high-intensity interval training; kcals = kilocalories; bpm = beats per minute; HR = Heart Rate; MHR = maximal heart rate; PPO = peak power output; estim. = estimated; Before = exercise was performed before the motor task practice; After = exercise was performed after the motor task practice; min = minutes; h = hours; d = days; NA = not available; ↗ = enhancement following exercise as reported by the authors; ↘ = decrease following exercise as reported by the authors; ↔ = no change following exercise as reported by the authors.

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Table S1. *continued*

Study	Total N	Type of population (n of exercise groups; age ± SD years)	Physical exercise	Exercise parameters	Motor Learning Category	Exercise Timing to Acquisition	Retention	Exercise effect on motor learning compared to control	
								Acquisition	Retention
Ferrer-Uris et al., 2017	29	Healthy adults (n = 10, 20.9 ± 1.8)	Shuttle run	High 13 min - HIIT 3min at 85% estimated VO2max 2min at 60% estimated VO2max	Motor adaptation	Before	1h, 24h, 7d	↔	↗ at 1h
		Healthy adults (n = 10, 20.5 ± 1.8)				After		NA	↗ at 1h
Ferrer-Uris et al., 2018	33	Healthy children (n = 10, 9.2 ± 1.1)	Shuttle run	High 13 min - HIIT 3min at 85% estimated VO2max 2min at 60% estimated VO2max	Motor adaptation	Before	1h, 24h, 7d	↔	↗
		Healthy children (n = 12, 9.1 ± 0.8)				After		NA	↔
Greeley et al., 2021	44	Healthy older adults (n = 19; 68.3 ± 9.2)	Lower-limb cycling (5 sessions)	High 23 min - HIIT 3min at 75% measured Wpeak 3min at 10W	Sequence	Before	24h, 35 days	↔	↔
Helm et al., 2017	54	Healthy adults (n = 27; 24.5 ± 2.8)	Upper-limb cycling	High 5 min - HIIT 1 min at 80% age-predicted MHR 1 min at half of cycling power	Motor adaptation	Before	24h	↔	↔
Holman et al., 2021	33	Healthy adults (n = 17; 21.6 ± 2.3)	Lower-limb cycling	High 5 min - CONT 70% age-predicted HRR	Motor adaptation	After	30min, 24h, 7d	NA	↗ at 7d
Hubner et al., 2018	38	Healthy older adults (n = 17; 68.2 ± 3.2)	Lower-limb cycling	Moderate 25 min - CONT 60% measured Wpeak	Motor acuity	Before	30 min, 24h	↔	↔
Hung et al., 2021	44	Healthy adults (n = 22; 23 ± 2)	Lower-limb cycling	High 25 min - HIIT 1 min at 90% measured Wpeak ; 1 min 25% measured Wpeak	Motor acuity	After	24h	NA	↔
James and Wang., 2023	16	Healthy adults (n = 16; 24.6 ± 4.7)	Lower-limb cycling	Moderate 25 min - CONT 65-70% age-predicted MHR	Motor adaptation	Before	< 30min	↔	↔
Jespersen et al., 2023	64	Healthy adults (n = 16; 24.1 ± 3.9)	Lower-limb cycling	Moderate 20 min - HIIT 3min at 45% measured Wpeak ; 2 min at 50W	Sequence	Before	<5 min, 7d	↔	↗ at 7d
		Healthy adults (n = 16; 23.8 ± 4.2)		High 20 min - HIIT 3min at 90% measured Wpeak; 2 min at 50W		After		NA	↗ at 7d
Khan et al., 2022	48	Healthy adults (n = 23; 22.9 ± 4.9)	Lower-limb cycling	High 20 min - HIIT 3min at 90% measured Wpeak 2min at 50W	Motor acuity	After	24h, 7d	NA	↗ at 7d
Kuo et al., 2023a	26	Healthy adults (n = 26; 27.2 ± 1.0)	Lower-limb cycling	Low 20 min - CONT 40-60% age-predicted MHR Moderate 20 min - CONT 61-74% age-predicted MHR High 20 min - CONT 75-95% age-predicted MHR	Sequence	After	0-5 min	NA	↗ for Moderate
Kuo et al., 2023b	20	Healthy adults (n = 20; 26.4 ± 1.0)	Lower-limb cycling	Moderate 20 min - CONT 61-74% age-predicted MHR	Sequence	After	0-5 min	NA	↗
Lehmann et al., 2020	31	Healthy adults (n = 15; 23 ± 7)	Lower-limb cycling (7 sessions)	High 20 min - HIIT 2x3min at 170 (PWC) 4 min at 120 (PWC)	Motor adaptation	Before	8 weeks	↗	↗
Loras et al., 2020 (no control)	40	Healthy adults (n = 40; 23.8 ± 2.0)	Lower-limb cycling	Low 25 min - CONT 50% age-predicted MHR Moderate 25 min - CONT 75% age-predicted MHR	Motor acuity	Before	24h	↔	↔
Lundbye-Jensen et al., 2017	77	Healthy children (n = 26; 10.4 ± 0.7)	Floorball	High 15 min - HIIT 3 min at high intensity 2 min at low intensity (measured via HR monitoring)	Motor acuity	After	1h, 24h, 7d	↔	↗ at 7d
		Healthy children (n = 25; 10.8 ± 0.8)	Running			After			↘ at 1h ↗ at 7d
Mang et al., 2014	16	Healthy adults (n = 16; 23.9 ± 3.7)	Lower-limb cycling	High 20 min - HIIT 3min at 90% measured PPO 2min at 50W	Sequence	Before	24h	↗	↗
Mang et al., 2016	16	Healthy adults (n = 16; 25.7 ± 4.6)	Lower-limb cycling	High 20min - HIIT 3min at 90% measured PPO 2min at 50W	Sequence	Before	24h	↔	↗

