INVITED REVIEW

Beyond FITT: addressing *density* in understanding the dose–response relationships of physical activity with health—an example based on brain health

Fabian Herold[1,2,3] · Liye Zou[4] · Paula Theobald[3] · Patrick Manser[5,6] · Ryan S. Falck[7,8,9,10] · Qian Yu[4] ·
Teresa Liu-Ambrose[8,9,10] · Arthur F. Kramer[11,12,13] · Kirk I. Erickson[14,15,16] · Boris Cheval[17,18] · Yanxia Chen[4] ·
Matthew Heath[19,20,21] · Zhihao Zhang[4] · Toru Ishihara[22] · Keita Kamijo[23] · Soichi Ando[24] · Joseph T. Costello[25] ·
Mats Hallgren[26,27] · David Moreau[28] · Vahid Farrahi[29] · David A. Raichlen[30,31] · Emmanuel Stamatakis[32,33] ·
Michael J. Wheeler[27,34] · Neville Owen[34,35] · Sebastian Ludyga[36] · Henning Budde[37] · Thomas Gronwald[2,38]

Abstract

Research on physical activity (PA) and health has a fundamental concern with dose–response relationships. The variables of (1) Frequency, (2) Intensity, (3) Time, and (4) Type (i.e., the FITT principle) have traditionally been used to operationalize the dosage of PA. We consider some limitations of FITT and propose that it can be complemented by the additional variable *density* (from the German exercise and training variable *Belastungsdichte),* which can be defined as the timing of successive work bouts within a single PA bout as well as the timing between successive PA bouts within a specific time period; it does so by quantifying the temporal intervals between successive work or PA bouts (i.e., time spent at a lower PA intensity or resting such as in napping/sleeping or sedentary behaviors). Using the field of PA and brain health as an example, we discuss the opportunities and challenges for further research employing the variable *density* and consider its potential to improve the understanding of dose–response relationships between PA and health outcomes.

Keywords Physical exercise · Sedentary behavior · Brain · Cognition · Dose

Introduction

Physical activity (PA), which includes planned and structured forms of acute and chronic physical exercise (see Table 1 for definition), is widely recognized as an important factor in maintaining and improving overall health (Bull et al. 2020; Warburton and Bredin 2017; World Health Organization 2020, 2022). However, the optimal dosage of PA, including but not limited to the time point at which PA should be initiated or repeated to trigger changes in specific measures of health, is not well understood (Bull et al. 2020; World Health Organization 2020). In this context, there is currently a need for greater clarity in the definition of the dosage of PA (Gronwald et al. 2018b, 2019, 2020b; Herold et al. 2019a, 2020c; Impellizzeri et al. 2023), with a call for a more complete reporting of dosage in intervention studies

using PA (Hansford et al. 2022; Bland et al. 2021; Solis-Urra et al. 2024; Gronwald et al. 2019). From a practical perspective, elucidating the complex dose–response relationships of PA with health outcomes, including intra- and inter-individual response variability, is an important prerequisite when aiming to maximize the benefits of PA interventions by individualizing PA prescription (Barha et al. 2017b, 2021a, b; Herold et al. 2019a, 2021; Solis-Urra et al. 2024).

The dose of PA traditionally has been characterized and prescribed using the FITT principle, an acronym representing: (1) *Frequency* (i.e., number of PA bouts in a specific time interval), (2) *Intensity* (i.e., level of exertion required by an individual to perform PA), (3) *Time* (i.e., duration spent for PA), and (4) *Type of PA* (i.e., specific kind of PA such as endurance, resistance or coordinative activities) (Festa et al. 2023; Hecksteden et al. 2018; Heisz and Waddington 2024; Li et al. 2024; Liguori et al. 2022; Noone et al. 2024; Oberg 2007; Zubin Maslov et al. 2018). The FITT principle can also be used to analyze how the dosage of free-living PA (e.g., unplanned and unstructured forms of PA) is associated

Table 1 Definition of key terms

Key terms	
Brain health	…is defined as the optimal development and maintenance of brain integrity and encompasses: (1) structural (e.g., hippocampal volume) and functional (e.g., changes in brain activity) brain parameters; (2) functions that depend on the integrity of the brain, including but not limited to mental health, cognition, and movement; and (3) the absence of neurological disorders (e.g., dementia) (Wang et al. 2020; Zou et al. 2024).
Dose / dosage	…is characterized by three key components: (1) external load (i.e., defined as the work performed by the individual independent of internal characteristics), (2) influencing factors (i.e., all factors [e.g., including environmental factors] that can strengthen or weaken the stimuli of a single bout of PA), and (3) internal load (i.e., defined as the individual and acute physiological, psychological, motor, and biomechanical responses to the external load and the influencing factors during and/or after the cessation of a single bout of PA). Thus, the dose can be determined and monitored by using specific indicators of internal load involved in the biological processes that drive the desired changes in outcomes of interest (Gronwald et al. 2020b; Herold et al. 2019a, 2020b).
	The term *dose* characterizes the PA stimuli *at a specific time*, whereas the term *dosage* refers to the *dose provided over a particular time* (Sharma and Dunham 2024).
Physical activity (PA)	…is defined as any voluntary skeletal muscle-induced bodily movement (e.g., in occupational or leisure time) that results in an increase in the energy expenditure (Bull et al. 2020; Caspersen et al. 1985; World Health Organization 2020, 2022) above ~1.5 metabolic equivalents of the task (MET; 1 MET = 1 kcal (4.184 kJ) kg^{-1} h^{-1}) (Budde et al. 2016; Falck et al. 2021; Herold et al. 2018a, 2022b; Zou et al. 2024). This includes planned and structured forms such as acute and chronic physical exercise (see the following definition). PA can be divided into acute (single bout/session) and chronic (multiple bout/session) PA based on temporal characteristics (Budde et al. 2016; Herold et al. 2018a, 2022b). Furthermore, PA can be differentiated based on the domains in which it occurs, including recreation/leisure time (such as household), transportation, education, or occupation (Bull et al. 2020; Dipietro et al. 2020; Falck et al. 2021; Howley 2001; Pettee Gabriel et al. 2012; Strath et al. 2013; World Health Organization 2020).
Physical exercise	…is defined as a specific form of PA that is planned and structured (Budde et al. 2016; Caspersen et al. 1985; Herold et al. 2018a, 2022b; World Health Organization 2020, 2022). Exercise can be divided into acute (single bout/session) and chronic (multiple bouts/sessions) based on temporal characteristics, also referred to as physical training when it is repetitive, and designed to improve or at least maintain the performance in one or more fitness dimensions (Budde et al. 2016; Caspersen et al. 1985; Herold et al. 2018a, 2022b; Howley 2001; World Health Organization 2020, 2022). In addition, physical exercise is typically performed in recreational/leisure time when it is not part of healthcare service (e.g., rehabilitation) or occupation (e.g., elite athlete). Notably, physical exercise is always PA, whereas PA is not necessarily physical exercise (Wegner et al. 2020).
Sedentary behavior (SB)	…is defined as any waking behavior characterized by a low energy expenditure (≤ 1.5 MET) while in a sitting, reclining, or lying posture (Bull et al. 2020; Falck et al. 2021; Sedentary Behaviour Research Network 2012; Tremblay et al. 2017; World Health Organization 2020, 2022). SB is ubiquitous, due to rapid changes in human environmental, economic, social, and technological contexts. SB has been identified as a newer component of the activity spectrum that can adversely impact health (Dunstan et al. 2021, 2012; Katzmarzyk et al. 2019; Pinto et al. 2023). SB can be categorized as mentally active (e.g., reading and computer use) and mentally passive (e.g., watching non-educational television programs) (Zou et al. 2024; Hallgren et al. 2020). For many adolescents and adults, the daily time spent SB is ≥ 5 h (Bauman et al. 2011; Raichlen et al. 2023; Yang et al. 2019)."

PA physical activity, *MET* metabolic equivalent of the task, *SB* sedentary behavior

with health-related outcomes. Some researchers have suggested extending the FITT principle to FITT-VP (Liguori et al. 2022; Bushman 2018) by including the factors of: (5) *Volume* (V), which is typically provided as a product of the frequency and duration of the acute PA bouts (e.g., total PA or PA spent in a particular intensity zone) (Assis et al. 2018; Di Liegro et al. 2019; Hecksteden et al. 2018); and, (6) *Progression* (P), which characterizes the gradual and systematic increase of the PA stimulus to maintain overload and, thus, provoke further adaptation(s) to overall physical and brain health (Kasper 2019).

Although adhering to the FITT and the FITT-VP principles can help standardize the variables that should be considered for PA prescription and dose–response analysis, this approach has several limitations. First, neither FITT nor FITT-VP takes into account all acute and chronic variables (e.g., movement frequency) that determine the dosage of PA (especially of planned and structured forms such as acute and chronic physical exercise) (Gronwald et al. 2020b; Herold et al. 2019a, 2020c; Toigo and Boutellier 2006). In addition, they provide an overall framework that includes a mixture of variables to prescribe PA (i.e., frequency, intensity, time, type, and volume) and one selected training principle (i.e., progression). Second, FITT-VP does not consider the timing of PA stimuli within a specific time interval, namely the temporal interval between successive bouts of PA, which is quantified by the time spent resting and conceptualized as density (see also definition below, (Desgorces et al. 2020; Hernández-Lougedo et al. 2021; Herold et al. 2019a, b, 2025; Manci et al. 2024; Törpel et al. 2018). Third, each component of the FITT and FITT-VP principle is treated somewhat independently when in fact the variables characterizing PA are interdependent

(Gronwald et al. 2020b; Toigo and Boutellier 2006). Indeed, intensity is significantly influenced by other variables such as acute duration (Hofmann and Tschakert 2017; Tschakert et al. 2022) and movement frequency (e.g., cadence measured as revolutions per minute when using a cycle ergometer) (Beneke and Leithäuser 2017; Gronwald et al. 2018a).

As illustrated by consideration of the aforementioned limitations of FITT and FITT-VP, determining or providing a specific dosage of PA is complex, and the oversimplification of PA dosage may hinder the accurate prediction and optimization of PA interventions on health (Gronwald et al. 2020b; Herold et al. 2019a, 2020c). As we will show, considering the variable *density* provides a more subtle approach that goes beyond FITT and FITT-VP (Herold et al. 2019a, 2025; Manci et al. 2024) and allows for a more precise determination of the PA dosage (Gronwald et al. 2020b; Herold et al. 2019a, 2020c; Manci et al. 2024). A more precise determination of PA dosage can, in turn, advance our understanding of the dose–response relationships between PA and health-related outcomes (Gronwald et al. 2020b; Herold et al. 2019a, 2020c).

To provide the reader with a concrete idea of how density can enrich our understanding of dose–response relationships between PA and health-related outcomes, we use brain health as an example (see Table 1 for the definition of key terms). Our rationale to focus on a single example is twofold. First, the mechanisms mediating the effects of PA on health-related outcomes are diverse, and dose–response relationships can depend on the specific endpoint (Warburton and Bredin 2016). Thus, it was necessary to focus on a particular endpoint. Second, disorders affecting brain health (e.g., dementia) are a growing public health concern (Gustavsson et al. 2023; Nichols et al. 2022; Velandia et al. 2022; Wimo et al. 2023) with evidence that the reduction of modifiable risk factors, such as physical inactivity, can be a cost-effective countermeasure (Livingston et al. 2024; Norton et al. 2014; World Health Organization 2019). Our focus on brain health is therefore intended to provide a broadly applicable, albeit sufficiently specific, example of the relevance of PA density to health-related outcomes. Furthermore, summarizing the current state of evidence concerning the role of density for other health-related outcomes (e.g., cardiovascular, metabolic, musculoskeletal) or intervention approaches (e.g., cognitive training, hypoxia and/or heat training/therapy) is beyond the scope of this article, although we acknowledge that the variable density is also relevant for those applications.

Method

The German exercise and training variable "Belastungsdichte" (Hottenrott et al. 2022, Schnabel et al. 2014) (hereafter referred to as *density*), which has its roots in the field of exercise science, is not well-recognized internationally, and is only occasionally mentioned in the literature (Desgorces et al. 2020; Hernández-Lougedo et al. 2021). Thus, we seek to improve its accessibility by introducing this variable to the broader exercise- and health-science community. In this context, we also extend the description and application of density to the field of free-living PA (a key concern for public health), where it has not previously been applied. Indicated by the fact that density is largely absent in the literature (e.g., in work reporting (Herold et al. 2019b; Manser et al. 2024), analyzing (Chang et al. 2012; Falck et al. 2019; Kao et al. 2022; Ludyga et al. 2020; Oberste et al. 2019, 2021; Pontifex et al. 2019), or providing recommendations on PA (World Health Organization 2019) in the context of brain health) and thus underappreciated in the exercise-science and health research communities, we opted to perform a narrative review because there is probably not a sufficiently large and specific evidence base to conduct a systematic review (e.g., on the role of density of PA on brain health). The author group comprises an international mix of junior, mid-career, and senior researchers from different disciplines, and cultural and ethnic backgrounds who have provided critical feedback about the conceptualization and theoretical position that we describe here.

Definition of density

Density characterizes the timing of PA (also referred to as *work bout*[*s*]) within a single PA bout as well as the timing between successive PA bouts within a specific time period (e.g., day, week, month, or year); it does so by providing information on the temporal intervals (i.e., time spent resting; also referred to as *rest, recovery,* or *relief bouts*) within or between successive PA bouts (Desgorces et al. 2020; Herold et al. 2019a, b, 2025; Hernández-Lougedo et al. 2021; Manci et al. 2024; Törpel et al. 2018).

From a mechanistic perspective, the effect of density on a dependent variable (e.g., a specific health-related outcome such as brain health) can be studied by keeping the characteristics of work bouts similar (i.e., in terms of acute and chronic variables that characterize PA) while modifying the duration of rest bouts. In other words, density can be modified by changing the duration of the rest bout(s) to adjust the work–rest ratio.

In this context, we highlight three important points. First, as shown in Table 2, density is conceptually different from existing concepts and variables (e.g., frequency, rest-activity rhythm (RAR), volume, work–rest ratio, interruptions to sedentary time) that are relevant to prescribing the PA dosage, and has a significant potential to complement approaches to analyze and promote PA. Second, based on the temporal context of PA, density needs to be further

Table 2 Overview of differences and synergies between density with other selected physical activity-related concepts. *PA* physical activity, *RAR* rest-activity rhythm, *VILPA* vigorous intermittent lifestyle physical activity

Variable/ concept	Relation to density
Differences between density and other selected PA-related concepts	
Physical activity (PA) variability	Density differs from the metric of PA variability (i.e., the standard deviation of minute-to-minute changes in device-based PA counts across a particular wear period; Donahue et al. 2025) because it quantifies the rest duration between successive PA bouts instead of the variability of PA patterns.
Frequency	Density captures information beyond that provided by frequency because frequency only specifies the number of PA bouts in a given time interval (e.g., day, week, month, year) (Bushman 2018; Garber et al. 2011; Hecksteden et al. 2018; Herold et al. 2019a) but not their timing *within* that interval (e.g., rest duration between successive PA bouts).
(Circadian) Rest-activity rhythm	Density has some conceptual overlap but differs from the construct of (circadian) rest-activity rhythm (RAR). Although both constructs deal with PA and rest patterns, density provides information on the time intervals between successive PA bouts within a specific time period because it provides information on the exact rest duration. In contrast, the construct of (circadian) RAR primarily focuses on investigating regularity, fragmentation, and amplitude of the rest-activity rhythms across different time frames (e.g., biological rhythms such as sleep–wake cycle throughout periods ≥ 24 h) (Calogiuri et al. 2013; Gao et al. 2023; Keihani et al. 2023; Smagula 2016; Smagula et al. 2019). In other words, density is more concerned with defining the precise rest duration between successive bouts of PA (Buchheit and Laursen 2013b; Desgorces et al. 2020; Herold et al. 2019a, b, 2025; Hernández-Lougedo et al. 2021; Manci et al. 2024; Törpel et al. 2018) while the metrics used to operationalize (circadian) RAR typically describe rest-activity patterns and their variability (Danilevicz et al. 2024a, 2024b; Gao et al. 2023). Furthermore, density can be used to analyze and prescribe PA (Herold et al. 2025; Manci et al. 2024), while RAR has only been used to analyze PA patterns (Danilevicz et al. 2024a, b; Gao et al. 2023; Smagula 2016).
Volume	Density differs from volume, which is typically described as the product of the frequency and duration of acute PA bouts (e.g., of total PA or PA spent in a particular intensity zone) (Assis et al. 2018; Di Liegro et al. 2019; Hecksteden et al. 2018) because volume lacks information on the exact temporal interval(s) between successive PA bouts *within* a specific time period.
Weekend warrior PA pattern	Density has some conceptual overlap but differs from the weekend warrior approach because a "weekend warrior" PA pattern is typically characterized by achieving a specific amount of PA (e.g., recommended by the World Health Organization such as ≥ 150 min of moderate- or ≥ 75 min of vigorous-intensity PA per week (World Health Organization 2020, 2022)) in $\leq 2\times$ bouts per week (Hamer et al. 2017; Lee et al. 2004; Min et al. 2024; Ning et al. 2024, 2025; O'Donovan et al. 2018; Wu et al. 2024) without taking the temporal interval(s) (i.e., rest duration) between those PA bouts into account, which is the key feature of density.
Work–rest-ratio	Density is associated with changing the time spent at rest (i.e., duration of the rest/recovery/relief bout[s]), whereas the work–rest ratio can also be adjusted by changing the duration of the work bout(s) (Buchheit and Laursen 2013b).
Potential synergies of density and other selected PA-related concepts	
Physical activity paradox	Density, defining the temporal intervals between successive PA bouts within a specific time period with greater precision, may help to explain the "PA paradox" that occupational PA has less clear or no health benefits compared to leisure-time PA (Holtermann et al. 2012, 2018, 2021b; Pronk 2024; Stamatakis et al. 2024). This phenomenon is perhaps related to the fact that a key distinction can be made between active and passive (sedentary) occupations (Owen et al. 2020) because active professions (e.g., construction workers, or farmers) often perform substantial occupational PA at higher intensities in relatively short time intervals (i.e., higher acute density) compared to others (e.g., office workers) (Owen et al. 2020). In this context, density may also help to identify "sweet spots" to individualize leisure-time PA recommendations by considering occupational PA levels (Holtermann et al. 2021a).
Time of day	Density can add the concept of and time of day (e.g., specifying whether PA is conducted in the morning, afternoon, or evening (Bruggisser et al. 2023; Ingham-Hill et al. 2024; Janssen et al. 2022; Sabag et al. 2024)) by providing more precise information on the temporal intervals between successive PA bouts within a specific time period (i.e., by quantifying the exact rest duration between PA bouts performed at a specific time of day).