CONT = continuous; HRR = Heart rate reserve; W = Watts; HIIT = high-intensity interval training; HR = Heart Rate; MHR = maximal heart rate; PPO = peak power output; PWC = physical working capacity; Before = exercise was performed before the motor task practice; after = exercise was performed after the motor task practice; min = minutes; h = hours; d = days; NA = not available; ↗ = enhancement following exercise as reported by the authors; ↘ = decrease following exercise as reported by the authors; ↔ = no change following exercise as reported by the authors.

Table S1. *continued*

Study	Total N	Type of population (n of exercise groups; age ± SD years)	Physical exercise	Exercise parameters	Motor Learning Category	Exercise Timing to Acquisition	Retention	Exercise effect on motor learning compared to control	
								Acquisition	Retention
Munz et al., 2021	12	Healthy children (n = 12; 10.2 ± 1.4)	Lower-limb cycling	High 40 min – CONT (4 blocks of 10 min) 85-90% of age-predicted MHR	Motor acuity	After	24h	NA	↗
Nepveu et al., 2017	22	Stroke patients (n = 11; 64.7 ± 11.6)	Lower-limb cycling	High 15 min - HIIT 3 min at 100% measured Wpeak 2min at 25% measured Wpeak	Motor acuity	After	24h	NA	↗
Neva et al., 2019	17	Healthy adults (n = 17; 24 ± 3)	Lower-limb cycling	Moderate 25 min - CONT 65-70% age-predicted MHR	Motor adaptation	Before	24h	↗	↗
Ostadan et al., 2016	38	Healthy adults (n = 25 ; 22.4 ± 3.9)	Lower-limb cycling	High 15 min - HIIT 3 min at 85-90% measured VO2peak 2 min at 25% measured Wpeak	Sequence	After	8h	NA	↔
Opie and Semmler., 2019	13	Healthy adults (n = 13 ; 24.0 ± 3.3)	Lower-limb cycling	Moderate 30 min - CONT 50% age-predicted HRR High 30 min - HIIT 77% age-predicted HRR	Motor acuity	Before	24h	↗ for Mod	↗ for Mod
Perini et al., 2016	38	Healthy adults (n = 18; 22.9 ± 2.2)	Lower-limb cycling	Moderate 30 min - CONT 70% measured MHR	Motor acuity	Before	NA	↗	NA
Pixa et al., 2021	27	Healthy adults (n = 30; 23.7 ± 4.4)	Lower-limb cycling	Low 25 min - CONT 20% measured PPO High 23 min - HIIT 3 min at 90% measured W_{peak} 2 min at 60% measured W_{peak}	Motor acuity	Before	15 min, 30min, 24h	↔	↔
Quaney et al., 2009	21	Stroke patients (n = 19; 64.1 ± 12.3)	Lower-limb cycling (24 sessions)	Moderate 45 min - CONT 70% measured MHR	Sequence	Before	8 weeks	↗	↔
Quinlan et al., 2021	29	Healthy adults (n = 15; 45 ± 5)	Lower-limb cycling	High 20 min - HIIT 4 min at 90% measured W_{peak} 2min of active recovery at 50-80W	Motor acuity	Before	5-7d	↔	↔
Rhee et al., 2016	60	Healthy adults (n = 22; 19.8 ± 1.3)	Lower-limb cycling	High 21 min - CONT 18min at 80% measured MHR 3min at 100% measured MHR	Motor acuity	After	24h	NA	↗
Roig et al., 2012	48	Healthy adults (n = 16; 24.1 [21-33])	Lower-limb cycling	High 15 min – HIIT 3min at high intensity 2min at 50W Based on measured lactate level Workload (200-315)	Motor acuity	Before	1h, 24h, 7d	↔	↗ for 24h and 7d (higher when exercise is performed after)
		Healthy adults (n = 16; 24.4 [20-30])				After		NA	
Roig-Hierro et al., 2023	32	Healthy adults (n = 30; 22.9 ± 0.3)	Shuttle run	High 13 min - HIIT 3 min at 80% age-predicted MHR 2min at 60% age-predicted MHR	Motor acuity	After	7d	NA	↗
Singh et al., 2016	23	Healthy adults (n = 13; avg = 27 yrs)	Lower-limb cycling	Moderate 20 min - CONT 65-70% age-predicted MHR	Motor adaptation	Before	NA	↔	NA
Skriver et al., 2014	32	Healthy adults (n = 16; 24.1 ± 3.4)	Lower-limb cycling	High 20 min – HIIT 3min at high intensity 2min at 50W Based on measured lactate level Workload (200-315)	Motor acuity	Before	1h, 24h, 7d	↔	↗ for 24h and 7d
Snow et al., 2016	16	Healthy adults (n = 16; 25.7 ± 3.1)	Lower-limb cycling	Moderate 30 min - CONT 60% measured VO2 peak	Motor acuity	Before	24h	↔	↔
Statton et al., 2015	24	Healthy adults (n = 8; 22.4 ± 1.1)	Running	High 30 min - CONT 65-85% age-predicted MHR (average was 84% MHR)	Motor acuity	Before	NA	↗	NA
	20	Healthy adults (n = 8; 24.9 ± 1.1)	Running (3 sessions)				24h	↗	↔
Stavrinos & Coxon 2017	24	Healthy adults (n = 12; 24.8 ± 5.8)	Lower-limb cycling	High 20 min - HIIT 2min at 90% age-predicted HRR 3min at 50% age-predicted HRR	Motor acuity	Before	5h	↔	↗
Steib et al., 2018	17	Parkinson's disease (n = 17; 64.4 ± 6.2)	Lower-limb cycling	Moderate 30 min - CONT 60-70% measured MHR	Motor adaptation	Before	24h	↔	↗
Stranda et al., 2019	26	Healthy adults (n = 13; 25.3 ± 2.5)	Lower-limb cycling (12 sessions)	Moderate 20 min - CONT 65% age-predicted MHR	Motor acuity	Before	7d	↔	↔

CONT = continuous; HRR = Heart rate reserve; W = Watts; HIIT = high-intensity interval training; HR = Heart Rate; MHR = maximal heart rate; PPO = peak power output; Before = exercise was performed before the motor task practice; After = exercise was performed after the motor task practice; min = minutes; h = hours; d = days; NA = not available; ↗ = enhancement following exercise as reported by the authors; ↘ = decrease following exercise as reported by the authors; ↔ = no change following exercise as reported by the authors.