Table 2 (continued)

Variable/ concept	Relation to density
VILPA or exercise snacks	Density, as a characteristic defining the PA dosage, can help to more precisely elucidate the influence of different rest bout durations between short work bouts of physical activity (e.g., conducted at vigorous intensity or other intensities in the context of free-living PA such as light- or moderate-intensity PA) on health-related outcomes.
	When such short work bouts are performed at a vigorous intensity, they are conceptualized in the *vigorous intermittent lifestyle physical activity* (*VILPA*) approach, which is defined as brief vigorous-intensity bouts of incidental PA occurring during daily living (e.g., fast stair-climbing) and lasting up to 1 or 2 min (Ahmadi et al. 2024; Stamatakis et al. 2022, 2023; Thøgersen-Ntoumani et al. 2024), and "*exercise snacks*" approach, which are defined loosely as single planned bouts of physical exercise that typically (1) lasts ≤ 1 min, (2) occurs multiple times throughout the day, and (3) are performed at a vigorous intensity (Islam et al. 2022; Stamatakis et al. 2020; Wang et al. 2024).

differentiated into acute density (i.e., in the context of variations within single shorter bouts of PA; see Fig. 1 a) and chronic density (i.e., in the context of repetitions of PA over longer periods; see Fig. 1b) (Gronwald et al. 2020b). Third, given that the key element defining density is the rest bout, it is also worth noting that in addition to rest duration, there are other variables, especially the type of activity (e.g., sedentary behavior (SB) or sleep), that need to be considered when prescribing or analyzing PA because they can moderate the effect of PA on brain health (see also Sect. "Chronic density — Sophisticated analysis approaches" and "Recommendations regarding the assessment of chronic density").

Density is important—but neglected—when investigating dose–response relationships between physical activity and health

In the current literature on PA and brain health, the FITT principle is also commonly used when analyzing the dose–response relationship between PA and measures of brain health (Cabral et al. 2019; Falck et al. 2019; Gallardo-Gómez et al. 2022; Northey et al. 2018), but the nature of the evidence examined indicates that: (1) acute density is typically not considered when analyzing the influence of acute bouts of PA on cognitive performance (i.e., as a moderator variable) (Chang et al. 2012; Kao et al. 2022; Oberste et al. 2019, 2021; Pontifex et al. 2019), (2) chronic density is often not reported in studies investigating the influence of chronic PA on cognition (Herold et al. 2019b; Manser et al. 2024), (3) chronic density is absent in moderator analyses in recent systematic reviews and meta-analyses investigating the influence of chronic PA on cognitive performance (Falck et al. 2019; Ludyga et al. 2020), and (4) chronic density is typically not mentioned in recommendations (e.g., from the World Health Organization) and policies aimed at reducing the risk of cognitive decline and dementia by lifestyle changes (e.g., via PA) (World Health Organization 2019). The absence of the variable density in the literature,

in analyses of dose–response relationships, and in the recommendations of official bodies could lead to the assumption that acute and chronic density are unimportant variables or that researchers studying the effects of PA on brain health may be unaware of the importance of density.

Given that neither the precise PA dosage (Bherer et al. 2013; Falck et al. 2019; Ludyga et al. 2020; Stillman et al. 2020) nor the neurobiological mechanisms that mediate the positive effects of acute and chronic PA on brain health are fully understood (Herold et al. 2018b, 2020a; Hou et al. 2024; McMorris 2021; Pontifex et al. 2019; Stillman et al. 2020; Voss 2016; Zou et al. 2023), density is a promising candidate for advancing our understanding in this direction. Specifically, considering density will allow for a more precise definition of the minimal and optimal PA dosage by providing information on how the duration of the rest or sedentary bout(s) between PA stimuli within a single bout of PA or successive bouts of PA (i.e., work bouts) influence specific measures of brain health. Generating such evidence holds great potential to inform and optimize intervention approaches aimed at promoting PA (e.g. "just-in-time adaptive PA interventions" (Hardeman et al. 2019; Müller et al. 2017; Wunsch et al. 2022)) to break up prolonged sitting with acute bouts of PA (Chueh et al. 2022; Li et al. 2022; Wheeler et al. 2019; Yu et al. 2022).

To illustrate how accounting for density can be crucial in the context of PA and brain health, we outline below several lines of evidence supporting our assumption. In this context, we highlight further directions for observational and intervention studies.

Acute density

A recent study provided direct evidence that acute density can influence the acute PA-related effects on specific behavioral measures of brain health. In particular, this study used a within-subject crossover design with a pretest–posttest comparison to investigate in healthy younger adults whether the use of different inter-set rest intervals (i.e., 1 min versus
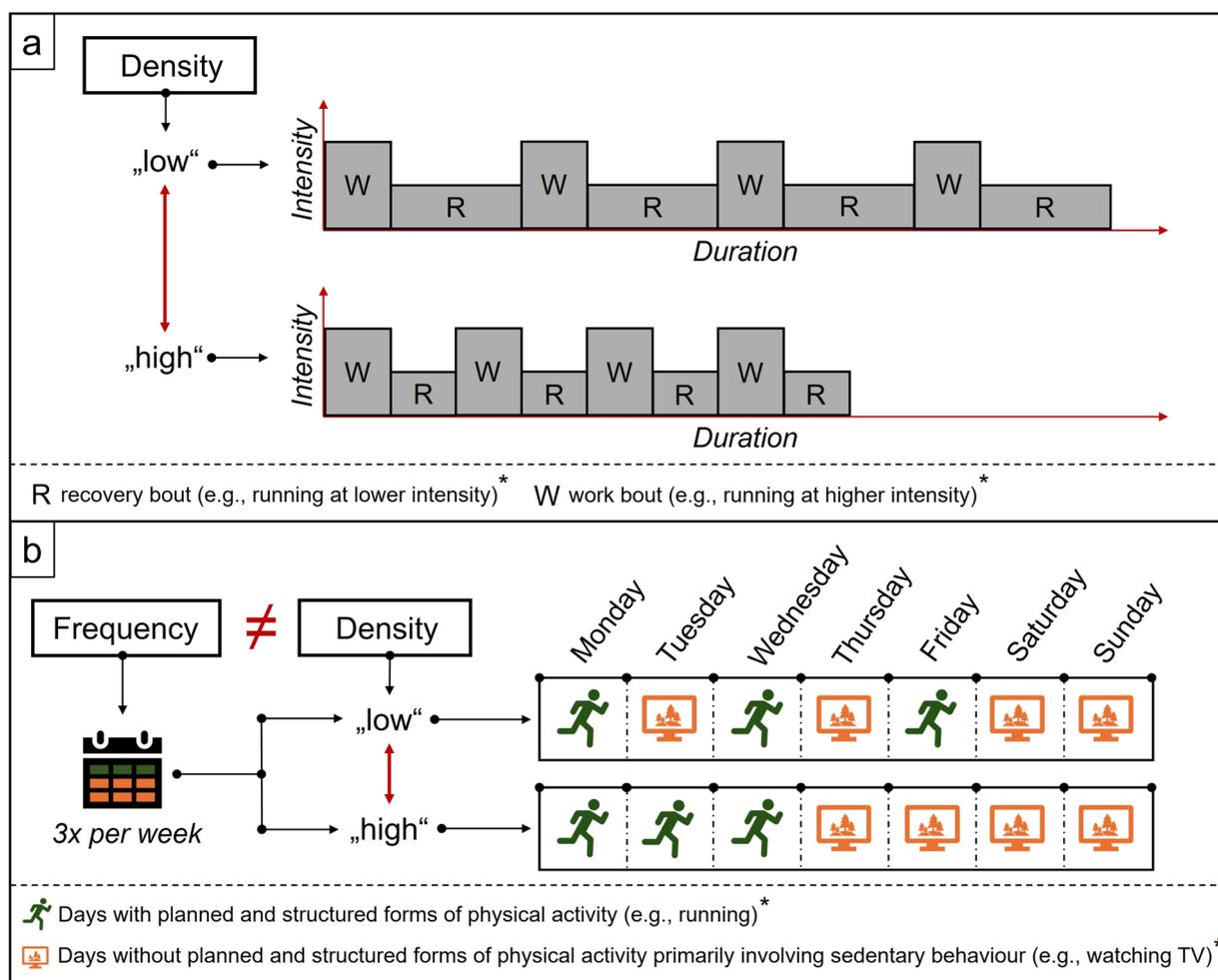
Fig. 1 Panel (**a**) upper: Schematic illustration of different densities, using an acute bout of physical exercise in interval mode as an example. Here, the number of the work bouts (4x) and rest bouts (4x) is equal whereas the duration of the rest bout in the upper panel (i.e., low acute density; the work–rest ratio of 1:2) is twice as long as in the lower panel (high acute density; the work–rest ratio of 1:1) resulting in a different acute density and, in turn, physical activity dosage. In this example, an active rest bout, which is conducted at half the intensity of the work bout, is selected. The example also illustrates that specific acute variables are interrelated (e.g., acute density, acute duration, and intensity of work and rest intervals). Panel (**b**) lower: Schematic illustration of the difference between frequency and chronic density in the context of chronic physical activity. The visualization shows that the same frequency (3× physical activity bouts per week) can be distributed differently over a week, resulting in a different chronic density and, in turn, physical activity dosage. The asterisk (*) indicates that other acute (i.e., type of physical activity, intensity, and acute duration) and chronic variables (i.e., chronic duration) that characterize the bout(s) of physical activity are assumed to be constant. Please note that we used sedentary behavior as an example for the rest bout(s) in panel B; however, depending on the context, such rest bout(s) can also encompass physical activity at a lower intensity than that of the work bout(s). Further, quantifying chronic density also depends on the period of interest (e.g., day, week, month, year)

3 min, representing higher and lower acute densities) during an acute bout of low-load resistance exercise (i.e., 40% of a one-repetition maximum, 6× sets of 10× repetitions) can influence acute exercise-induced changes in inhibitory control (i.e., assessed with the Stroop test) (Tomoo et al. 2021). In this study, shorter inter-set rest intervals (i.e., 1 min—higher acute density) improved inhibitory control (i.e., operationalized by a reverse Stroop interference score) immediately, 10 min, 20 min, and 30 min after exercise cessation, whereas such effects were absent for longer inter-set rest intervals (i.e., 3 min—lower acute density) (Tomoo et al. 2021). These findings support the notion that considering acute PA density has great potential to advance the understanding of the dose–response relationship of acute PA on specific measures of brain health.

Chronic density

There is a growing interest in the scientific community in developing a more holistic understanding of the chronic influence of the 24-h activity cycle (Collins et al. 2023; Mellow et al. 2019, 2022) and the distribution of PA across

a defined time interval (e.g., including but not limited to concepts such as "weekend warrior" (Min et al. 2024; Ning et al. 2025; O'Donovan et al. 2024; Wu et al. 2024), time of day (Maeneja et al. 2022), or fragmentation (Marino et al. 2024, 2025; Wanigatunga et al. 2022)) on brain health. In the following sections, we show that chronic PA density is a candidate determinant of brain health effects that should not be overlooked in observational and intervention studies, and when analyzing dose–response relationships within the context of chronic PA-related benefits on specific measures of brain health.

Observational studies

Five observational studies analyzed population-based data in adults, regarding the role of achieving a specific amount of PA recommended by the World Health Organization (i.e., 50% (Min et al. 2024; Ning et al. 2024, 2025) or 100% (Wu et al. 2024) of ≥ 150 min of moderate- or ≥ 75 min of vigorous-intensity PA per week (World Health Organization 2020, 2022) in $\leq 2\times$ bouts per week (i.e., denoted as "weekend warrior") or $\geq 3\times$ bouts per week on cognition and risk of developing chronic disease that affect brain health (Min et al. 2024; Ning et al. 2025; Wu et al. 2024).

In one of these observational studies, middle-aged to older adults with a weekend warrior PA pattern exhibited, regardless of the daily SB duration, a lower dementia risk compared to physically inactive adults with a long daily SB duration (i.e., < 150 min of moderate-to-vigorous-intensity PA and ≥ 8.5 h of SB) (Ning et al. 2025). Furthermore, another study reported that adults with a weekend warrior PA pattern showed a reduced risk of disorders that negatively affect brain health (i.e., all-cause dementia and Parkinson's disease) compared to those being physically inactive (i.e., < 150 min of moderate-to-vigorous-intensity PA) (Ning et al. 2024), with evidence that adults with a such an PA pattern had a comparable risk reduction for such disorders (e.g., dementia, stroke, Parkinson's disease, depressive or anxiety disorder) compared to those engaging more often in PA (i.e., $\geq 3\times$ PA bouts per week) (Min et al. 2024). The latter observation is consistent with the findings of another prospective study in Mexican adults that showed that compared to those who did not engage in planned and structured forms of leisure-time PA, "weekend warriors" (i.e., $\leq 2\times$ PA bouts per week) had a comparable risk reduction for mild dementia (i.e., operationalized by a score in the Mini-Mental Status Test of ≤ 22 points) relative to those who regularly engaged in PA ($\geq 3\times$ PA bouts per week) (O'Donovan et al. 2024). In the other studies, healthy adults with a weekend warrior and non-weekend warrior PA pattern showed comparable benefits in the cognitive composite score relative to those who were physically inactive (i.e., < 150 min of moderate-to-vigorous-intensity PA), whereas in adults with depressive symptoms, only those engaging in a non-weekend warrior PA pattern showed statistically significant improvements in cognitive functions (Wu et al. 2024).

Although neither of those five observational studies considered chronic density — because they did not account for the rest duration between the successive bouts of PA — several studies indicated that healthy adults achieving the recommended amount of PA in $\leq 2\times$ bouts per week had a comparable positive influence on cognitive performance and dementia risk as achieving this amount of PA in $\geq 3\times$ bouts per week. Whether such observations extend to other measures of brain health when the moderating role of the chronic density of PA is considered is an important area for further investigation. However, the finding that among individuals with depressive symptoms, only those with a non-weekend warrior PA pattern benefited in terms of cognition (Wu et al. 2024), supports the idea that considering chronic PA density is an important variable to gain insights into mechanisms explaining this observation.

Intervention studies

Although one 15-week intervention study in healthy older adults did not observe an effect of manipulating PA distribution via a modification of the work bout (i.e., performing multicomponent exercise for 30 min in the morning and the afternoon versus 60 min in the morning) on behavioral measures of brain health (i.e., executive functions) (Monteagudo et al. 2021), to the best of our knowledge, no intervention study has explicitly focused on modifying the chronic density of a PA intervention to investigate its causal influence on brain health. However, a meta-analysis suggests that a higher frequency (i.e., 5–7× PA bouts per week), which is typically achieved by exercising almost or every day in a week (i.e., probably mirrored in a high chronic density due to short rest duration, when assuming that commonly only 1× PA session is conducted per day), is more beneficial for improving cognitive performance in adults older than 50 years (i.e., double the effect size; 0.69 versus 0.32) than a lower frequency (i.e., 1–2× PA bouts per week) (Northey et al. 2018). Given that remains open whether such an observation might be related to a higher density or a higher total volume of PA, future intervention studies that purposefully manipulate chronic density or at least appropriately report acute and chronic density are needed to broaden the evidence base on the influence of different PA densities on brain health.

In this context, providing information on acute and chronic density can be especially relevant for interventions with lower levels of direct supervision (e.g., home- and technology-based interventions using exergames). For example, in home-based studies using exergames and providing only general supervision, partial direct supervision, or even no supervision [for more information on

supervision please see (Denton et al. 2021; Herold et al. 2024a, b)], older adults are typically instructed to achieve a certain duration of physical exercise over a week but are often allowed to self-select the frequency of the acute PA bouts (Callisaya et al. 2021; Delbaere et al. 2015; Gschwind et al. 2015a, b; Hoang et al. 2016; Schoene et al. 2013, 2015; Song et al. 2018). Such studies have documented that older participants who are highly motivated can exceed the recommended training frequency and/or perform multiple PA bouts throughout the day (Gschwind et al. 2015a; Hoang et al. 2016; Manser and Bruin 2024; Manser et al. 2023). This may result in insufficient rest time, which is perhaps less than optimal for the materialization of adaptation processes (i.e., consolidation). The above theoretical assumption is supported by (1) an experimental study showing that in younger adults too much consecutive computer-based training can be detrimental to learning performance (i.e., accuracy of motion discrimination) (Ashley and Pearson 2012) and (2) a systematic review observing that cognitive performance declines when endurance athletes are overtrained (Symons et al. 2023). These latter findings support the assumption that acute and chronic exercise density should be considered when prescribing and monitoring interventions aimed at promoting brain health.

Acute and chronic density are important variables in the prescription of physical exercise (i.e., periodization, and programming of sessions) because they further characterize the dosage by defining the duration of rest bout(s) within a single bout of physical exercise or between successive bouts of physical exercise (i.e., work bouts). Whereas periodization is the temporal organization (i.e., macro-management) of the characteristics of physical exercise sessions and phases of training (e.g., purposeful adjustment of variables such as exercise intensity and volume for progression) and application of training principles (Brown and Greenwood 2005; Cunanan et al. 2018; Kataoka et al. 2021; Ratamess et al. 2009), programming is defined as the micro-management of physical exercise that includes but is not limited to the organization of exercise and training variables (e.g., type of physical exercise, exercise intensity, exercise duration, and acute and chronic density) (Cunanan et al. 2018; Herold et al. 2019a; Kataoka et al. 2021). Thus, acute density is especially relevant for programming single physical exercise sessions within physical training, wherein physical exercises are performed in an interval mode or a set structure. This is because acute density defines the rest duration between the work bouts (e.g., also referred to as intervals or repetitions), between interval series or sets, or between different physical exercises (Buchheit and Laursen 2013a, b; Ratamess et al. 2009). As shown in Fig. 1, the acute PA stimulus can be modified by decreasing or increasing

the duration of rest between successive work bouts (i.e., higher or lower acute PA density, respectively).

Assessment and prescription of acute and chronic density

In the following sections, we discuss different prescription and analysis approaches for PA density considering the temporal context, the availability and accessibility of population-based datasets, and recent technological advances to assess PA (i.e., miniaturized wearables to track lifestyle activities within the 24-h activity cycle). Typically, the operationalization of chronic PA density becomes more challenging when longer time intervals are considered (e.g., week, month, year), especially for unplanned and unstructured forms of PA. Thus, we describe simple and more sophisticated analysis approaches relating to the chronic density of PA.

Acute density

Within a single session of PA, acute density can be operationalized by the duration of the rest bout(s) between the successive work bouts (i.e., in seconds or minutes or relative to the duration of the work bout; see Fig. 1a). Thus, a modification of acute PA density can be achieved by decreasing or increasing the duration of the rest bout(s), resulting in a higher acute work–rest ratio (i.e., higher PA density) or a lower acute work–rest ratio (i.e., lower PA density), respectively.

Recommendations concerning the assessment and prescription of acute density

As we will demonstrate below, temporal dynamics on different levels of analysis (e.g., behavioral, functional brain, and molecular and cellular levels (Erickson et al. 2022; Stillman et al. 2016, 2020)), particularly the after-effects of PA, are important sources of evidence to inform the prescription of acute PA density.

On the behavioral level, two meta-analyses showed that the after-effects of acute physical exercise on cognitive performance are transient, depending on the characteristics of the physical exercise, such as type, intensity, and duration (Chang et al. 2012; Garrett et al. 2024). More specifically, according to these meta-analyses, the greatest effects of acute physical exercise on cognitive performance can be expected to be 11–20 min (Chang et al. 2012) or 20–75 min (Garrett et al. 2024) after the cessation of the acute physical exercise bout and diminishes with longer delays (Chang et al. 2012; Garrett et al. 2024). However, some studies provide evidence that the after-effects of acute physical exercise

on specific cognitive domains (e.g., executive functions) can even persist for up to 60 min in children (Ludyga et al. 2019) and up to 30 to 90 min in healthy younger adults (Dora et al. 2021; Hung et al. 2013; Martínez-Díaz and Carrasco Páez 2023; Tian et al. 2021; Tomoo et al. 2020; Tsukamoto et al. 2016a). Moreover, in healthy younger adults, performing acute physical exercise four hours after learning is more beneficial for improving memory performance and hippocampal pattern similarity (i.e., assessed 48 h later) than performing acute physical exercise immediately after learning the task (van Dongen et al. 2016).

The above evidence suggests that the effects of acute PA on cognitive performance are transient. Thus, it seems reasonable to assume that repeating acute PA may be required to preserve the positive PA-related effects on cognition over prolonged periods of SB (e.g., office working hours or esports training (Manci et al. 2024)). The precise time points to repeat acute PA may be conceptualized by the PA density construct.

That density can be an important variable for informing the prescription of PA is also supported by several lines of evidence extending from the behavioral level to the molecular and cellular levels and functional brain level. In particular, two studies in healthy younger adults investigated the effects of two repeated acute bouts of high-intensity interval exercise (HIIE, 4×4-min work bouts at 90% of VO_2 peak interspersed with 3-min rest bouts at 60% VO_2 peak) on inhibitory control (i.e., assessed by the Stroop task every 10 min after the cessation of each bout of physical exercise for $5 \times$ times) (Hashimoto et al. 2018; Tsukamoto et al. 2016b). In both studies, a recovery interval of 60 min separated the first bout of acute HIIE from the second bout of HIIE, in which the Stroop task performance was repeatedly assessed (Hashimoto et al. 2018; Tsukamoto et al. 2016b). These studies showed that inhibitory control (i.e., reverse Stroop interference score) improved immediately (Hashimoto et al. 2018; Tsukamoto et al. 2016b) and 10 min (Tsukamoto et al. 2016b) after exercise cessation in both the first and second bout acute bouts of HIIE compared to the pretest. For the first acute bout of HIIE an inhibitory control benefit persisted for up to 40 min following exercise cessation (Hashimoto et al. 2018; Tsukamoto et al. 2016b). For the second bout of HIIE the change in inhibitory control at the 10 (Hashimoto et al. 2018) or 20 min (Tsukamoto et al. 2016b) assessment interval after exercise cessation was not significantly different from the pretest and was less pronounced compared to the first bout of HIIE when considering the post-exercise assessments at 20 (Hashimoto et al. 2018), 30 (Hashimoto et al. 2018), and 40 (Hashimoto et al. 2018; Tsukamoto et al. 2016b) but not 50 min (Hashimoto et al. 2018; Tsukamoto et al. 2016b).

Collectively, these observations suggest that the acute PA-related effects on inhibitory control were less pronounced in the second bout of HIIE compared to the first bout of HIIE. Hypothetically, such a diminished effect after the second bout of HIIE could be, among other factors, related to the relatively close temporal proximity (i.e., high density) between the two single bouts of HIIE (i.e., 60 min).

In addition to examining postexercise inhibitory control, the work described in the previous paragraph observed that acute PA-induced performance improvements in inhibitory control correlated with changes in blood lactate concentration in both studies (Hashimoto et al. 2018; Tsukamoto et al. 2016b), and that changes in peripheral blood lactate concentration were significantly lower during and after the second bout of HIIE (Tsukamoto et al. 2016b). Given these results, it seems reasonable to speculate that there is a neurobehavioral relationship between each measure (Hashimoto et al. 2021; Herold et al. 2019a, b; Törpel et al. 2018; Yamada et al. 2021) and is an assumption supported by evidence that peripheral blood lactate can cross the blood–brain barrier via monocarboxylate transporters and be utilized as "fuel" for cognitive processes (Brooks 2018, 2020a, b; Brooks et al. 2021, 2022, 2023; Quistorff et al. 2008; Riske et al. 2017; Taher et al. 2016). Indeed, recent studies have reported that changes in peripheral blood lactate concentration are correlated with acute PA-related improvements in cognitive performance (Ballester-Ferrer et al. 2022; Herold et al. 2022a; Nunes Pereira Oliva et al. 2023); however, it remains unclear whether blood lactate changes are a mediator of acute PA-induced benefits on cognitive performance (Li et al. 2023). In addition, there is evidence that a change in peripheral blood lactate concentration (e.g., induced by acute physical exercise (Ferris et al. 2007) or infusion at rest (Schiffer et al. 2011) is associated with a change in the concentration of serum levels of the brain-derived neurotrophic factor (BDNF), an important neurotrophin involved in processes of PA-related neuroplasticity and brain health (Cefis et al. 2023; Erickson et al. 2010, 2011; Knaepen et al. 2010; Leckie et al. 2014; Marston et al. 2019; Stimpson et al. 2018; Walsh et al. 2020; Walsh and Tschakovsky 2018).

In younger healthy adults, acute PA-induced changes in the BDNF are correlated with cognitive improvements (Hwang et al. 2016), lending credence to the hypothesis that BDNF is involved in cognitive performance improvements after an acute bout of PA (Borror 2017). Such acute PA-triggered effects of BDNF on measures of cognitive performance are transient, as several studies on the kinetics of BDNF have consistently shown that elevated BDNF levels return to baseline 15–60 min after exercise cessation (for review, see (Dinoff et al. 2017)), and is a result that may explain, among other factors, why the after-effects of acute PA on cognitive performance lasting for a limited time. Accounting for the transient nature of the "facilitation effect", which is characterized by the acute PA-induced release of neurotrophic factors such as BDNF (Herold et al.

2018a; Fissler et al. 2013), by the PA variable density is highly relevant for specific types of PA interventions (e.g., sequential motor-cognitive training). Concerning motor-cognitive interventions, considering acute density would allow for better standardization of the time at which prolonged periods of cognitive exercise need to be interrupted by acute PA to ensure an optimal facilitation effect across the entire training session (Herold et al. 2018a).

The transient effects of acute PA are not only evinced at the behavioral, or molecular and cellular levels but also at the functional brain level (e.g., cerebral blood flow [CBF]), which is hypothesized to mediate the acute effects of PA on cognitive performance (Pontifex et al. 2019). Indeed, some studies provide evidence that acute PA-induced changes in cerebral artery velocity (CBV), a surrogate for CBF that is typically measured by monitoring middle CBV via transcranial Doppler ultrasound (Ide and Secher 2000; Kennedy et al. 2022; Mulser and Moreau 2023; Tymko et al. 2018), correlate with acute PA-induced cognitive improvements (i.e., executive functioning assessed by the antisaccade task) (Shirzad et al. 2022; Tari et al. 2020). The acute PA-induced increase in CBV can persist for up to 2 h after exercise cessation depending on several factors (e.g., characteristics of the person and the acute bout of PA, methodological factors—for review see (Kennedy et al. 2022)) but typically return to baseline levels relatively shortly after exercise cessation (Mulser and Moreau 2023; Kennedy et al. 2022) (e.g., 30 min—for review see (Kennedy et al. 2022)) underpinning the transient nature of PA-induced effects on putative neurobiological mechanisms which may mediate the effects of acute PA on behavioral measures of brain health.

Taken together, the current state of evidence supports the view that acute PA-related changes may be transient although the exact time course (e.g., precise time point to harvest the largest after-effects of acute PA) and potential moderators of the after-effects of acute PA (e.g., acute PA-related factors such as type, intensity, duration, and non-PA-related factors such as age, biological sex, health status, and fitness level) on specific measures of brain health are not fully understood and is — in part — related to methodological challenges (e.g., a limited number of follow-up assessments, confounding influence of activities performed between cessation of acute PA and cognitive test administration) (Pontifex et al. 2019). However, the evidence on the after-effects of acute PA urges future research to consider acute PA density as a variable to facilitate our understanding of the dose–response relationship between acute PA and brain health. In particular, considering the after-effects of acute PA on different levels of analysis can help to inform the prescription of PA density, which, in turn, allows for the standardized prescription of the time point(s) at which the acute PA stimulus needs to be repeated to prolong the acute PA-related benefits on specific measures of brain health

(e.g., time points to interrupt prolonged sitting during sedentary working activities or cognitive exercise in sequential motor-cognitive interventions). Such information on the appropriate timing to set a PA stimulus is crucial to inform the experimental design of studies (e.g., studies investigating the effects of breaking up prolonged sitting by acute PA on brain health (Chueh et al. 2022; Li et al. 2022)) and to maximize the effectiveness of PA interventions (e.g., "just-in-time adaptive PA interventions" (Hardeman et al. 2019; Müller et al. 2017; Wunsch et al. 2022) or interventions with sequential motor-cognitive exercises (Herold et al. 2018a)).

As shown in Fig. 2, we propose two different approaches, namely (1) "*fixed acute PA density*" in which the time intervals are fixed for all individuals (e.g., breaking up prolonged sitting of 8 h every 30 min by acute PA), and (2) "*psychophysiological-informed acute PA density*" in which the time intervals are informed by actual changes in specific psychophysiological markers (e.g., comparable to the approach to use psychophysiological changes such as in CBF (Herold et al. 2020b) or affective response (Baldwin et al. 2016; Ladwig et al. 2017; Parfitt et al. 2012; Zenko et al. 2024) for exercise intensity prescription) to set and study the influence of acute PA density (Manci et al. 2024). For example, a "psychophysiological-informed acute PA density" approach might use changes in physiological markers such as pupil size (i.e., a decrease of pupil size below a specific threshold) to determine the exact duration at which periods of prolonged sitting should be interrupted by acute PA – as highlighted for a specific application scenario (i.e., esports) elsewhere (Manci et al. 2024).

Chronic density—simple analysis approaches

In observational or intervention studies, an approach to investigate the influence of different chronic density patterns on brain health is to study different groups of individuals based on their chronic PA density patterns (e.g., a low chronic PA density group in which individuals perform PA on non-consecutive days versus a high chronic PA density group in which individuals perform PA on consecutive days—see also Fig. 1 b).

Chronic density—sophisticated analysis approaches

The use of more sophisticated approaches, including distributional data analysis (Ghosal and Matabuena 2024; Ghosal et al. 2022), compositional isotemporal data analysis (Bezerra et al. 2021; Dumuid et al. 2019, 2020; Hyodo et al. 2022; Lau et al. 2023; Lu et al. 2023; Mitchell et al. 2023), burstiness analysis (Culverhouse et al. 2024; Takeuchi and Sano 2024), and machine learning (Memel et al. 2016; Poudel et al. 2022), holds promise for identifying groups of individuals with distinct chronic PA density
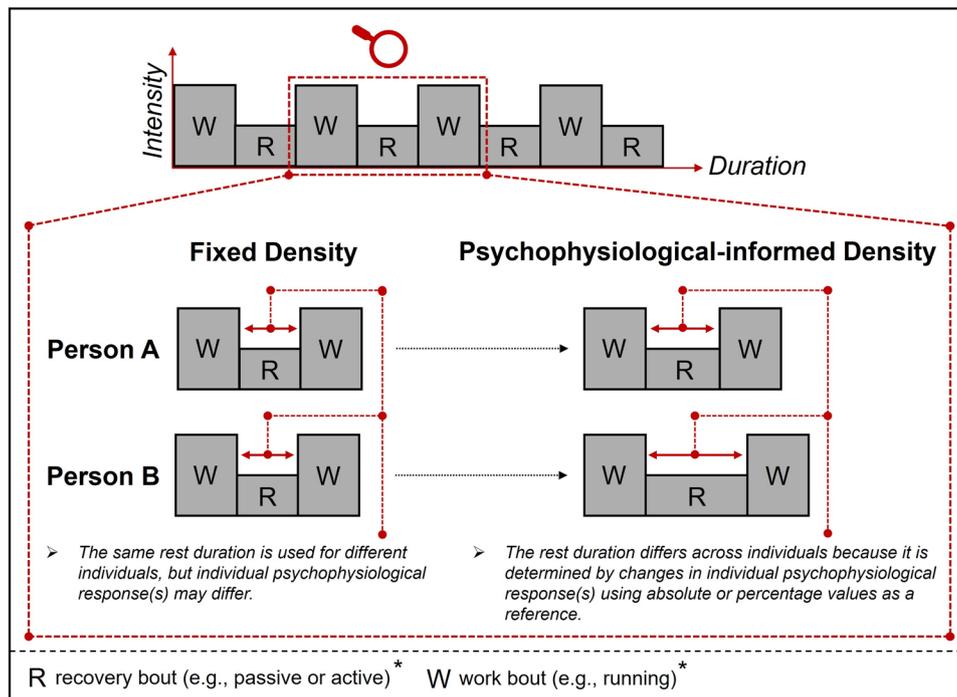
Fig. 2 Schematic illustration of the conceptual differences between (1) *fixed density* and (2) *psychophysiological-informed density* that can be used to prescribe a specific (acute) density of physical activity (Manci et al. 2024). Based on recent work, we propose that in addition to using traditional psychophysiological parameters (e.g., heart rate; Buchheit and Laursen 2013b) to prescribe acute density in planned and structured forms of physical activity, changes in pupil size (Matsui et al. 2024) and brain hemodynamics (Herold et al. 2020b) can be promising psychophysiological parameters to inform an acute, brain health-centered, psychophysiological-informed density prescription (e.g., using a fixed value or percentage of a reference value; Buchheit and Laursen 2013b). The asterisk (*) indicates that other acute (i.e., type of physical activity, intensity, and acute duration) and chronic variables (i.e., chronic duration) that characterize the bout(s) of physical activity are assumed to be constant

patterns. Despite some limitations and challenges (e.g., the need for large sample sizes and high-dimensional data, the time-consuming nature of training algorithms, and the lack of benchmark data), machine learning-based approaches in particular provide several advantages for the purpose of profiling PA patterns (e.g., more accurate classification and prediction, the possibility of a hypothesis-free/generating approach) (Clark et al. 2021; Farrahi and Clare 2024; Farrahi et al. 2019; Farrahi and Rostami 2024; Fuller et al. 2022). Another advantage of machine learning-based approaches is their capacity to handle large, complex, and high-dimensional datasets (Farrahi and Rostami 2024). The ability and flexibility to handle such datasets make machine learning-based approaches well-suited for analyzing the influence of PA density on specific markers of brain health because density is a more complex variable than other PA variables (e.g., frequency, duration). This assumption is supported by the fact that these approaches have been successfully applied to elucidate the influence of "micropatterns" of PA including intensity and duration (also referred to as bout length) on health-related outcomes such as mortality (Ahmadi et al. 2023; Stamatakis et al. 2022) and cancer

incidence (Stamatakis et al. 2023). Thus, extending machine learning-based approaches to density is a promising area for future research to elucidate the influence of different chronic PA density patterns on measures of health in general and brain health in particular.

The application of sophisticated classification and analysis techniques may enable the investigation of specific research questions (e.g., *Is a low density of moderate-intensity PA in older adults more, less, or equally beneficial for brain health than having a high density of moderate-intensity PA?*) or to study the association of specific density-related PA patterns, such as the regularity and randomness of PA density, with measures of brain health. In this context, we propose that the regularity and its antithesis randomness can be characterized by the periodicity and the stability (Shi et al. 2024) that is in the case of the PA density reflected by the degree of variability of the duration of the rest bouts between successive work bouts within a given time interval (e.g., day, week, month, year). We suggest that, among other approaches (Rowlands et al. 2015), the regularity and randomness of PA density can be operationalized by further developing different measures used to assess fragmentation

(Gao et al. 2023; Danilevicz et al. 2024a, b; Marino et al. 2024, 2025; Wanigatunga et al. 2022), complexity and fractal dynamics (Blodgett et al. 2023; Cavanaugh et al. 2010; Hu et al. 2016; Raichlen et al. 2019), or entropy (Shi et al. 2024).

Fragmentation of the RAR is typically assessed using metrics (for an overview see (Gao et al. 2023)) such as intra-daily variability (IV) and inter-daily stability (IS), providing information on how constant RAR is within or across days (Danilevicz et al. 2024b, 2024a; Gao et al. 2023; Vetter 2020), or transition probability (TP), a measure quantifying the likelihood of transitioning from rest (e.g., sleep) to activity (e.g., PA), or vice versa (Danilevicz et al. 2024b, 2024a; Lim et al. 2011; Marino et al. 2025).

Concerning IV of the RAR, there is evidence that (1) older adults with early-onset dementia (Hooghiemstra et al. 2015) or Alzheimer Disease (van Egroo et al. 2024) have a higher baseline IV of RAR compared to healthy controls, (2) in older adults with mild-moderate Alzheimer's disease a higher baseline IV of RAR is associated with accelerated cognitive decline after a one-year follow-up (Targa et al. 2021), (3) in older adults a higher slope of IV of RAR is associated with stepper global cognitive decline (van Egroo et al. 2024), (4) in a sample of older adults with and without mild cognitive impairment (MCI) a lower baseline IV of RAR is associated with better executive functioning (Alfini et al. 2021), (5) in middle-aged and older adults a higher baseline IV of RAR is associated with higher risk for developing cognitive impairments (Haghayegh et al. 2024; Xiao et al. 2022) and dementia (Haghayegh et al. 2024), worse cognitive functioning (i.e. slower processing speed (Luik et al. 2015; Oosterman et al. 2009), worse executive functioning (Luik et al. 2015; Oosterman et al. 2009), worse memory (Oosterman et al. 2009), and worse global cognition (Luik et al. 2015)) as well as detrimental functional and structural brain changes (i.e., more pronounced amyloid deposit in the brain and cerebrospinal fluid (Musiek et al. 2018), lower temporal lobe volume (van Someren et al. 2019) and posterior parietal grey matter volume (Smagula et al. 2020), higher white matter lesion volume (Zuurbier et al. 2015), and the presence of cerebral microbleeds (Zuurbier et al. 2015)), (6) in a sample of older adults a higher baseline IV of RAR is associated with an increased risk of displaying hypopigmentation of the locus coeruleus, a marker of neurodegeneration, which relationship with cognitive performance (i.e., episodic memory, and global cognition) is mediated by IV of RAR (van Egroo et al. 2024), and (7) in a sample of middle-aged and older adults with subjective and/or objective cognitive impairment a higher baseline IV of RAR is associated lower cortical thickness in different cortical areas (i.e., right cuneus, left middle frontal gyrus, and lateral orbital frontal cortex) (Espinosa et al. 2025).

Regarding IS of RAR, there is evidence that (1) older adults with Alzheimer's Disease have a lower baseline IS compared to healthy controls (van Egroo et al. 2024), (2) in a sample of older adults with and without MCI, a higher baseline IS of RAR is associated with better episodic memory performance (Alfini et al. 2021), (3) in middle-aged and older adults, lower baseline IS of RAR is associated with worse cognitive performance (i.e., slower processing speed, worse executive functioning (Luik et al. 2015; Rabinowitz et al. 2022; Sun et al. 2023), worse memory performance (Sun et al. 2023), and faster memory decline (Rabinowitz et al. 2022)), as well as detrimental structural brain changes (e.g., more pronounced occipital periventricular and frontal white matter lesions (Oosterman et al. 2008), or a greater likelihood of white matter lesion burden in the anterior thalamic radiation (Palmer et al. 2022)), (4) in a sample of middle-aged to older adults with subjective and/or objective cognitive impairment a lower baseline IS of RAR with lower cortical thickness in frontal, temporal, and postcentral brain regions (i.e., left and right superior frontal gyrus, left superior temporal gyrus, and left postcentral gyrus) (Espinosa et al. 2025).

Concerning fragmentation (i.e., TP), an observational study reported that a lower PA fragmentation is associated with less cognitive decline in memory and visuospatial processing performance in cognitively unimpaired older adults (Marino et al. 2025).