Table S1. *continued*

Study	Total N	Type of population (n of exercise groups; age ± SD years)	Physical exercise	Exercise parameters	Motor Learning Category	Exercise Timing to Acquisition	Retention	Exercise effect on motor learning compared to control	
								Acquisition	Retention
Swarbrick et al., 2020 (no control)	25	Healthy adults (n = 12; 21.5 ± 2.1)	Lower-limb cycling	Low 19 min - LIIT 2 min at 8% Wpeak 3 min at 12% Wpeak	Motor acuity	Before	1h, 24h. 7d	↔	↔
		Healthy adults (n = 13; 22.2 ± 3.1)		High 19 min - HIIT 2 min at 60% measured Wpeak 3 min at 90% measured Wpeak					
Taylor et al., 2024 (Active rest)	23	Healthy older adults (n = 11; 65.3 ± 6.3)	Lower-limb cycling	High 20 min - HIIT 3 min at 50% measured HRR 2 min at 90% measured HRR	Motor acuity	Before	6h	↘	↗
Thomas et al., 2016	36	Healthy adults (n = 12; 23.5 ± 2.3)	Lower-limb cycling	Low 17 min - LIIT 2 min at 25% measured W_{peak} 3 min at 45% measured W_{peak}	Motor acuity	After	24h, 7d	NA	↗ for High at 24h ↗ for Low and High at 7d
		Healthy adults (n = 12; 24.3 ± 2.3)		High 17 min - HIIT 2 min at 60% measured W_{peak} 3 min at 90% measured W_{peak}					
Thomas et al., 2017	40	Healthy adults (n = 10; 24.7 ± 3.5)	Strength training	High 45-50 min Resistance training program (4 RM and 8 RM)	Motor acuity	After	1h, 24h	NA	↘ at 1h ↗ at 1d
		Healthy adults (n = 10; 25.9 ± 4.5)	Circuit training	High 45-50 min (30% of 1 RM)		After			
		Healthy adults (n = 10; 25.9 ± 3.7)	Hockey training	High 48 min 5 x 7 min; 2 min rest		After			
Thompson et al., 2023	45	Stroke patients (n = 15; 68.1 ± 7.1)	Whole-body cycling	High 5 min- CONT 70-85% age-predicted MHR	Motor adaptation	After	24h	NA	↔
		Stroke patients (n = 15; 61.8 ± 7.5)		High 15min - HIIT 3 min at 70%-85% age-predicted MHR 2 min at < 70% age-predicted MHR					
Tomporowski and Pendleton, 2018	32	Healthy adults (n = 11; 22.4 ± 3.0)	Dancing	Moderate 10 min - CONT Simple Dance Dance Revolution Intensity determined based on HR	Motor acuity	Before	13min, 24h, 7d	↔	↔
		Healthy adults (n = 10; 22.9 ± 2.9)		Moderate 10 min - CONT Complex Dance Dance Revolution Intensity determined based on HR		After		NA	↗ at 7d
Wanga et al., 2023	33	Healthy adults (n = 11; 20.5 ± 2.3)	Lower-limb cycling	Low 23 min - HIIT 3min at 45% measured W_{peak} 2min at 25% measured W_{peak}	Sequence	After	24h, 48h	NA	↗ (higher for Low)
		Healthy adults (n = 11; 20.3 ± 2.3)		High 23 min - HIIT 2min at 60% measured W_{peak} 3min at 90% measured W_{peak}					
Wanner et al., 2020	50	Healthy adults (n = 17; 25.3 ± 2.7)	Lower-limb cycling	Low 17 min - CONT 25W	Motor adaptation	Before	24h	↔	↔
		Healthy adults (n = 18; 25.1 ± 2.3)		Moderate 17 min - HIIT 2min at 25% measured W_{peak} 3min at 45% measured W_{peak}					
		Healthy adults (n = 15; 25.7 ± 3.6)		High 17 min - HIIT 2min at 60% measured W_{peak} 3min at 90% measured W_{peak}					
Wanner et al., 2021	17	Parkinson's disease (n = 8; 59.3 ± 5.4)	Lower-limb cycling	Moderate 25 min - CONT 60% maximal W_{peak}	Motor adaptation	Before	1d, 7d	↔	↗ at 7d
Williams et al., 1985	90	Healthy adults (n = 30; 20.9 ± 1.9)	Arm cranking	Low 5 min - CONT WO maintained at 10W (30 rpm) (110-125 bpm)	Motor acuity	Before	24h	↔	↔
		Healthy adults (n = 30; 20.9 ± 1.9)		High 5 min - CONT WO maintained at 75W (90 rpm) (165-180 bpm)					
Yildirim et al., 2024	70	Healthy adults (n = 15; 20.5 ± 0.7)	Running	Low 30 min- CONT 57%-63% estimated MHR	Motor acuity	Before	24h, 7d	↔	↔
		Healthy adults (n = 15; 20.1 ± 0.5)				After		↔	↔
		Healthy adults (n = 15; 20.8 ± 1.5)		Moderate 30 min- CONT 64%-76% estimated MHR		Before		↔	↔
		Healthy adults (n = 15; 20.9 ± 1.0)				After		↔	↔