Collectively, the evidence suggests that in middle-aged and older adults less fragmented, especially less variable RAR patterns (i.e., lower IV and higher IS of RAR) are associated with better brain health although additional, more rigorously designed examinations with larger and more diverse samples are warranted before more robust conclusions can be drawn (for review see also (Smagula et al. 2019; Zhang et al. 2024)). Whether such a finding is generalizable to patterns of chronic PA density needs to be elucidated in future studies, especially since another observational study using a different metric for fragmentation (i.e., PA variability quantified by the minute-to-minute PA changes across the observation period) reported that in a nationally representative sample of older adults less variable PA patterns are associated with higher odds of cognitive impairment, even after accounting for total PA and other demographic covariates such as age, sex, education, race/ethnicity, and health status (Donahue et al. 2025).

Fractal dynamics are characterized by self-affinity (also referred to as self-similarity or scale invariance) of a given signal (e.g., derived from accelerometers) across time scales (Arsac and Deschodt-Arsac 2018; Goldberger et al. 2002; Hardstone et al. 2012; Paraschiv-Ionescu et al. 2008; Pittman-Polletta et al. 2013). There is a strong case to be made that fractal dynamics can help to better understand the periodization of chronic physical exercise (Brown and Greenwood 2005), and several studies have used this approach to analyze physiological data (e.g., frequently applied to heart rate variability data (Gronwald et al. 2020a, 2021; Kaufmann et al.

2023; Rogers et al. 2021)), or PA patterns (Blodgett et al. 2023; Cavanaugh et al. 2010; Hu et al. 2016; Raichlen et al. 2019). In the context of PA, a popular method for assessing fractal dynamics (e.g., of PA (Blodgett et al. 2023; Cavanaugh et al. 2010; Hu et al. 2016; Raichlen et al. 2019)) is detrended fluctuation analysis (DFA), which is a nonstationary time-series analysis of specific signals (e.g., accelerometer data) that reflects the correlative structure and fractal dimension of signal fluctuations across a range of time scales based on a modified root-mean-square analysis (Hardstone et al. 2012; Peng et al. 1994, 1995a, 1995b; Pittman-Polletta et al. 2013). For example, a study using data from 5097 middle-aged adults showed that greater fractal stability of daily PA (i.e., assessed via a thigh-mounted accelerometer over seven days and reflected in a higher DFA scaling exponent) was associated with better verbal fluency performance in males but not in females (Blodgett et al. 2023). Such biological, sex-specific differences are consistent with the growing body of evidence suggesting that biological sex is an important moderator in the relationship between PA and brain health (Barha et al. 2020, 2017a, 2017c, 2019, 2023; Barha and Liu-Ambrose 2018, 2020). However, whether such findings extend to the chronic density of PA remains a promising area for further investigations.

Recommendations regarding the assessment and prescription of chronic density

To quantify the chronic density of PA, we recommend the application of device-based assessments to complement subjective assessments (i.e., questionnaires) for the following reasons. First, popular questionnaires to assess chronic PA, such as the International Physical Activity Questionnaire (IPAQ), quantify frequency but not chronic PA density (i.e., neither the long form (Craig et al. 2003) nor the short form (Lee et al. 2011) of the IPAQ), although some recently developed questionnaires do, at least in part, collect such information (e.g., Daily Activity Behaviours Questionnaire (Kastelic et al. 2023, 2021, 2022; Kastelic and Sarabon 2023)). Second, although subjective assessment tools (e.g., questionnaires) have several advantages (e.g., low burden for participants, cost-effective and convenient administration), they are prone to several sources of bias (e.g., recall bias or social desirability bias) that can confound the estimation of chronic PA patterns (Nigg et al. 2020; Prince et al. 2020; Strath et al. 2013; Warren et al. 2010). Hence, device-based assessment tools can circumvent the above-described limitations of subjective assessment tools; however, it should be considered that (1) the applied device-based measurement tool needs to be valid and reliable (Argent et al. 2022; Johnston et al. 2020; Mühlen et al. 2021), and (2) there is not yet a fully established consensus on the application of device-based measurement tools (e.g., placement and sampling

frequency of the device) or on the data processing procedures to obtain specific indices of PA (e.g., minimal length of the epochs, filter, cut-off points, non-wear-time definition) although some recommendations exist (Migueles et al. 2021, 2017; Pulsford et al. 2023; Rodrigues et al. 2025). Further, we recommend combining popular device-based tools such as accelerometers with other sensors (e.g., for ambient light, barometer/altimeter, or geolocation) and digital tools (e.g., smartphones) to allow for the recording of contextual information (e.g., weather via geolocation at a specific time point (Timm et al. 2023) or type of activity conducted during rest bout(s) via an accelerometer-triggered electronic-diary (Ebner-Priemer et al. 2013; Giurgiu et al. 2019, 2020a, 2020b, 2020c; Reichert et al. 2020; Timm et al. 2023)). The latter approach is also referred to as ambulatory assessment (see Fig. 3), which typically also includes the assessment of the context in which behaviors occur (Haaren-Mack et al. 2022; Reichert et al. 2020; Trull and Ebner-Priemer 2013).

Regarding PA density, rest bouts are a key construct and may be considered synonymous with, or primary to, the time spent in SB when considering waking hours. When accounting for non-waking hours, rest encompasses time spent sleeping. As we will demonstrate below, SB and sleep, are lifestyle behaviors that can moderate the effect of PA on brain health (Collins et al. 2023; Mellow et al. 2019, 2022). Thus, they should be considered important moderators when aiming to elucidate the effect of PA density on brain health, especially when studying chronic PA.

Concerning SB, there is emerging evidence that the effect of acute PA on cognitive function is altered by subsequent exposure to prolonged sitting versus breaks in sitting (Wheeler et al. 2019), and that the characteristics of activities that are primarily involved in the rest bout(s) can differentially influence brain health (Hallgren et al. 2020; Mallawaarachchi et al. 2024; Raichlen et al. 2022; Zou et al. 2024). In particular, there is evidence that the type of SB can moderate the effects of SB on brain health because mentally active SB (e.g., reading or working on a computer) are often positively associated with brain health, whereas mentally passive SB (e.g., watching non-educational television programs) does not confer such benefits (Hallgren et al. 2020; Mallawaarachchi et al. 2024; Raichlen et al. 2022; Zou et al. 2024). In addition, a growing body of evidence suggests that the brain and cardiometabolic consequences of too much time spent in SB are distinct from those of too little PA (Dunstan et al. 2021) (Pinto et al. 2023; Raichlen et al. 2023; Zou et al. 2024). This reinforces the utility of considering SB as a mechanism for the importance of density as a key novel element to complement the FITT and FITT-VP principles.

Concerning sleep (i.e., often quantified as time in bed), there is accumulating evidence that it can mediate and/or moderate the effect of PA on brain health (Bloomberg et al. 2023;

Fig. 3 Schematic illustration of how the density of physical activity can be assessed considering narrower periods (i.e., a week and a day). Please note that the figure zooms in on a day without planned and structured physical activity (i.e., no physical exercise), but with incidental physical activity. The color code is as follows: (1) green color is related to physical activity, (2) orange color is related to sedentary behavior, and (3) blue color is related to sleep. In addition, we intentionally refrained from including other, less important, activities (e.g., showering, going to the toilet, talking to coworkers) in the 24-h activity cycle to maintain the clarity of the display item
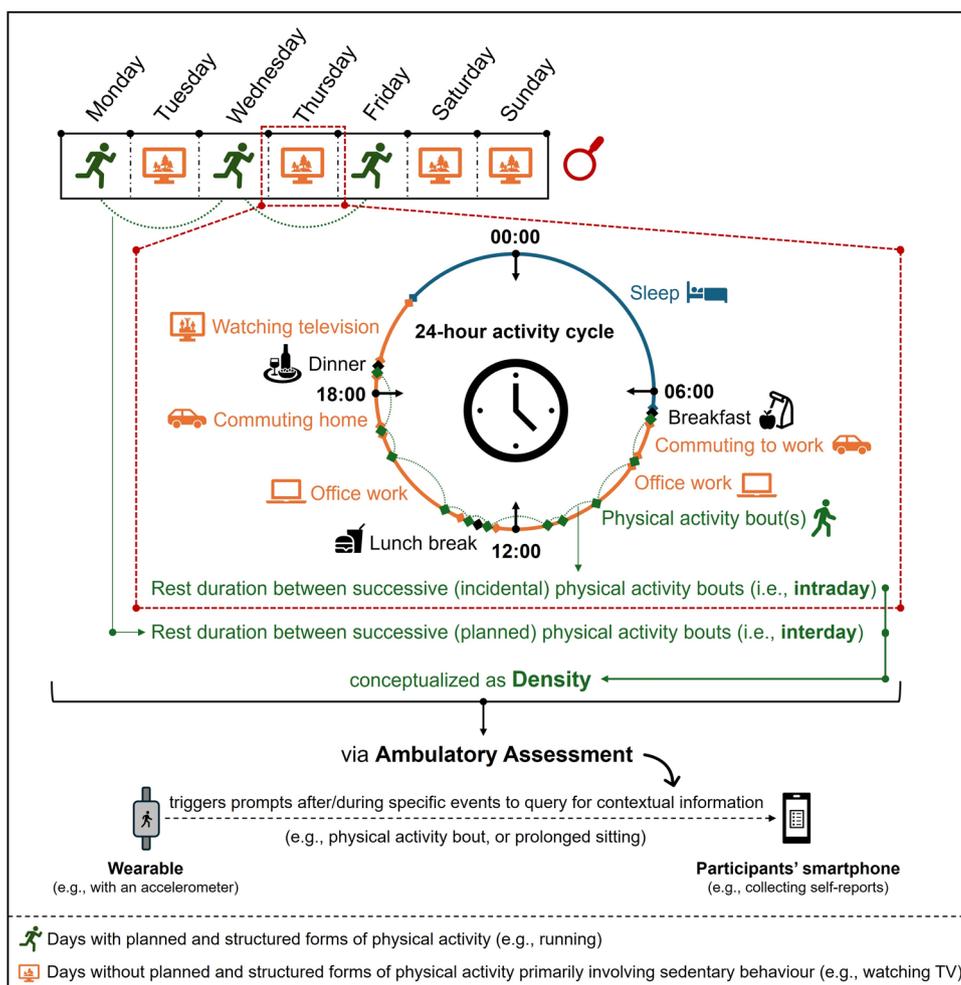
Liu-Ambrose and Falck 2019; Mellow et al. 2019, 2022). For example, several cross-sectional studies provide evidence that (1) subjective sleep quality and sleep efficiency mediate the relationship between PA level and inhibitory control in younger adults (Li et al. 2021), (2) sleep efficiency mediates the relationship between PA and working memory, task switching, verbal ability and fluency, and memory recall in a mixed sample of younger and older adults (Wilckens et al. 2020), (3) better subjective sleep quality mediates the relationship between PA and verbal fluency, immediate recall, delayed recall (Cheval et al. 2022) and working memory (Guardia et al. 2024) in middle-aged and older adults, and (4) older adults with poor sleep efficiency (i.e., percent of the time in bed spent asleep) benefit most from PA in terms of global cognition (Callow et al. 2024). As well, a 6-month intervention study wherein cognitively healthy older adults performed moderate- or vigorous-intensity interval exercise twice a week, reported that participants in the moderate-intensity group with documented poorer baseline sleep efficiency showed a greater exercise-induced improvement in episodic memory and global cognition (Sewell et al. 2023).

In conjunction with the observations that other activities of the 24-h cycle, which can form rest bout(s), including free-living standing activity (Halloway et al. 2021) and light-intensity PA (Erlenbach et al. 2021) are positively associated with cognitive performance, the above-summarized evidence on the moderating role of SB and sleep supports the idea that considering all activities in the 24-h activity cycle is important to advance our understanding of the influence of PA on brain health (Mellow et al. 2022, 2019; Collins et al. 2023). To this end, complementing the 24-h activity approach with PA density may enable more nuanced insights into the complex relationships between lifestyle behaviors and brain health (see Fig. 3).

Limitations

Using brain health as the case in point, we have discussed the opportunities and challenges for further research employing the variable *density* to improve the understanding of

dose–response relationships between PA and brain health; however, the following limitations need to be considered.

First, others have previously advocated for complementing FITT from a psychological perspective. In this view, an additional "F" representing "fun", an umbrella term for psychological factors such as affective valence and enjoyment of PA (Burnet et al. 2018), is used to reflect that these factors are important determinants of PA engagement and adherence (Brand and Cheval 2019; Brand and Ekkekakis 2018, 2021; Cheval and Boisgontier 2021; Collado-Mateo et al. 2021; Ekkekakis and Brand 2019).

Second, specific populations (e.g., individuals with chronic diseases), depending on other exercise and training variables (e.g., exercise intensity and training frequency) that determine the overall PA dosage, may not well-tolerate PA with a relatively high acute or chronic PA density. Thus, to minimize the risk of PA-related adverse health events in such special populations (e.g., individuals with eating disorders, or older adults without/with cognitive impairment), they may require a personalized PA prescription, which especially considers adapting PA density based on the individual PA capacity and tolerance.

Third, although we provide a strong theoretical rationale that complementing FITT and FITT-VP with the variable density will improve our understanding of the dose–response relationship between PA and brain health, we wish to emphasize that the precise characterization or prescription of a specific PA dosage will remain a considerable challenge because of the myriad of (1) non-modifiable factors (e.g., age, biological sex, genetics), (2) potentially modifiable non-PA-related factors (e.g., diet, sleep, stress, environmental conditions), and (3) modifiable PA-related factors (e.g., PA type, intensity, duration, movement frequency), which include but are not limited to setting (e.g., home-based or center-based, and indoor or outdoor), method of delivery (e.g., in-person or online), level of supervision (e.g., no supervision, general supervision, direct supervision) and social interaction (e.g., individual or group-based), that can influence the dosage and individual psychophysiological response(s) to PA, as discussed elsewhere in more detail (Barha et al. 2017a, b, 2019, 2021a, b; Barha and Liu-Ambrose 2020, 2018; Gronwald et al. 2020b; Herold et al. 2019a, 2024a, b; Meyler et al. 2021; Solis-Urra et al. 2024; Toigo and Boutellier 2006). In other words, adding density to FITT and FITT-VP is another piece of the puzzle to improve the determination of the PA dosage and, in turn, disentangle its influence on specific health-related outcomes such as brain health.

Conclusions

Density, a variable that characterizes the timing of PA within a specific time period; it does so by quantifying the temporal intervals (i.e. time spent resting) between successive working bouts within a single PA bout as well as between successive PA bouts within a specific time period, has been under-recognized in the contemporary scientific practice when studying the relationship between PA and health-related outcomes. Using the field of brain health as an example, this article has provided an overview of the implications and the potential of addressing PA density as a variable that gives an additional piece of information that complements traditional concepts (i.e., FITT and FITT-VP) for PA dosage determination and allows for more precise prescription of it for improved health effects and the prevention and treatment of chronic disease. Considering that (1) there is an increasing interest in understanding the health effects of PA dosage, including but not limited to "micropatterns" of PA typically assessed via high-resolution data of wearables (Ahmadi et al. 2023; Gill et al. 2023; Stamatakis et al. 2022), and (2) an explicit focus on the density variable has been largely absent from PA research to date, we discussed approaches for operationalizing PA density and showing how investing greater effort in understanding its effects can add fruitful nuance to identifying the dose–response relationship between PA and health-related outcomes (e.g., brain health), and thus has the potential to provide important information on the optimal and minimal beneficial PA dosage.

Data availability Data sharing does not apply to this article because no data were created or analyzed for this review article.

Declarations

References

Ahmadi MN, Hamer M, Gill JMR, Murphy M, Sanders JP, Doherty A, Stamatakis E (2023) Brief bouts of device-measured intermittent lifestyle physical activity and its association with major adverse cardiovascular events and mortality in people who do not exercise: a prospective cohort study. Lancet Public Health 8(10):e800–e810. https://doi.org/10.1016/S2468-2667(23)00183-4

Ahmadi MN, Holtermann A, Tudor-Locke C, Koster A, Johnson N, Chau J, Wei Le, Sabag A, Maher C, Thøgersen-Ntoumani C, Stamatakis E (2024) Time to elicit physiological and exertional vigorous responses from daily living activities: setting foundations of an empirical definition of VILPA. Med Sci Sports Exerc. https://doi.org/10.1249/MSS.0000000000003521

Alfini A, Albert M, Faria AV, Soldan A, Pettigrew C, Wanigatunga S, Zipunnikov V, Spira AP (2021) Associations of actigraphic sleep and circadian rest/activity rhythms with cognition in the early phase of Alzheimer's disease. Sleep Adv J Sleep Res Soc 2(1):zpab007. https://doi.org/10.1093/sleepadvances/zpab007

Argent R, Hetherington-Rauth M, Stang J, Tarp J, Ortega FB, Molina-Garcia P, Schumann M, Bloch W, Cheng S, Grøntved A, Brønd JC, Ekelund U, Sardinha LB, Caulfield B (2022) Recommendations for Determining the Validity of Consumer Wearables and Smartphones for the Estimation of Energy Expenditure: Expert Statement and Checklist of the INTERLIVE Network. Sports Med(Auckland, N.z). https://doi.org/10.1007/s40279-022-01665-4

Arsac LM, Deschodt-Arsac V (2018) Detrended fluctuation analysis in a simple spreadsheet as a tool for teaching fractal physiology. Adv Physiol Educ 42(3):493–499. https://doi.org/10.1152/advan.00181.2017

Ashley S, Pearson J (2012) When more equals less: overtraining inhibits perceptual learning owing to lack of wakeful consolidation. Proc Biol Sci 279(1745):4143–4147. https://doi.org/10.1098/rspb.2012.1423

Baldwin AS, Kangas JL, Denman DC, Smits JAJ, Yamada T, Otto MW (2016) Cardiorespiratory fitness moderates the effect of an affect-guided physical activity prescription: a pilot randomized controlled trial. Cogn Behav Ther 45(6):445–457. https://doi.org/10.1080/16506073.2016.1194454

Ballester-Ferrer JA, Bonete-López B, Roldan A, Cervelló E, Pastor D (2022) Effect of acute exercise intensity on cognitive inhibition and well-being: role of lactate and BDNF polymorphism in the dose-response relationship. Front Psychol. https://doi.org/10.3389/fpsyg.2022.1057475

Barha CK, Liu-Ambrose T (2018) Exercise and the aging brain: considerations for sex differences. BPL 3(3):1–11. https://doi.org/10.3233/BPL-1867

Barha CK, Liu-Ambrose T (2020) Sex differences in exercise efficacy: Is midlife a critical window for promoting healthy cognitive aging? FASEB J 34(9):11329–11336. https://doi.org/10.1096/fj.202000857R

Barha CK, Davis JC, Falck RS, Nagamatsu LS, Liu-Ambrose T (2017a) Sex differences in exercise efficacy to improve cognition: A systematic review and meta-analysis of randomized controlled trials in older humans. A systematic review and meta-analysis of randomized controlled trials in older humans. Front Neuroendocrinol 46:71–85. https://doi.org/10.1016/j.yfrne.2017.04.002

Barha CK, Galea LA, Nagamatsu LS, Erickson KI, Liu-Ambrose T (2017b) Personalising exercise recommendations for brain health Considerations and future directions. Br J Sports Med 51(8):636–639. https://doi.org/10.1136/bjsports-2016-096710

Barha CK, Hsiung G-YR, Best JR, Davis JC, Eng JJ, Jacova C, Lee PE, Munkacsy M, Cheung W, Liu-Ambrose T (2017c) Sex difference in aerobic exercise efficacy to improve cognition in older adults with vascular cognitive impairment: secondary analysis of a randomized controlled trial. J Alzheimer's Dis JAD 60(4):1397–1410. https://doi.org/10.3233/JAD-170221

Barha CK, Hsu C-L, ten Brinke L, Liu-Ambrose T (2019) Biological sex: a potential moderator of physical activity efficacy on brain health. Front Aging Neurosci 11:67. https://doi.org/10.3389/fnagi.2019.00329

Barha CK, Best JR, Rosano C, Yaffe K, Catov JM, Liu-Ambrose T (2020) Sex-specific relationship between long-term maintenance of physical activity and cognition in the health ABC study: potential role of hippocampal and dorsolateral prefrontal cortex volume. J Gerontol Ser Biol Sci Med Sci 75(4):764–770. https://doi.org/10.1093/gerona/glz093

Barha CK, Falck RS, Skou ST, Liu-Ambrose T (2021a) Personalising exercise recommendations for healthy cognition and mobility in ageing: time to consider one's pre-existing function and genotype (Part 2). Br J Sports Med 55(6):301–303. https://doi.org/10.1136/bjsports-2020-102865

Barha CK, Falck RS, Skou ST, Liu-Ambrose T (2021b) Personalising exercise recommendations for healthy cognition and mobility in aging: time to address sex and gender (Part 1). Br J Sports Med 55(6):300–301. https://doi.org/10.1136/bjsports-2020-102864

Barha CK, Starkey SY, Hsiung GYR, Tam R, Liu-Ambrose T (2023) Aerobic exercise improves executive functions in females, but not males, without the BDNF Val66Met polymorphism. Biol Sex Differ 14(1):16. https://doi.org/10.1186/s13293-023-00499-7

Bauman A, Ainsworth BE, Sallis JF, Hagströmer M, Craig CL, Bull FC, Pratt M, Venugopal K, Chau J, Sjöström M (2011) The descriptive epidemiology of sitting. A 20-country comparison using the International Physical Activity Questionnaire (IPAQ). Am J Prev Med 41(2):228–235. https://doi.org/10.1016/j.amepre.2011.05.003

Beneke R, Leithäuser RM (2017) Maximal Lactate Steady State's Dependence on Cycling Cadence. Int J Sports Physiol Perform 12(3):304–309. https://doi.org/10.1123/ijspp.2015-0573

Bezerra TA, Clark CCT, de Souza Filho AN, Fortes LDS, Mota JAPS, Duncan MJ, Martins CMDL (2021) 24-hour movement behaviour and executive function in preschoolers: a compositional and isotemporal reallocation analysis. Eur J Sport Sci 21(7):1064–1072. https://doi.org/10.1080/17461391.2020.1795274

Bherer L, Erickson KI, Liu-Ambrose T (2013) A review of the effects of physical activity and exercise on cognitive and brain functions in older adults. J Aging Res 2013:657508. https://doi.org/10.1155/2013/657508

Bland KA, Neil-Sztramko SE, Zadravec K, Medysky ME, Kong J, Winters-Stone KM, Campbell KL (2021) Attention to principles of exercise training: an updated systematic review of randomized controlled trials in cancers other than breast and prostate. BMC Cancer 21(1):1179. https://doi.org/10.1186/s12885-021-08701-y

Blodgett JM, Ahmadi M, Stamatakis E, Rockwood K, Hamer M (2023) Fractal complexity of daily physical activity and cognitive function in a midlife cohort. Sci Rep 13(1):20340. https://doi.org/10.1038/s41598-023-47200-x

Bloomberg M, Brocklebank L, Hamer M, Steptoe A (2023) Joint associations of physical activity and sleep duration with cognitive ageing: longitudinal analysis of an English cohort study. Lancet Healthy Longev 4(7):e345–e353. https://doi.org/10.1016/S2666-7568(23)00083-1

Borror A (2017) Brain-derived neurotrophic factor mediates cognitive improvements following acute exercise. Med Hypotheses 106:1–5. https://doi.org/10.1016/j.mehy.2017.06.024

Brand R, Cheval B (2019) Theories to explain exercise motivation and physical inactivity: ways of expanding our current theoretical perspective. Front Psychol 10:1147. https://doi.org/10.3389/fpsyg.2019.01147

Brand R, Ekkekakis P (2018) Affective-Reflective Theory of physical inactivity and exercise. Ger J Exerc Sport Res 48(1):48–58. https://doi.org/10.1007/s12662-017-0477-9

Brand R, Ekkekakis P (2021) Exercise behavior change revisited: Affective-reflective theory. In: Zenko Z, Jones L (eds) Essentials of exercise and sport psychology: An open access textbook. Society for Transparency, Openness, and Replication in Kinesiology, pp 62–92

Brooks GA (2018) The Science and Translation of Lactate Shuttle Theory. Cell Metab 27(4):757–785. https://doi.org/10.1016/j.cmet.2018.03.008

Brooks GA (2020a) Lactate as a fulcrum of metabolism. Redox Biol 35:101454. https://doi.org/10.1016/j.redox.2020.101454

Brooks GA (2020b) The tortuous path of lactate shuttle discovery: from cinders and boards to the lab and ICU. J Sport Health Sci 9(5):446–460. https://doi.org/10.1016/j.jshs.2020.02.006

Brooks GA, Arevalo JA, Osmond AD, Leija RG, Curl CC, Tovar AP (2021) Lactate in contemporary biology: a phoenix risen. J Physiol. https://doi.org/10.1113/JP280955

Brooks GA, Osmond AD, Arevalo JA, Curl CC, Duong JJ, Horning MA, Moreno Santillan DD, Leija RG (2022) Lactate as a major myokine and exerkine. Nat Rev Endocrinol. https://doi.org/10.1038/s41574-022-00724-0

Brooks GA, Osmond AD, Arevalo JA, Duong JJ, Curl CC, Moreno-Santillan DD, Leija RG (2023) Lactate as a myokine and exerkine: drivers and signals of physiology and metabolism. J Appl Physiol (Bethesda, Md.: 1985) 134(3):529–548. https://doi.org/10.1152/japplphysiol.00497.2022

Brown LE, Greenwood M (2005) Periodization essentials and innovations in resistance training protocols. Strength Condit J 27(4):80–85. https://doi.org/10.1519/00126548-200508000-00014

Bruggisser F, Knaier R, Roth R, Wang W, Qian J, Scheer FAJL (2023) Best time of day for strength and endurance training to improve health and performance? A systematic review with meta-analysis. Sports Med Open 9(1):34. https://doi.org/10.1186/s40798-023-00577-5

Buchheit M, Laursen PB (2013a) High-intensity interval training, solutions to the programming puzzle. Part II: anaerobic energy, neuromuscular load and practical applications. Sports Med (Auckland, N.z.) 43(10):927–954. https://doi.org/10.1007/s40279-013-0066-5

Buchheit M, Laursen PB (2013b) High-intensity interval training, solutions to the programming puzzle: part I: cardiopulmonary emphasis. Sports Med (Auckland, N.z.) 43(5):313–338. https://doi.org/10.1007/s40279-013-0029-x

Budde H, Schwarz R, Velasques B, Ribeiro P, Holzweg M, Machado S, Brazaitis M, Staack F, Wegner M (2016) The need for differentiating between exercise, physical activity, and training. Autoimmun Rev 15(1):110–111. https://doi.org/10.1016/j.autrev.2015.09.004

Bull FC, Al-Ansari SS, Biddle S, Borodulin K, Buman MP, Cardon G, Carty C, Chaput J-P, Chastin S, Chou R, Dempsey PC, Dipietro L, Ekelund U, Firth J, Friedenreich CM, Garcia L, Gichu M, Jago R, Katzmarzyk PT, Lambert E, Leitzmann M, Milton K, Ortega FB, Ranasinghe C, Stamatakis E, Tiedemann A, Troiano RP, van der Ploeg HP, Wari V, Willumsen JF (2020) World Health Organization 2020 guidelines on physical activity and sedentary behaviour. Br J Sports Med 54(24):1451–1462. https://doi.org/10.1136/bjsports-2020-102955.

Burnet K, Kelsch E, Zieff G, Moore JB, Stoner L (2018) How fitting is F.I.T.T.?: a perspective on a transition from the sole use of frequency, intensity, time, and type in exercise prescription. Physiol Behav 199(3):33–34. https://doi.org/10.1016/j.physbeh.2018.11.007

Bushman BA (2018) Developing the P (for Progression) in a FITT-VP Exercise Prescription. Acsm's Health & Fitness Journal 22(3):6–9. https://doi.org/10.1249/FIT.0000000000000378

Cabral DF, Rice J, Morris TP, Rundek T, Pascual-Leone A, Gomes-Osman J (2019) Exercise for brain health: an investigation into the underlying mechanisms guided by dose. Neurotherapeutics. https://doi.org/10.1007/s13311-019-00749-w

Callisaya ML, Jayakody O, Vaidya A, Srikanth V, Farrow M, Delbaere K (2021) A novel cognitive-motor exercise program delivered via a tablet to improve mobility in older people with cognitive impairment—StandingTall Cognition and Mobility. Exp Gerontol 152:111434. https://doi.org/10.1016/j.exger.2021.111434

Callow DD, Zipunnikov V, Spira AP, Wanigatunga SK, Pettigrew C, Albert M, Soldan A (2024) Actigraphy estimated sleep moderates the relationship between physical activity and cognition in older adults. Ment Health Phys Activ. https://doi.org/10.1016/j.mhpa.2023.100573

Calogiuri G, Weydahl A, Carandente F (2013) Methodological issues for studying the rest-activity cycle and sleep disturbances: a chronobiological approach using actigraphy data. Biol Res Nurs 15(1):5–12. https://doi.org/10.1177/1099800411416224

Caspersen CJ, Powell KE, Christenson GM (1985) Physical activity, exercise, and physical fitness Definitions and distinctions for health-related research. Public Health Reports (Washington, D.c.: 1974) 100(2):126–131

Cavanaugh JT, Kochi N, Stergiou N (2010) Nonlinear analysis of ambulatory activity patterns in community-dwelling older adults. J Gerontol Ser Biol Sci Med Sci 65(2):197–203. https://doi.org/10.1093/gerona/glp144

Cefis M, Chaney R, Wirtz J, Méloux A, Quirié A, Leger C, Prigent-Tessier A, Garnier P (2023) Molecular mechanisms underlying physical exercise-induced brain BDNF overproduction. Front Mol Neurosci 16:1275924. https://doi.org/10.3389/fnmol.2023.1275924

Chang YK, Labban JD, Gapin JI, Etnier JL (2012) The effects of acute exercise on cognitive performance: a meta-analysis. Brain Res 1453:87–101. https://doi.org/10.1016/j.brainres.2012.02.068

Cheval B, Boisgontier MP (2021) The theory of effort minimization in physical activity. Exerc Sport Sci Rev 49(3):168–178. https://doi.org/10.1249/JES.0000000000000252

Cheval B, Maltagliati S, Sieber S, Cullati S, Zou L, Ihle A, Kramer AF, Yu Q, Sander D, Boisgontier MP (2022) Better subjective sleep quality partly explains the association between self-reported physical activity and better cognitive function. J Alzheimer's Dis JAD 87(2):919–931. https://doi.org/10.3233/JAD-215484

Chueh T-Y, Chen Y-C, Hung T-M (2022) Acute effect of breaking up prolonged sitting on cognition: a systematic review. BMJ Open 12(3):e050458. https://doi.org/10.1136/bmjopen-2021-050458

Clark S, Lomax N, Morris M, Pontin F, Birkin M (2021) Clustering accelerometer activity patterns from the UK Biobank Cohort. Sensors (Basel, Switzerland). https://doi.org/10.3390/s21248220

Collado-Mateo D, Lavín-Pérez AM, Peñacoba C, Del Coso J, Leyton-Román M, Luque-Casado A, Gasque P, Fernández-Del-Olmo MÁ, Amado-Alonso D (2021) Key factors associated with adherence to physical exercise in patients with chronic diseases and older adults: an umbrella review. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph18042023

Collins AM, Molina-Hidalgo C, Aghjayan SL, Fanning J, Erlenbach ED, Gothe NP, Velazquez-Diaz D, Erickson KI (2023) Differentiating the influence of sedentary behavior and physical activity on brain health in late adulthood. Exp Gerontol. https://doi.org/10.1016/j.exger.2023.112246

Craig CL, Marshall AL, Sjöstrom M, Bauman AE, Booth ML, Ainsworth BE, Pratt M, Ekelund UL, Yngve A, Sallis JF, Oja P (2003) International Physical Activity Questionnaire. 12-Country reliability and validity. Med Sci Sports Exercise 35(8):1381–1395. https://doi.org/10.1249/01.MSS.0000078924.61453.FB

Culverhouse J, Hillsdon M, Koster A, Bosma H, de Galan BE, Savelberg HHCM, Pulsford R (2024) Cross-sectional associations between patterns and composition of upright and stepping events with physical function: insights from The Maastricht Study. Eur Rev Aging Phys Activ 21(1):10. https://doi.org/10.1186/s11556-024-00343-w

Cunanan AJ, DeWeese BH, Wagle JP, Carroll KM, Sausaman R, Hornsby WG, Haff GG, Triplett NT, Pierce KC, Stone MH (2018) Authors' Reply to Buckner et al.: 'Comment on: "The General Adaptation Syndrome: A Foundation for the Concept of Periodization." Sports Med (Auckland, N.z.) 48(7):1755–1757. https://doi.org/10.1007/s40279-018-0884-6

Danilevicz IM, van Hees VT, van der Heide FCT, Jacob L, Landré B, Benadjaoud MA, Sabia S (2024a) Measures of fragmentation of rest activity patterns: mathematical properties and interpretability based on accelerometer real life data. BMC Med Res Methodol 24(1):132. https://doi.org/10.1186/s12874-024-02255-w

Danilevicz IM, Vidil S, Landré B, Dugravot A, van Hees VT, Sabia S (2024b) Reliable measures of rest-activity rhythm fragmentation: how many days are needed? Eur Rev Aging Phys Activ 21(1):29. https://doi.org/10.1186/s11556-024-00364-5

de Assis GG, Gasanov EV, de Sousa MBC, Kozacz A, Murawska-Cialowicz E (2018) Brain derived neutrophic factor, a link of aerobic metabolism to neuroplasticity. J Physiol Pharmacol. https://doi.org/10.26402/jpp.2018.3.12

Delbaere K, Valenzuela T, Woodbury A, Davies T, Yeong J, Steffens D, Miles L, Pickett L, Zijlstra GAR, Clemson L, Close JCT, Howard K, Lord SR (2015) Evaluating the effectiveness of a home-based exercise programme delivered through a tablet computer for preventing falls in older community-dwelling people over 2 years: study protocol for the Standing Tall randomised controlled trial. BMJ Open 5(10):e009173. https://doi.org/10.1136/bmjopen-2015-009173

Denton F, Power S, Waddell A, Birkett S, Duncan M, Harwood A, McGregor G, Rowley N, Broom D (2021) Is it really home-based? A commentary on the necessity for accurate definitions across exercise and physical activity programmes. Int J Environ Res Public Health 18(17):10. https://doi.org/10.3390/ijerph18179244

Desgorces F-D, Hourcade J-C, Dubois R, Toussaint J-F, Noirez P (2020) Training load quantification of high intensity exercises: discrepancies between original and alternative methods. PLoS ONE 15(8):e0237027. https://doi.org/10.1371/journal.pone.0237027

Di Liegro CM, Schiera G, Proia P, Di Liegro I (2019) physical activity and brain health. Genes. https://doi.org/10.3390/genes10090720

Dinoff A, Herrmann N, Swardfager W, Lanctôt KL (2017) The effect of acute exercise on blood concentrations of brain-derived neurotrophic factor in healthy adults. A meta-analysis. Eur J Neurosci. https://doi.org/10.1111/ejn.13603

Dipietro L, Al-Ansari SS, Biddle SJH, Borodulin K, Bull FC, Buman MP, Cardon G, Carty C, Chaput J-P, Chastin S, Chou R, Dempsey PC, Ekelund U, Firth J, Friedenreich CM, Garcia L, Gichu M, Jago R, Katzmarzyk PT, Lambert E, Leitzmann M, Milton K, Ortega FB, Ranasinghe C, Stamatakis E, Tiedemann A, Troiano RP, van der Ploeg HP, Willumsen JF (2020) Advancing the global physical activity agenda: recommendations for future research by the 2020 WHO physical activity and sedentary behavior guidelines development group. Int J Behav Nutr Phys Activ 17(1):143. https://doi.org/10.1186/s12966-020-01042-2

Donahue PT, Schrack JA, Thrul J, Carlson MC (2025) Activity variability: A novel physical activity metric and its association with cognitive impairment. Alzheimer's Dement (New York, NY) 11(2):e70079. https://doi.org/10.1002/trc2.70079

Dora K, Suga T, Tomoo K, Sugimoto T, Mok E, Tsukamoto H, Takada S, Hashimoto T, Isaka T (2021) Similar improvements in cognitive inhibitory control following low-intensity resistance exercise with slow movement and tonic force generation and high-intensity resistance exercise in healthy young adults: a preliminary study. J Physiol Sci. https://doi.org/10.1186/s12576-021-00806-0

Dumuid D, Pedišić Ž, Stanford TE, Martín-Fernández J-A, Hron K, Maher CA, Lewis LK, Olds T (2019) The compositional isotemporal substitution model: a method for estimating changes in a health outcome for reallocation of time between sleep, physical activity and sedentary behaviour. Stat Methods Med Res 28(3):846–857. https://doi.org/10.1177/0962280217737805

Dumuid D, Pedišić Ž, Palarea-Albaladejo J, Martín-Fernández JA, Hron K, Olds T (2020) Compositional data analysis in time-use epidemiology: what, why, how. Int J Environ Res Public Health 17(7):10. https://doi.org/10.3390/ijerph17072220

Dunstan DW, Howard B, Healy GN, Owen N (2012) Too much sitting–a health hazard. Diabetes Res Clin Pract 97(3):368–376. https://doi.org/10.1016/j.diabres.2012.05.020

Dunstan DW, Dogra S, Carter SE, Owen N (2021) Sit less and move more for cardiovascular health: emerging insights and opportunities. Nat Rev Cardiol. https://doi.org/10.1038/s41569-021-00547-y

Ebner-Priemer UW, Koudela S, Mutz G, Kanning M (2013) Interactive multimodal ambulatory monitoring to investigate the association between physical activity and affect. Front Psychol 3:596. https://doi.org/10.3389/fpsyg.2012.00596

Ekkekakis P, Brand R (2019) Affective responses to and automatic affective valuations of physical activity: fifty years of progress on the seminal question in exercise psychology. Psychol Sport Exerc 42:130–137. https://doi.org/10.1016/j.psychsport.2018.12.018

Erickson KI, Prakash RS, Voss MW, Chaddock L, Heo S, McLaren M, Pence BD, Martin SA, Vieira VJ, Woods JA, McAuley E, Kramer AF (2010) Brain-derived neurotrophic factor is associated with age-related decline in hippocampal volume. J Neurosci 30(15):5368–5375. https://doi.org/10.1523/JNEUROSCI.6251-09.2010