CONT = continuous; HRR = Heart rate reserve; W = Watts; HIIT = high-intensity interval training; LIIT = light-intensity interval training; HR = Heart Rate; MHR = maximal heart rate; PPO = peak power output; rpm = revolutions per minute; bpm = beats per minute; RM = repetition maximum; Before = exercise was performed before the motor task practice; After = exercise was performed after the motor task practice; min = minutes; h = hours; d = days; NA = not available; ↗ = enhancement following exercise as reported by the authors; ↘ = decrease following exercise as reported by the authors; ↔ = no change following exercise as reported by the authors.

Supplementary Material 2

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	Page 1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	Page 2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	Pages 4 to 6
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	Page 6
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	Page 7
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	Pages 7 to 8
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	Page 7
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	Supplementary material 3
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	Page 8 and Figure 1
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	Pages 9 to 11
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	Page 9

Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	-
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	Pages 9 and 10
SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	Page 11
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	Pages 14 to 19 and Figures 2 to 6
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	-
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Pages 15 to 21 and Figures 2 to 6
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	Pages 15 to 21
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	Page 24
Limitations	20	Discuss the limitations of the scoping review process.	Page 30
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	Page 31
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	Page 32

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.
* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.
† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).
‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.
§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

Supplementary Material 3

Search equations

Web of Science Core Collection : A&HCI , ESCI , CPCI-SSH , CPCI-S , SCI-EXPANDED , SSCI

(exercise OR training) NEAR/5 ("motor learning" OR "motor skill" OR "motor skills" OR "motor adaptation" OR "motor acuity" OR "motor coordination" OR "de novo learning" OR "motor control" OR "motor sequence" OR "motor behavior" OR "motor behaviour" OR "sensorimotor learning" OR "motor competence" OR "motor competences") (Topic)

-

ERIC (ProQuest)