Erickson KI, Voss MW, Prakash RS, Basak C, Szabo A, Chaddock L, Kim JS, Heo S, Alves H, White SM, Wojcicki TR, Mailey E, Vieira VJ, Martin SA, Pence BD, Woods JA, McAuley E, Kramer AF (2011) Exercise training increases size of hippocampus and improves memory. Proc Natl Acad Sci USA 108(7):3017–3022. https://doi.org/10.1073/pnas.1015950108

Erickson KI, Donofry SD, Sewell KR, Brown BM, Stillman CM (2022) Cognitive aging and the promise of physical activity. Annu Rev Clin Psychol 18:417–442. https://doi.org/10.1146/annurev-clinpsy-072720-014213

Erlenbach E, McAuley E, Gothe NP (2021) The association between light physical activity and cognition among adults: a scoping review. J Gerontol Ser Biol Sci Med Sci 76(4):716–724. https://doi.org/10.1093/gerona/glab013

Espinosa N, Hoyos CM, McKinnon AC, Almgren H, Duffy SL, Naismith SL (2025) Rest-activity rhythm fragmentation and synchronization are linked with reduced cortical thickness in older adults "at risk" for dementia. Sleep. https://doi.org/10.1093/sleep/zsaf017

Falck RS, Davis JC, Best JR, Crockett RA, Liu-Ambrose T (2019) Impact of exercise training on physical and cognitive function among older adults: a systematic review and meta-analysis. Neurobiol Aging 79:119–130. https://doi.org/10.1016/j.neurobiolaging.2019.03.007

Falck RS, Davis JC, Khan KM, Handy TC, Liu-Ambrose T (2021) A wrinkle in measuring time use for cognitive health: how should we measure physical activity, sedentary behaviour and sleep? Am J Lifestyle Med. https://doi.org/10.1177/15598276211031495

Farrahi V, Clare P (2024) Artificial intelligence and machine learning-powerful yet underutilized tools and algorithms in physical activity and sedentary behavior research. J Phys Activ Health 11:1–3. https://doi.org/10.1123/jpah.2024-0021

Farrahi V, Rostami M (2024) Machine learning in physical activity, sedentary, and sleep behavior research. JASSB. https://doi.org/10.1186/s44167-024-00045-9

Farrahi V, Niemelä M, Kangas M, Korpelainen R, Jämsä T (2019) Calibration and validation of accelerometer-based activity monitors: a systematic review of machine-learning approaches. Gait Posture 68:285–299. https://doi.org/10.1016/j.gaitpost.2018.12.003

Ferris LT, Williams JS, Shen C-L (2007) The effect of acute exercise on serum brain-derived neurotrophic factor levels and cognitive function. Med Sci Sports Exerc 39(4):728–734. https://doi.org/10.1249/mss.0b013e31802f04c7

Festa RR, Jofré-Saldía E, Candia AA, Monsalves-Álvarez M, Flores-Opazo M, Peñailillo L, Marzuca-Nassr GN, Aguilar-Farias N, Fritz-Silva N, Cancino-Lopez J, Soto-Sánchez J, Sepulveda C, Huerta Ojeda Á, Núñez-Espinosa C, Valladares-Ide D, Jannas-Vela S (2023) Next steps to advance general physical activity recommendations towards physical exercise prescription: a narrative review. BMJ Open Sport Exerc Med 9(4):e001749. https://doi.org/10.1136/bmjsem-2023-001749

Fissler P, Küster O, Schlee W, Kolassa I-T (2013) Novelty interventions to enhance broad cognitive abilities and prevent dementia. Synergistic approaches for the facilitation of positive plastic change. Prog Brain Res 207:403–434. https://doi.org/10.1016/B978-0-444-63327-9.00017-5

Fuller D, Ferber R, Stanley K (2022) Why machine learning (ML) has failed physical activity research and how we can improve. BMJ Open Sport Exerc Med 8(1):e001259. https://doi.org/10.1136/bmjsem-2021-001259

Gallardo-Gómez D, Del Pozo-Cruz J, Noetel M, Álvarez-Barbosa F, Alfonso-Rosa RM, Del Pozo CB (2022) Optimal dose and type of exercise to improve cognitive function in older adults: a systematic review and Bayesian model-based network meta-analysis of RCTs. Ageing Res Rev. https://doi.org/10.1016/j.arr.2022.101591

Gao C, Haghayegh S, Wagner M, Cai R, Hu K, Gao L, Li P (2023) Approaches for assessing circadian rest-activity patterns using actigraphy in cohort and population-based studies. Curr Sleep Medicine Rep 9(4):247–256. https://doi.org/10.1007/s40675-023-00267-4

Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee I-M, Nieman DC, Swain DP (2011) American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. Med Sci Sports Exerc 43(7):1334–1359. https://doi.org/10.1249/MSS.0b013e318213fefb

Garrett J, Chak C, Bullock T, Giesbrecht B (2024) A systematic review and Bayesian meta-analysis provide evidence for an effect of acute physical activity on cognition in young adults. Commun Psychol. https://doi.org/10.1038/s44271-024-00124-2

Ghosal R, Matabuena M (2024) Multivariate scalar on multidimensional distribution regression with application to modeling the association between physical activity and cognitive functions. Biometr J Biometrische Zeitschrift 66(7):e202400042. https://doi.org/10.1002/bimj.202400042

Ghosal R, Varma VR, Volfson D, Urbanek J, Hausdorff JM, Watts A, Zipunnikov V (2022) Scalar on time-by-distribution regression and its application for modelling associations between daily-living physical activity and cognitive functions in Alzheimer's Disease. Sci Rep 12(1):11558. https://doi.org/10.1038/s41598-022-15528-5

Gill J, Chico TJ, Doherty A, Dunn J, Ekelund U, Katzmarzyk PT, Milton K, Murphy MH, Stamatakis E (2023) Potential impact of wearables on physical activity guidelines and interventions: opportunities and challenges. Br J Sports Med. https://doi.org/10.1136/bjsports-2023-106822

Giurgiu M, Koch ED, Ottenbacher J, Plotnikoff RC, Ebner-Priemer UW, Reichert M (2019) Sedentary behavior in everyday life relates negatively to mood: An ambulatory assessment study. Scand J Med Sci Sports 29(9):1340–1351. https://doi.org/10.1111/sms.13448

Giurgiu M, Koch ED, Plotnikoff RC, Ebner-Priemer UW, Reichert M (2020a) Breaking up sedentary behavior optimally to enhance mood. Med Sci Sports Exerc 52(2):457–465. https://doi.org/10.1249/MSS.0000000000002132

Giurgiu M, Niermann C, Ebner-Priemer U, Kanning M (2020b) Accuracy of sedentary behavior-triggered ecological momentary assessment for collecting contextual information: development and feasibility study. JMIR Mhealth Uhealth 8(9):e17852. https://doi.org/10.2196/17852

Giurgiu M, Plotnikoff RC, Nigg CR, Koch ED, Ebner-Priemer UW, Reichert M (2020c) Momentary mood predicts upcoming real-life sedentary behavior. Scand J Med Sci Sports 30(7):1276–1286. https://doi.org/10.1111/sms.13652

Goldberger AL, Amaral LAN, Hausdorff JM, Ivanov PC, Peng C-K, Stanley HE (2002) Fractal dynamics in physiology: alterations with disease and aging. Proc Natl Acad Sci USA 99 Suppl 1(Suppl 1):2466–2472. https://doi.org/10.1073/pnas.012579499

Gronwald T, Ludyga S, Hoos O, Hottenrott K (2018a) Non-linear dynamics of cardiac autonomic activity during cycling exercise with varied cadence. Hum Mov Sci 60:225–233. https://doi.org/10.1016/j.humov.2018.06.013

Gronwald T, Velasques B, Ribeiro P, Machado S, Murillo-Rodríguez E, Ludyga S, Yamamoto T, Budde H (2018b) Increasing exercise's effect on mental health: Exercise intensity does matter. Proc Natl Acad Sci USA 115(51):E11890–E11891. https://doi.org/10.1073/pnas.1818161115

Gronwald T, Rogers B, Hoos O (2020a) Fractal correlation properties of heart rate variability: a new biomarker for intensity distribution in endurance exercise and training prescription? Front Physiol. https://doi.org/10.3389/fphys.2020.550572

Gronwald T, Törpel A, Herold F, Budde H (2020b) Perspective of dose and response for individualized physical exercise and training prescription. JFMK 5(3):48. https://doi.org/10.3390/jfmk5030048

Gronwald T, Bem Alves AC de, Murillo-Rodríguez E, Latini A, Schuette J, Budde H (2019) Standardization of exercise intensity and consideration of a dose-response is essential Commentary on "Exercise-linked FNDC5/irisin rescues synaptic plasticity and memory defects in Alzheimer's models", by Lourenco et al., published 2019 in Nature Medicine. J Sport Health Sci 8(4):353–354. https://doi.org/10.1016/j.jshs.2019.03.006

Gronwald T, Rogers B, Hottenrott L, Hoos O, Hottenrott K (2021) Correlation properties of heart rate variability during a marathon race in recreational runners: potential biomarker of complex regulation during endurance exercise. jsportscimed:557–563. https://doi.org/10.52082/jssm.2021.557

Gschwind YJ, Eichberg S, Ejupi A, de Rosario H, Kroll M, Marston HR, Drobics M, Annegarn J, Wieching R, Lord SR, Aal K, Vaziri D, Woodbury A, Fink D, Delbaere K (2015a) ICT-based system to predict and prevent falls (iStoppFalls): results from an international multicenter randomized controlled trial. Eur Rev Aging Phys Activ 12:10. https://doi.org/10.1186/s11556-015-0155-6

Gschwind YJ, Schoene D, Lord SR, Ejupi A, Valenzuela T, Aal K, Woodbury A, Delbaere K (2015b) The effect of sensor-based exercise at home on functional performance associated with fall risk in older people—a comparison of two exergame interventions. Eur Rev Aging Phys Activ 12:11. https://doi.org/10.1186/s11556-015-0156-5

Guardia T, Cote KA, Healey MK, Gammage KL, Campbell KL (2024) Self-reported physical activity and sleep quality is associated with working memory function in middle-aged and older adults during the COVID-19 pandemic. Neuropsychol Dev Cognit Sect B Aging Neuropsychol Cognit 11:1–20. https://doi.org/10.1080/13825585.2024.2333066

Gustavsson A, Norton N, Fast T, Frölich L, Georges J, Holzapfel D, Kirabali T, Krolak-Salmon P, Rossini PM, Ferretti MT, Lanman L, Chadha AS, van der Flier WM (2023) Global estimates on the number of persons across the Alzheimer's disease continuum. Alzheimer's Dement 19(2):658–670. https://doi.org/10.1002/alz.12694

Haghayegh S, Gao C, Sugg E, Zheng X, Yang H-W, Saxena R, Rutter MK, Weedon M, Ibanez A, Bennett DA, Li P, Gao L, Hu K (2024) Association of rest-activity rhythm and risk of developing dementia or mild cognitive impairment in the middle-aged and older population: prospective cohort study. JMIR Public Health Surveill 10:e55211. https://doi.org/10.2196/55211

Hallgren M, Dunstan DW, Owen N (2020) Passive versus mentally active sedentary behaviors and depression. Exerc Sport Sci Rev 48(1):20–27. https://doi.org/10.1249/JES.0000000000000211

Halloway S, Dhana K, Desai P, Agarwal P, Holland T, Aggarwal NT, Evers J, Sacks FM, Carey VJ, Barnes LL (2021) Free-living standing activity as assessed by seismic accelerometers and cognitive function in community-dwelling older adults: the MIND trial. J Gerontol Ser Biol Sci Med Sci 76(11):1981–1987. https://doi.org/10.1093/gerona/glab106

Hamer M, O'Donovan G, Lee I-M, Stamatakis E (2017) The "weekend warrior" physical activity pattern: how little is enough? Br J Sports Med 51(19):1384–1385. https://doi.org/10.1136/bjsports-2017-097538

Hansford HJ, Wewege MA, Cashin AG, Hagstrom AD, Clifford BK, McAuley JH, Jones MD (2022) If exercise is medicine, why don't we know the dose? An overview of systematic reviews assessing reporting quality of exercise interventions in health and disease. Br J Sports Med 56(12):692–700. https://doi.org/10.1136/bjsports-2021-104977

Hardeman W, Houghton J, Lane K, Jones A, Naughton F (2019) A systematic review of just-in-time adaptive interventions (JITAIs) to promote physical activity. Int J Behav Nutr Phys Activ 16(1):31. https://doi.org/10.1186/s12966-019-0792-7

Hardstone R, Poil S-S, Schiavone G, Jansen R, Nikulin VV, Mansvelder HD, Linkenkaer-Hansen K (2012) Detrended fluctuation analysis: a scale-free view on neuronal oscillations. Front Physiol 3:450. https://doi.org/10.3389/fphys.2012.00450

Hashimoto T, Tsukamoto H, Takenaka S, Olesen ND, Petersen LG, Sørensen H, Nielsen HB, Secher NH, Ogoh S (2018) Maintained exercise-enhanced brain executive function related to cerebral lactate metabolism in men. FASEB J 32(3):1417–1427. https://doi.org/10.1096/fj.201700381RR

Hashimoto T, Tsukamoto H, Ando S, Ogoh S (2021) Effect of exercise on brain health: the potential role of lactate as a myokine. Metabolites 11(12):813. https://doi.org/10.3390/metabo11120813

Hecksteden A, Faude O, Meyer T, Donath L (2018) How to construct, conduct and analyze an exercise training study? Front Physiol 9:239. https://doi.org/10.3389/fphys.2018.01007

Heisz JJ, Waddington EE (2024) The principles of exercise prescription for brain health in aging. Exerc Sport Mov 2(1):1–5. https://doi.org/10.1249/ESM.0000000000000019

Hernández-Lougedo J, Cimadevilla-Pola E, Fernández-Rodríguez T, Guodemar-Pérez J, Otero-Campos Á, Del Carmen L-E, Cañuelo-Márquez AM, de Jesús-Franco F, Garnacho-Castaño MV, García-Fernández P, Maté-Muñoz JL (2021) Effects of introducing rest intervals in functional fitness training. Appl Sci 11(20):9731. https://doi.org/10.3390/app11209731

Herold F, Hamacher D, Schega L, Müller NG (2018a) Thinking while moving or moving while thinking—concepts of motor-cognitive training for cognitive performance enhancement. Front Ag Neurosci 10:228. https://doi.org/10.3389/fnagi.2018.00228

Herold F, Wiegel P, Scholkmann F, Müller NG (2018b) Applications of Functional Near-Infrared Spectroscopy (fNIRS) neuroimaging in exercise‾cognition science: a systematic methodology-focus. Rev J Clin Med 7(12):1–43. https://doi.org/10.3390/jcm7120466

Herold F, Müller P, Gronwald T, Müller NG (2019a) Dose-response matters!—a perspective on the exercise prescription in exercise-cognition research. Front Psychology 10:2338. https://doi.org/10.3389/fpsyg.2019.02338

Herold F, Törpel A, Schega L, Müller NG (2019b) Functional and/or structural brain changes in response to resistance exercises and resistance training lead to cognitive improvements - a systematic review. Eur Rev Aging Phys Activ 16(1):10. https://doi.org/10.1186/s11556-019-0217-2

Herold F, Aye N, Lehmann N, Taubert M, Müller NG (2020a) The contribution of functional magnetic resonance imaging to the understanding of the effects of acute physical exercise on cognition. Brain Sci 10(3):175. https://doi.org/10.3390/brainsci10030175

Herold F, Gronwald T, Scholkmann F, Zohdi H, Wyser D, Müller NG, Hamacher D (2020b) New Directions in exercise prescription: is there a role for brain-derived parameters obtained by functional near-infrared spectroscopy? Brain Sci. https://doi.org/10.3390/brainsci10060342

Herold F, Törpel A, Hamacher D, Budde H, Gronwald T (2020c) A discussion on different approaches for prescribing physical interventions—four roads lead to rome, but which one should we choose? JPM 10(3):55. https://doi.org/10.3390/jpm10030055

Herold F, Törpel A, Hamacher D, Budde H, Zou L, Strobach T, Müller NG, Gronwald T (2021) Causes and consequences of interindividual response variability: a call to apply a more rigorous research design in acute exercise-cognition studies. Front Physiol 12:682891. https://doi.org/10.3389/fphys.2021.682891

Herold F, Behrendt T, Meißner C, Müller NG, Schega L (2022a) The influence of acute sprint interval training on cognitive performance of healthy younger adults. Int J Environ Res Public Health 19(1):613. https://doi.org/10.3390/ijerph19010613

Herold F, Theobald P, Gronwald T, Rapp MA, Müller NG (2022b) Going digital – a commentary on the terminology used at the intersection of physical activity and digital health. Eur Rev Aging Phys Act 19(1):10. https://doi.org/10.1186/s11556-022-00296-y

Herold F, Theobald P, Gronwald T, Kaushal N, Zou L, de Bruin ED, Bherer L, Müller NG (2024a) Alexa, let's train now!—a systematic review and classification approach to digital and home-based physical training interventions aiming to support healthy cognitive aging. J Sport Health Sci 13(1):30–46. https://doi.org/10.1016/j.jshs.2023.01.004

Herold F, Theobald P, Gronwald T, Kaushal N, Zou L, de Bruin ED, Bherer L, Müller NG (2024b) The best of two worlds to promote healthy cognitive aging: definition and classification approach of hybrid physical training interventions. JMIR Aging 7:e56433. https://doi.org/10.2196/56433

Herold F, Owen N, Brakenridge CJ, Kujach S, Gronwald T (2025) Differentiating physical activity frequency and density—commentary on: "Optimal Frequency of Interrupting Prolonged Sitting for Cardiometabolic Health: A Systematic Review and Meta-Analysis of Randomized Crossover Trials". Scand J Med Sci Sports (**in press**)

Hoang P, Schoene D, Gandevia S, Smith S, Lord SR (2016) Effects of a home-based step training programme on balance, stepping, cognition and functional performance in people with multiple sclerosis–a randomized controlled trial. Multiple Scler (Houndmills, Basingstoke, England) 22(1):94–103. https://doi.org/10.1177/1352458515579442

Hofmann P, Tschakert G (2017) Intensity- and duration-based options to regulate endurance training. Front Physiol 8:337. https://doi.org/10.3389/fphys.2017.00337

Holtermann A, Hansen JV, Burr H, Søgaard K, Sjøgaard G (2012) The health paradox of occupational and leisure-time physical activity. Br J Sports Med 46(4):291–295. https://doi.org/10.1136/bjsm.2010.079582

Holtermann A, Krause N, van der Beek AJ, Straker L (2018) The physical activity paradox: six reasons why occupational physical activity (OPA) does not confer the cardiovascular health benefits that leisure time physical activity does. Br J Sports Med 52(3):149–150. https://doi.org/10.1136/bjsports-2017-097965

Holtermann A, Rasmussen CL, Hallman DM, Ding D, Dumuid D, Gupta N (2021a) 24-hour physical behavior balance for better health for all: "The Sweet-Spot Hypothesis." Sports Medicine - Open 7(1):98. https://doi.org/10.1186/s40798-021-00394-8

Holtermann A, Schnohr P, Nordestgaard BG, Marott JL (2021b) The physical activity paradox in cardiovascular disease and all-cause mortality: the contemporary Copenhagen General Population Study with 104 046 adults. Eur Heart J 42(15):1499–1511. https://doi.org/10.1093/eurheartj/ehab087