((MAINSUBJECT.EXACT("Perceptual Motor Learning") OR MAINSUBJECT.EXACT("Movement Education") OR MAINSUBJECT.EXACT("Perceptual Motor Coordination") OR MAINSUBJECT.EXACT("Multisensory Learning") OR MAINSUBJECT.EXACT("Psychomotor Skills")) AND MAINSUBJECT.EXACT("Exercise")) AND PEER(yes)
OR
noft((exercise OR training) NEAR/5 ("motor learning" OR "motor skill" OR "motor skills" OR "motor adaptation" OR "motor acuity" OR "motor coordination" OR "de novo learning" OR "motor control" OR "motor sequence" OR "motor behavior" OR "motor behaviour" OR "sensorimotor learning" OR "motor competence" OR "motor competences")) AND PEER(yes)

Limité par : Revu par les pairs

-

SPORTDiscus with Full Text

#	Question
	S5 OR S6 Opérateurs de restriction - Relu par un comité de lecture; Type de publication: Academic Journal Opérateurs d'expansion - Appliquer des sujets équivalents
S7	Modes de recherche - Booléen/Phrase
S6	TI (exercise OR training) N5 ("motor learning" OR "motor skill" OR "motor skills" OR "motor adaptation" OR "motor acuity" OR "motor coordination" OR "de novo learning" OR "motor control" OR "motor sequence" OR "motor behavior" OR "motor behaviour" OR "sensorimotor learning" OR "motor competence" OR "motor competences")) OR AB (exercise OR training) N5 ("motor learning" OR "motor skill" OR "motor skills" OR "motor adaptation" OR "motor acuity" OR "motor coordination" OR "de novo learning" OR "motor control" OR "motor sequence" OR "motor behavior" OR "motor behaviour" OR "sensorimotor learning" OR "motor competence" OR "motor competences"))
S5	S3 AND S4
S4	DE "MOTOR learning" OR DE "PERCEPTUAL motor learning"
S3	S1 OR S2

S2 DE "EXERCISE" +

S1 DE "PHYSICAL training & conditioning" +

-

Database(s): **APA PsycInfo** 1806 to March 2025 Week 2

Search Strategy:

#	Searches
1	athletic training/
2	exp exercise/
3	1 or 2
4	Motor Coordination/ or Motor Skills/ or Motor Control/ or Perceptual Motor Coordination/ or Perceptual Motor Learning/ or Gross Motor Skill Learning/ or Fine Motor Skill Learning/
5	3 and 4
6	((exercise or "physical training" or "endurance training" or "resistance training") adj6 ("motor learning" or "motor skill" or "motor skills" or "motor adaptation" or "motor acuity" or "motor coordination" or "de novo learning" or "motor control" or "motor sequence" or "motor behavior" or "motor behaviour" or "sensorimotor learning" or "motor competence" or "motor competences")).ab,id,ti.
7	5 or 6
8	limit 7 to human

-

Database(s): **Ovid MEDLINE(R) ALL** 1946 to March 18, 2025

Search Strategy:

#	Searches
1	((exercise or "physical training" or "endurance training" or "resistance training") adj6 ("motor learning" or "motor skill" or "motor skills" or "motor adaptation" or "motor acuity" or "motor coordination" or "de novo learning" or "motor control" or "motor sequence" or "motor behavior" or "motor behaviour" or "sensorimotor learning" or "motor competence" or "motor competences")).ab,kf,ti.
2	exp animals/ not humans/
3	1 not 2

-

Database(s): **Embase** 1974 to 2025 March 18

Search Strategy:

#	Searches
1	((exercise or "physical training" or "endurance training" or "resistance training") adj6 ("motor learning" or "motor skill" or "motor skills" or "motor adaptation" or "motor acuity" or "motor coordination" or "de novo learning" or "motor control" or "motor sequence" or "motor behavior" or "motor behaviour" or "sensorimotor learning" or "motor competence" or "motor competences")).ab,kf,ti.
2	exp exercise/
3	resistance training/ or endurance training/
4	2 or 3
5	motor learning/
6	4 and 5
7	1 or 6
8	(exp animal/ or nonhuman/) not exp human/
9	7 not 8

Supplementary Material 4

Data extraction sheet is attached to this manuscript on BioRxiv.