Hooghiemstra AM, Eggermont LHP, Scheltens P, van der Flier WM, Scherder EJA (2015) The rest-activity rhythm and physical activity in early-onset dementia. Alzheimer Dis Assoc Disord 29(1):45–49. https://doi.org/10.1097/WAD.0000000000000037

Hottenrott K, Hoos O, Stoll O, Blazek I (2022) Sportmotorische Fähigkeiten und sportliche Leistungen – Trainingswissenschaft. In: Güllich A, Krüger M (eds) Sport. Springer Berlin Heidelberg, Berlin, pp 563–634

Hou M, Herold F, Zhang Z, Ando S, Cheval B, Ludyga S, Erickson KI, Hillman CH, Yu Q, Liu-Ambrose T, Kuang J, Kramer AF, Chen Y, Costello JT, Chen C, Dupuy O, Pindus DM, McMorris T, Stiernman L, Zou L (2024) Human dopaminergic system in the exercise-cognition link. Trends Mol Med 30(8):708–712. https://doi.org/10.1016/j.molmed.2024.04.011

Howley ET (2001) Type of activity. Resistance, aerobic and leisure versus occupational physical activity. Medi Sci Sports Exerc 33(6):S364–S369 (**discussion S419-20**)

Hu K, Riemersma-van der Lek RF, Patxot M, Li P, Shea SA, Scheer FAJL, van Someren EJW (2016) Progression of dementia assessed by temporal correlations of physical activity: results from a 3.5-year, longitudinal randomized controlled trial. Sci Rep 6:27742. https://doi.org/10.1038/srep27742

Hung T-M, Tsai C-L, Chen F-T, Wang C-C, Chang Y-K (2013) The immediate and sustained effects of acute exercise on planning aspect of executive function. Psychol Sport Exerc 14(5):728–736. https://doi.org/10.1016/j.psychsport.2013.05.004

Hwang J, Brothers RM, Castelli DM, Glowacki EM, Chen YT, Salinas MM, Kim J, Jung Y, Calvert H (2016) Acute high-intensity exercise-induced cognitive enhancement and brain-derived neurotrophic factor in young, healthy adults. Neurosci Lett 630:247–253. https://doi.org/10.1016/j.neulet.2016.07.033

Hyodo K, Kitano N, Ueno A, Yamaguchi D, Watanabe Y, Noda T, Nishida S, Kai Y, Arao T (2022) Association between intensity or accumulating pattern of physical activity and executive function in community-dwelling older adults: a cross-sectional study with compositional data analysis. Front Hum Neurosci 16:1018087. https://doi.org/10.3389/fnhum.2022.1018087

Ide K, Secher NH (2000) Cerebral blood flow and metabolism during exercise. Prog Neurobiol 61(4):397–414. https://doi.org/10.1016/S0301-0082(99)00057-X

Impellizzeri FM, Shrier I, McLaren SJ, Coutts AJ, McCall A, Slattery K, Jeffries AC, Kalkhoven JT (2023) Understanding training load as exposure and dose. Sports Mei (Auckland, N.z.) 53(9):1667–1679. https://doi.org/10.1007/s40279-023-01833-0

Ingham-Hill E, Hewitt A, Lester A, Bond B (2024) Morning compared to afternoon school-based exercise on cognitive function in adolescents. Brain Cogn 175:106135. https://doi.org/10.1016/j.bandc.2024.106135

Islam H, Gibala MJ, Little JP (2022) Exercise snacks: a novel strategy to improve cardiometabolic health. Exerc Sport Sci Rev 50(1):31–37. https://doi.org/10.1249/JES.0000000000000275

Janssen I, Campbell JE, Zahran S, Saunders TJ, Tomasone JR, Chaput J-P (2022) Timing of physical activity within the 24-hour day and its influence on health: a systematic review (Timing of physical activity within the 24-hour day and its influence on health: a systematic review). Health Promot Chronic Dis Prev Can Res Policy Pract 42(4):129–138. https://doi.org/10.24095/hpcdp.42.4.02

Johnston W, Judice PB, Molina García P, Mühlen JM, Lykke Skovgaard E, Stang J, Schumann M, Cheng S, Bloch W, Brønd JC, Ekelund U, Grøntved A, Caulfield B, Ortega FB, Sardinha LB (2020) Recommendations for determining the validity of consumer wearable and smartphone step count: expert statement and checklist of the INTERLIVE network. Br J Sports Med. https://doi.org/10.1136/bjsports-2020-103147

Kao S-C, Chen F-T, Moreau D, Drollette ES, Amireault S, Chu C-H, Chang Y-K (2022) Acute effects of exercise engagement on neurocognitive function: a systematic review and meta-analysis on P3 amplitude and latency. Int Rev Sport Exerc Psychol. https://doi.org/10.1080/1750984X.2022.2155488

Kasper K (2019) Sports training principles. Curr Sports Med Rep 18(4):95–96. https://doi.org/10.1249/JSR.0000000000000576

Kastelic K, Sarabon N (2023) Validity and reliability of the Daily Activity Behaviours Questionnaire (DABQ) for the assessment of 24-h movement behaviours among adolescents. Kinesiology 55(2):289–297. https://doi.org/10.26582/k.55.2.12

Kastelic K, Pedišić Ž, Lipovac D, Kastelic N, Chen S-T, Šarabon N (2021) Associations of meeting 24-h movement guidelines with stress and self-rated health among adults: is meeting more guidelines associated with greater benefits? BMC Public Health 21(1):929. https://doi.org/10.1186/s12889-021-10979-3

Kastelic K, Šarabon N, Burnard MD, Pedišić Ž (2022) Validity and Reliability of the Daily Activity Behaviours Questionnaire (DABQ) for assessment of time spent in sleep, sedentary behaviour, and physical activity. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph19095362

Kastelic K, Löfler S, Matko Š, Šarabon N (2023) Validity of the German version of daily activity behaviours questionnaire among older adults. J Aging Phys Act. https://doi.org/10.1123/japa.2022-0417

Kataoka R, Vasenina E, Loenneke J, Buckner SL (2021) Periodization: variation in the definition and discrepancies in study design. Sports Med. https://doi.org/10.1007/s40279-020-01414-5

Katzmarzyk PT, Powell KE, Jakicic JM, Troiano RP, Piercy K, Tennant B (2019) Sedentary behavior and health: update from the 2018 physical activity guidelines advisory committee. Med Sci Sports Exerc 51(6):1227–1241. https://doi.org/10.1249/MSS.0000000000001935

Kaufmann S, Gronwald T, Herold F, Hoos O (2023) Heart rate variability-derived thresholds for exercise intensity prescription in endurance sports: a systematic review of interrelations and agreement with different ventilatory and blood lactate thresholds. Sports Med Open 9(1):59. https://doi.org/10.1186/s40798-023-00607-2

Keihani A, Mayeli A, Ferrarelli F (2023) Circadian rhythm changes in healthy aging and mild cognitive impairment. Adv Biol 7(11):e2200237. https://doi.org/10.1002/adbi.202200237

Kennedy CM, Burma JS, Newel KT, Brassard P, Smirl JD (2022) Time-course recovery of cerebral blood velocity metrics post aerobic exercise: a systematic review. J Appl Physiol (Bethesda, Md.: 1985) 133(2):471–489. https://doi.org/10.1152/japplphysiol.00630.2021

Knaepen K, Goekint M, Heyman EM, Meeusen R (2010) Neuroplasticity - exercise-induced response of peripheral brain-derived neurotrophic factor: a systematic review of experimental studies in human subjects. Sports Med (Auckland, N.z.) 40(9):765–801. https://doi.org/10.2165/11534530-000000000-00000

Ladwig MA, Hartman ME, Ekkekakis P (2017) Affect-based exercise prescription. An idea whose time has come? Acsm's Health Fitness J 21(5):10–15. https://doi.org/10.1249/FIT.0000000000000332

Lau PWC, Song H, Song Di, Wang J-J, Zhen S, Shi L, Yu R (2023) 24-Hour movement behaviors and executive functions in preschoolers: A compositional and isotemporal reallocation analysis. Child Dev. https://doi.org/10.1111/cdev.14013

Leckie RL, Oberlin LE, Voss MW, Prakash RS, Szabo-Reed A, Chaddock-Heyman L, Phillips SM, Gothe NP, Mailey E, Vieira-Potter VJ, Martin SA, Pence BD, Lin M, Parasuraman R, Greenwood PM, Fryxell KJ, Woods JA, McAuley E, Kramer AF, Erickson KI (2014) BDNF mediates improvements in executive function following a 1-year exercise intervention. Front Hum Neurosci 8:985. https://doi.org/10.3389/fnhum.2014.00985

Lee I-M, Sesso HD, Oguma Y, Paffenbarger RS (2004) The "weekend warrior" and risk of mortality. Am J Epidemiol 160(7):636–641. https://doi.org/10.1093/aje/kwh274

Lee PH, Macfarlane DJ, Lam TH, Stewart SM (2011) Validity of the International Physical Activity Questionnaire Short Form (IPAQ-SF): a systematic review. Int J Behav Nutr Phys Activ 8:115. https://doi.org/10.1186/1479-5868-8-115

Li L, Yu Q, Zhao W, Herold F, Cheval B, Kong Z, Li J, Mueller N, Kramer AF, Cui J, Pan H, Zhan Z, Hui M, Zou L (2021) Physical activity and inhibitory control: the mediating role of sleep quality and sleep efficiency. Brain Sci 11(5):664. https://doi.org/10.3390/brainsci11050664

Li J, Herold F, Ludyga S, Yu Q, Zhang X, Zou L (2022) The acute effects of physical exercise breaks on cognitive function during prolonged sitting: The first quantitative evidence. Complement Ther Clin Pract 48:101594. https://doi.org/10.1016/j.ctcp.2022.101594

Li R-H, Karageorghis CI, Chen Y-C, Chen Y-C, Liao Y-H, Hung T-M, Chang Y-K (2023) Effect of acute concurrent exercise training and the mediating role of lactate on executive function: An ERP study. Psychol Sport Exerc 70:102531. https://doi.org/10.1016/j.psychsport.2023.102531

Li G, Wang Z, Hao Y, Qian J, Hu B, Wang Y, Luo X, Ning Y, Lin F (2024) Consensus statement of Chinese experts on exercise prescription (2023). Sports Med Health Sci. https://doi.org/10.1016/j.smhs.2024.02.003

Liguori G, Feito Y, Fountaine CJ, Roy B (eds) (2022) ACSM's guidelines for exercise testing and prescription, Eleventh. Wolters Kluwer, Philadelphia

Lim ASP, Yu L, Costa MD, Buchman AS, Bennett DA, Leurgans SE, Saper CB (2011) Quantification of the fragmentation of rest-activity patterns in elderly individuals using a state transition analysis. Sleep 34(11):1569–1581. https://doi.org/10.5665/sleep.1400

Liu-Ambrose T, Falck RS (2019) Sleep, physical activity, and cognitive health in older adults. In: Handbook of Sleep Research, vol 30. Elsevier, pp 665–676

Livingston G, Huntley J, Liu KY, Costafreda SG, Selbæk G, Alladi S, Ames D, Banerjee S, Burns A, Brayne C, Fox NC, Ferri CP, Gitlin LN, Howard R, Kales HC, Kivimäki M, Larson EB, Nakasujja N, Rockwood K, Samus Q, Shirai K, Singh-Manoux A, Schneider LS, Walsh S, Yao Y, Sommerlad A, Mukadam N (2024) Dementia prevention, intervention, and care: 2024 report of the Lancet standing Commission. The Lancet. https://doi.org/10.1016/S0140-6736(24)01296-0

Lu Z, Qu X, Chang J, Xu M, Song G, Wang X, Okely AD, Zhang T, Guan H, Wu J (2023) Reallocation of time between preschoolers' 24-h movement behaviours and executive functions: A compositional data analysis. J Sports Sci 41(12):1187–1195. https://doi.org/10.1080/02640414.2023.2260632

Ludyga S, Pühse U, Lucchi S, Marti J, Gerber M (2019) Immediate and sustained effects of intermittent exercise on inhibitory control and task-related heart rate variability in adolescents. J Sci Med Sport/sports Med Austr 22(1):96–100. https://doi.org/10.1016/j.jsams.2018.05.027

Ludyga S, Gerber M, Pühse U, Looser VN, Kamijo K (2020) Systematic review and meta-analysis investigating moderators of long-term effects of exercise on cognition in healthy individuals. Nat Hum Behav 4(6):603–612. https://doi.org/10.1038/s41562-020-0851-8

Luik AI, Zuurbier LA, Hofman A, van Someren EJW, Ikram MA, Tiemeier H (2015) Associations of the 24-h activity rhythm and sleep with cognition: a population-based study of middle-aged and elderly persons. Sleep Med 16(7):850–855. https://doi.org/10.1016/j.sleep.2015.03.012

Maeneja R, Ferreira IS, Silva CR, Abreu AM (2022) cognitive benefits of exercise: is there a time-of-day effect? Healthcare (Basel, Switzerland). https://doi.org/10.3390/healthcare10091766

Mallawaarachchi S, Burley J, Mavilidi M, Howard SJ, Straker L, Kervin L, Staton S, Hayes N, Machell A, Torjinski M, Brady B, Thomas G, Horwood S, White SLJ, Zabatiero J, Rivera C, Cliff D (2024) Early childhood screen use contexts and cognitive and psychosocial outcomes: a systematic review and meta-analysis. JAMA Pediatr. https://doi.org/10.1001/jamapediatrics.2024.2620

Manci E, Theobald P, Toth A, Campbell M, DiFrancisco-Donoghue J, Gebel A, Müller NG, Gronwald T, Herold F (2024) It's about timing: how density can benefit future research on the optimal dosage of acute physical exercise breaks in esports. BMJ Open Sport Exerc Med 10(4):e002243. https://doi.org/10.1136/bmjsem-2024-002243

Manser P, de Bruin ED (2024) "Brain-IT": Exergame training with biofeedback breathing in neurocognitive disorders. Alzheimer's Dement. https://doi.org/10.1002/alz.13913

Manser P, Poikonen H, de Bruin ED (2023) Feasibility, usability, and acceptance of "Brain-IT"—A newly developed exergame-based training concept for the secondary prevention of mild neurocognitive disorder: a pilot randomized controlled trial. Front Aging Neurosci. https://doi.org/10.3389/fnagi.2023.1163388

Manser P, Herold F, de Bruin ED (2024) Components of effective exergame-based training to improve cognitive functioning in middle-aged to older adults - a systematic review and meta-analysis. Ageing Res Rev. https://doi.org/10.1016/j.arr.2024.102385

Marino FR, Deal JA, Dougherty RJ, Bilgel M, Tian Q, An Y, Simonsick EM, Resnick SM, Ferrucci L, Spira AP, Wanigatunga AA, Schrack JA (2024) Differences in daily physical activity by alzheimer's risk markers among older adults. J Gerontol Ser Biol Sci Med Sci. https://doi.org/10.1093/gerona/glae119

Marino FR, Deal JA, Gross AL, An Y, Tian Q, Simonsick EM, Ferrucci L, Resnick SM, Schrack JA, Wanigatunga AA (2025) Directionality between cognitive function and daily physical activity patterns. Alzheimer's Dementia (New York, N.y.) 11(2):e70068. https://doi.org/10.1002/trc2.70068

Marston KJ, Brown BM, Rainey-Smith SR, Peiffer JJ (2019) Resistance exercise-induced responses in physiological factors linked with cognitive health. JAD 68(1):39–64. https://doi.org/10.3233/JAD-181079

Martínez-Díaz IC, Carrasco Páez L (2023) Little but intense: using a HIIT-based strategy to improve mood and cognitive functioning in college students. Healthcare (Basel, Switzerland). https://doi.org/10.3390/healthcare11131880

Matsui T, Takahashi S, Ochi G, Yoshitake S, Funabashi D, Matsuoka H, Kagesawa J, Dobashi S, Yoshimoto H, Sakairi Y, Takagi H (2024) Cognitive decline with pupil constriction independent of subjective fatigue during prolonged esports across player expertise levels. Comput Hum Behav 156:108219. https://doi.org/10.1016/j.chb.2024.108219

McMorris T (2021) The acute exercise-cognition interaction: From the catecholamines hypothesis to an interoception model. Int J Psychophysiol 170:75–88. https://doi.org/10.1016/j.ijpsycho.2021.10.005

Mellow ML, Dumuid D, Thacker JS, Dorrian J, Smith AE (2019) Building your best day for healthy brain aging-The neuroprotective effects of optimal time use. Maturitas 125:33–40. https://doi.org/10.1016/j.maturitas.2019.04.204

Mellow ML, Crozier AJ, Dumuid D, Wade AT, Goldsworthy MR, Dorrian J, Smith AE (2022) How are combinations of physical activity, sedentary behaviour and sleep related to cognitive function in older adults? A systematic review. Exp Gerontol 159:111698. https://doi.org/10.1016/j.exger.2022.111698

Memel M, Bourassa K, Woolverton C, Sbarra DA (2016) Body mass and physical activity uniquely predict change in cognition for aging adults. Ann Beha Med Publ Soc Behav Med 50(3):397–408. https://doi.org/10.1007/s12160-015-9768-2

Meyler S, Bottoms L, Muniz-Pumares D (2021) Biological and methodological factors affecting VO2max response variability to endurance training and the influence of exercise intensity prescription. Exp Physiol. https://doi.org/10.1113/EP089565

Migueles JH, Cadenas-Sanchez C, Ekelund U, Delisle Nyström C, Mora-Gonzalez J, Löf M, Labayen I, Ruiz JR, Ortega FB (2017) Accelerometer data collection and processing criteria to assess physical activity and other outcomes: a systematic review and practical considerations. Sports Med (Auckland, N.z.) 47(9):1821–1845. https://doi.org/10.1007/s40279-017-0716-0

Migueles JH, Aadland E, Andersen LB, Brønd JC, Chastin SF, Hansen BH, Konstabel K, Kvalheim OM, McGregor DE, Rowlands AV, Sabia S, van Hees VT, Walmsley R, Ortega FB (2021) GRANADA consensus on analytical approaches to assess associations with accelerometer-determined physical behaviours (physical activity, sedentary behaviour and sleep) in epidemiological studies. Br J Sports Med. https://doi.org/10.1136/bjsports-2020-103604

Min J, Cao Z, Duan T, Wang Y, Xu C (2024) Accelerometer-derived "weekend warrior" physical activity pattern and brain health. Nature Aging. https://doi.org/10.1038/s43587-024-00688-y

Mitchell JJ, Blodgett JM, Chastin SF, Jefferis BJ, Wannamethee SG, Hamer M (2023) Exploring the associations of daily movement behaviours and mid-life cognition: a compositional analysis of the 1970 British Cohort Study. J Epidemiol Community Health. https://doi.org/10.1136/jech-2022-219829

Monteagudo P, Cordellat A, Roldán A, Gómez-Cabrera MC, Pesce C, Blasco-Lafarga C (2021) Exploring potential benefits of accumulated multicomponent-training in non-active older adults: from physical fitness to mental health. IJERPH 18(18):9645. https://doi.org/10.3390/ijerph18189645

Mühlen JM, Stang J, Lykke Skovgaard E, Judice PB, Molina-Garcia P, Johnston W, Sardinha LB, Ortega FB, Caulfield B, Bloch W, Cheng S, Ekelund U, Brønd JC, Grøntved A, Schumann M (2021) Recommendations for determining the validity of consumer wearable heart rate devices: expert statement and checklist of the INTERLIVE Network. Br J Sports Med. https://doi.org/10.1136/bjsports-2020-103148

Müller AM, Blandford A, Yardley L (2017) The conceptualization of a Just-In-Time Adaptive Intervention (JITAI) for the reduction of sedentary behavior in older adults. mHealth 3:37. https://doi.org/10.21037/mhealth.2017.08.05

Mulser L, Moreau D (2023) Effect of acute cardiovascular exercise on cerebral blood flow: A systematic review. Brain Res 1809:148355. https://doi.org/10.1016/j.brainres.2023.148355

Musiek ES, Bhimasani M, Zangrilli MA, Morris JC, Holtzman DM, Ju Y-ES (2018) Circadian Rest-Activity Pattern Changes in Aging and Preclinical Alzheimer Disease. JAMA Neurol 75(5):582–590. https://doi.org/10.1001/jamaneurol.2017.4719

Nichols E, Steinmetz JD, Vollset SE, Fukutaki K, Chalek J, Abd-Allah F, Abdoli A, Abualhasan A, Abu-Gharbieh E, Akram TT, Al Hamad H, Alahdab F, Alanezi FM, Alipour V, Almustanyir S, Amu H, Ansari I, Arabloo J, Ashraf T, Astell-Burt T, Ayano G, Ayuso-Mateos JL, Baig AA, Barnett A, Barrow A, Baune BT, Béjot Y, Bezabhe WMM, Bezabih YM, Bhagavathula AS, Bhaskar S, Bhattacharyya K, Bijani A, Biswas A, Bolla SR, Boloor A, Brayne C, Brenner H, Burkart K, Burns RA, Cámera LA, Cao C, Carvalho F, Castro-de-Araujo LFS, Catalá-López F, Cerin E, Chavan PP, Cherbuin N, Chu D-T, Costa VM, Couto RAS, Dadras O, Dai X, Dandona L, Dandona R, La Cruz-Góngora V de, Dhamnetiya D, Da Dias Silva D, Diaz D, Douiri A, Edvardsson D, Ekholuenetale M, El Sayed I, El-Jaafary SI, Eskandari K, Eskandarieh S, Esmaeilnejad S, Fares J, Faro A, Farooque U, Feigin VL, Feng X, Fereshtehnejad S-M, Fernandes E, Ferrara P, Filip I, Fillit H, Fischer F, Gaidhane S, Galluzzo L, Ghashghaee A, Ghith N, Gialluisi A, Gilani SA, Glavan I-R, Gnedovskaya EV, Golechha M, Gupta R, Gupta VB, Gupta VK, Haider MR, Hall BJ, Hamidi S, Hanif A, Hankey GJ, Haque S, Hartono RK, Hasaballah AI, Hasan MT, Hassan A, Hay SI, Hayat K, Hegazy MI, Heidari G, Heidari-Soureshjani R, Herteliu C, Househ M, Hussain R, Hwang B-F, Iacoviello L, Iavicoli I, Ilesanmi OS, Ilic IM, Ilic MD, Irvani SSN, Iso H, Iwagami M, Jabbarinejad R, Jacob L, Jain V, Jayapal SK, Jayawardena R, Jha RP, Jonas JB, Joseph N, Kalani R, Kandel A, Kandel H, Karch A, Kasa AS, Kassie GM, Keshavarz P, Khan MAB, Khatib MN, Khoja TAM, Khubchandani J, Kim MS, Kim YJ, Kisa A, Kisa S, Kivimäki M, Koroshetz WJ, Koyanagi A, Kumar GA, Kumar M, Lak HM, Leonardi M, Li B, Lim SS, Liu X, Liu Y, Logroscino G, Lorkowski S, Lucchetti G, Lutzky Saute R, Magnani FG, Malik AA, Massano J, Mehndiratta MM, Menezes RG, Meretoja A, Mohajer B, Mohamed Ibrahim N, Mohammad Y, Mohammed A, Mokdad AH, Mondello S, Moni MAA, Moniruzzaman M, Mossie TB, Nagel G, Naveed M, Nayak VC, Neupane Kandel S, Nguyen TH, Oancea B, Otstavnov N, Otstavnov SS, Owolabi MO, Panda-Jonas S, Pashazadeh Kan F, Pasovic M, Patel UK, Pathak M, Peres MFP, Perianayagam A, Peterson CB, Phillips MR, Pinheiro M, Piradov MA, Pond CD, Potashman MH, Pottoo FH, Prada SI, Radfar A, Raggi A, Rahim F, Rahman M, Ram P, Ranasinghe P, Rawaf DL, Rawaf S, Rezaei N, Rezapour A, Robinson SR, Romoli M, Roshandel G, Sahathevan R, Sahebkar A, Sahraian MA, Sathian B, Sattin D, Sawhney M, Saylan M, Schiavolin S, Seylani A, Sha F, Shaikh MA, Shaji KS, Shannawaz M, Shetty JK, Shigematsu M, Shin JI, Shiri R, Silva DAS, Silva JP, Silva R, Singh JA, Skryabin VY, Skryabina AA, Smith AE, Soshnikov S, Spurlock EE, Stein DJ, Sun J, Tabarés-Seisdedos R, Thakur B, Timalsina B, Tovani-Palone MR, Tran BX, Tsegaye GW, Valadan Tahbaz S, Valdez PR, Venketasubramanian N, Vlassov V, Vu GT, Vu LG, Wang Y-P, Wimo A, Winkler AS, Yadav L, Yahyazadeh Jabbari SH, Yamagishi K, Yang L, Yano Y, Yonemoto N, Yu C, Yunusa I, Zadey S, Zastrozhin MS, Zastrozhina A, Zhang Z-J, Murray CJL, Vos T (2022) Estimation of

the global prevalence of dementia in 2019 and forecasted prevalence in 2050: an analysis for the Global Burden of Disease Study 2019. Lancet Public Health 7(2):e105-e125. https://doi.org/10.1016/S2468-2667(21)00249-8

Nigg CR, Fuchs R, Gerber M, Jekauc D, Koch T, Krell-Roesch J, Lippke S, Mnich C, Novak B, Ju Q, Sattler MC, Schmidt SC, van Poppel M, Reimers AK, Wagner P, Woods C, Woll A (2020) Assessing physical activity through questionnaires—a consensus of best practices and future directions. Psychol Sport Exerc 50:101715. https://doi.org/10.1016/j.psychsport.2020.101715

Ning Y, Chen M, An J, Tang M, Tse G, Chan JSK, Zhao C, Liu Y, Lei X, Qiang H, Bai C, Li H, Yu H, Yan Y, Wang D, Li G (2024) Association between "weekend warrior" physical activity and the incidence of neurodegenerative diseases. Neurotherapeutics 21(5):e00430. https://doi.org/10.1016/j.neurot.2024.e00430

Ning Y, Chen M, Yang H, Jia J (2025) Accelerometer-derived "weekend warrior" physical activity, sedentary behavior, and risk of dementia. Alz Res Therapy. https://doi.org/10.1186/s13195-024-01657-8

Noone J, Mucinski JM, DeLany JP, Sparks LM, Goodpaster BH (2024) Understanding the variation in exercise responses to guide personalized physical activity prescriptions. Cell Metab. https://doi.org/10.1016/j.cmet.2023.12.025

Northey JM, Cherbuin N, Pumpa KL, Smee DJ, Rattray B (2018) Exercise interventions for cognitive function in adults older than 50: a systematic review with meta-analysis. A systematic review with meta-analysis. Br J Sports Med 52(3):154–160. https://doi.org/10.1136/bjsports-2016-096587

Norton S, Matthews FE, Barnes DE, Yaffe K, Brayne C (2014) Potential for primary prevention of Alzheimer's disease: an analysis of population-based data. Lancet Neurol 13(8):788–794. https://doi.org/10.1016/S1474-4422(14)70136-X

Nunes Pereira Oliva H, Miranda Oliveira G, Oliveira Oliva I, Cardoso Cassilhas R, Maurício Batista de Paula A, Monteiro-Junior RS (2023) Middle cerebral artery blood velocity and cognitive function after high- and moderate-intensity aerobic exercise sessions. Neurosci Lett. https://doi.org/10.1016/j.neulet.2023.137511

Oberg E (2007) Physical activity prescription: our best medicine. Integra Med 6(5):18–22

Oberste M, Javelle F, Sharma S, Joisten N, Walzik D, Bloch W, Zimmer P (2019) Effects and moderators of acute aerobic exercise on subsequent interference control: a systematic review and meta-analysis. Front Psychol 10:609. https://doi.org/10.3389/fpsyg.2019.02616

Oberste M, Sharma S, Bloch W, Zimmer P (2021) Acute exercise-induced set shifting benefits in healthy adults and its moderators: a systematic review and meta-analysis. Front Psychol. https://doi.org/10.3389/fpsyg.2021.528352

O'Donovan G, Sarmiento OL, Hamer M (2018) The rise of the "Weekend Warrior." J Orthop Sports Phys Ther 48(8):604–606. https://doi.org/10.2519/jospt.2018.0611

O'Donovan G, Petermann-Rocha F, Ferrari G, Medina C, Ochoa-Rosales C, Sarmiento OLL, Ibáñez A (2024) Associations of the "weekend warrior" physical activity pattern with mild dementia: findings from the Mexico City Prospective Study. Br J Sports Med. https://doi.org/10.1136/bjsports-2024-108460

Oosterman J, van Harten B, Vogels R, Gouw A, Weinstein H, Scheltens P, Scherder E (2008) Distortions in rest-activity rhythm in aging relate to white matter hyperintensities. Neurobiol Aging 29(8):1265–1271. https://doi.org/10.1016/j.neurobiolaging.2007.02.014

Oosterman JM, van Someren EJW, Vogels RLC, van Harten B, Scherder EJA (2009) Fragmentation of the rest-activity rhythm correlates with age-related cognitive deficits. J Sleep Res

18(1):129–135. https://doi.org/10.1111/j.1365-2869.2008.00704.x

Owen N, Healy GN, Dempsey PC, Salmon J, Timperio A, Clark BK, Goode AD, Koorts H, Ridgers ND, Hadgraft NT, Lambert G, Eakin EG, Kingwell BA, Dunstan DW (2020) Sedentary behavior and public health: integrating the evidence and identifying potential solutions. Annu Rev Public Health 41:265–287. https://doi.org/10.1146/annurev-publhealth-040119-094201

Palmer JR, Wang C, Kong D, Cespedes M, Pye J, Hickie IB, Barnett M, Naismith SL (2022) Rest-activity rhythms and tract specific white matter lesions in older adults at risk for cognitive decline. Mol Psychiatry 27(8):3410–3416. https://doi.org/10.1038/s41380-022-01641-4

Paraschiv-Ionescu A, Buchser E, Rutschmann B, Aminian K (2008) Nonlinear analysis of human physical activity patterns in health and disease. Phys Rev e, Stat Nonlinear Soft Matter Phys 77(2 Pt 1):21913. https://doi.org/10.1103/PhysRevE.77.021913

Parfitt G, Alrumh A, Rowlands AV (2012) Affect-regulated exercise intensity: does training at an intensity that feels "good" improve physical health? J Sci Med Sport 15(6):548–553. https://doi.org/10.1016/j.jsams.2012.01.005

Peng CK, Buldyrev SV, Havlin S, Simons M, Stanley HE, Goldberger AL (1994) Mosaic organization of DNA nucleotides. Phys Rev E Stat Phys Plasmas Fluids Related Interdiscip Top 49(2):1685–1689. https://doi.org/10.1103/physreve.49.1685

Peng CK, Havlin S, Hausdorff JM, Mietus JE, Stanley HE, Goldberger AL (1995a) Fractal mechanisms and heart rate dynamics. Long-range correlations and their breakdown with disease. J Electrocardiol 28:59–65. https://doi.org/10.1016/s0022-0736(95)80017-4

Peng CK, Havlin S, Stanley HE, Goldberger AL (1995b) Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. Chaos (Woodbury, N.y.) 5(1):82–87. https://doi.org/10.1063/1.166141

Pettee Gabriel KK, Morrow JR, Woolsey A-LT (2012) Framework for physical activity as a complex and multidimensional behavior. J Phys Act Health 9(Suppl 1):S11–S18. https://doi.org/10.1123/jpah.9.s1.s11

Pinto AJ, Bergouignan A, Dempsey PC, Roschel H, Owen N, Gualano B, Dunstan DW (2023) Physiology of sedentary behavior. Physiol Rev 103(4):2561–2622. https://doi.org/10.1152/physrev.00022.2022

Pittman-Polletta BR, Scheer FAJL, Butler MP, Shea SA, Hu K (2013) The role of the circadian system in fractal neurophysiological control. Biol Rev Camb Philos Soc 88(4):873–894. https://doi.org/10.1111/brv.12032

Pontifex MB, McGowan AL, Chandler MC, Gwizdala KL, Parks AC, Fenn K, Kamijo K (2019) A primer on investigating the after effects of acute bouts of physical activity on cognition. Psychol Sport Exerc 40:1–22. https://doi.org/10.1016/j.psychsport.2018.08.015

Poudel GR, Barnett A, Akram M, Martino E, Knibbs LD, Anstey KJ, Shaw JE, Cerin E (2022) machine learning for prediction of cognitive health in adults using sociodemographic, neighbourhood environmental, and lifestyle factors. Int J Environ Res Public Health 19(17):10. https://doi.org/10.3390/ijerph191710977

Prince SA, Cardilli L, Reed JL, Saunders TJ, Kite C, Douillette K, Fournier K, Buckley JP (2020) A comparison of self-reported and device measured sedentary behaviour in adults: a systematic review and meta-analysis. Int J Behav Nutr Phys Activ 17(1):31. https://doi.org/10.1186/s12966-020-00938-3

Pronk N (2024) Physical activity paradox: providing evidence-based guidance while closing research gaps. Br J Sports Med. https://doi.org/10.1136/bjsports-2024-108294

Pulsford RM, Brocklebank L, Fenton SAM, Bakker E, Mielke GI, Tsai L-T, Atkin AJ, Harvey DL, Blodgett JM, Ahmadi M, Wei Le, Rowlands A, Doherty A, Rangul V, Koster A, Sherar LB, Holtermann A, Hamer M, Stamatakis E (2023) The impact of selected methodological factors on data collection outcomes in observational studies of device-measured physical behaviour in adults: A systematic review. Int J Behav Nutr Phys Activ 20(1):26. https://doi.org/10.1186/s12966-022-01388-9

Quistorff B, Secher NH, van Lieshout JJ (2008) Lactate fuels the human brain during exercise. FASEB J 22(10):3443–3449. https://doi.org/10.1096/fj.08-106104

Rabinowitz JA, An Y, He L, Alfini AJ, Zipunnikov V, Wu MN, Wanigatunga SK, Schrack JA, Jackson CL, Ferrucci L, Simonsick EM, Resnick SM, Spira AP (2022) Associations of circadian rest/activity rhythms with cognition in middle-aged and older adults: Demographic and genetic interactions. Front Neurosci 16:952204. https://doi.org/10.3389/fnins.2022.952204

Raichlen DA, Klimentidis YC, Hsu C-H, Alexander GE (2019) Fractal complexity of daily physical activity patterns differs with age over the life span and is associated with mortality in older adults. J Gerontol Ser A Biol Sci Med Sci 74(9):1461–1467. https://doi.org/10.1093/gerona/gly247

Raichlen DA, Klimentidis YC, Sayre MK, Bharadwaj PK, Lai MHC, Wilcox RR, Alexander GE (2022) Leisure-time sedentary behaviors are differentially associated with all-cause dementia regardless of engagement in physical activity. Proc Natl Acad Sci USA 119(35):e2206931119. https://doi.org/10.1073/pnas.2206931119

Raichlen DA, Aslan DH, Sayre MK, Bharadwaj PK, Ally M, Maltagliati S, Lai MHC, Wilcox RR, Klimentidis YC, Alexander GE (2023) Sedentary behavior and incident dementia among older adults. JAMA 330(10):934–940. https://doi.org/10.1001/jama.2023.15231

Ratamess N, Alvar BA, Evetoch TK, Housh TJ, Kibler WB, Kraemer WJ, Triplett NT (2009) American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. Med Sci Sports Exerc 41(3):687–708. https://doi.org/10.1249/MSS.0b013e3181915670

Reichert M, Giurgiu M, Koch E, Wieland LM, Lautenbach S, Neubauer AB, von Haaren-Mack B, Schilling R, Timm I, Notthoff N, Marzi I, Hill H, Brüßler S, Eckert T, Fiedler J, Burchartz A, Anedda B, Wunsch K, Gerber M, Jekauc D, Woll A, Dunton GF, Kanning M, Nigg CR, Ebner-Priemer U, Liao Y (2020) Ambulatory assessment for physical activity research: state of the science, best practices and future directions. Psychol Sport Exerc. https://doi.org/10.1016/j.psychsport.2020.101742

Riske L, Thomas RK, Baker GB, Dursun SM (2017) Lactate in the brain: an update on its relevance to brain energy, neurons, glia and panic disorder. Therapeutic Advances in Psychopharmacology 7(2):85–89. https://doi.org/10.1177/2045125316675579

Rodrigues B, Videira-Silva A, Lopes L, Sousa-Sá E, Vale S, Cliff DP, Mendes R, Santos R (2025) Methodological choices on 24-h movement behavior assessment by accelerometry: a scoping review. Sports Med Open 11(1):25. https://doi.org/10.1186/s40798-025-00820-1

Rogers B, Mourot L, Doucende G, Gronwald T (2021) Fractal correlation properties of heart rate variability as a biomarker of endurance exercise fatigue in ultramarathon runners. Physiol Rep. https://doi.org/10.14814/phy2.14956

Rowlands AV, Gomersall SR, Tudor-Locke C, Bassett DR, Kang M, Fraysse F, Ainsworth B, Olds TS (2015) Introducing novel approaches for examining the variability of individuals' physical activity. J Sports Sci 33(5):457–466. https://doi.org/10.1080/02640414.2014.951067

Sabag A, Ahmadi MN, Francois ME, Postnova S, Cistulli PA, Fontana L, Stamatakis E (2024) Timing of moderate to vigorous physical activity, mortality, cardiovascular disease, and microvascular disease in adults with obesity. Diabetes Care. https://doi.org/10.2337/dc23-2448

Schiffer T, Schulte S, Sperlich B, Achtzehn S, Fricke H, Struder HK (2011) Lactate infusion at rest increases BDNF blood concentration in humans. Neurosci Lett 488(3):234–237. https://doi.org/10.1016/j.neulet.2010.11.035

Schnabel G, Harre D, Krug J (eds) (2014) Trainingslehre - Trainingswissenschaft. Leistung - Training - Wettkampf, 3., aktualisierte Auflage. Meyer & Meyer Verlag, Aachen, Auckland, Beirut, Budapest, Kairo, Cape Town, Dubai, Hägendorf, Indianapolis, Maidenhead, Singapur, Sydney, Teheran, Wien

Schoene D, Lord SR, Delbaere K, Severino C, Davies TA, Smith ST (2013) A randomized controlled pilot study of home-based step training in older people using videogame technology. PLoS ONE 8(3):e57734. https://doi.org/10.1371/journal.pone.0057734

Schoene D, Valenzuela T, Toson B, Delbaere K, Severino C, Garcia J, Davies TA, Russell F, Smith ST, Lord SR (2015) Interactive cognitive-motor step training improves cognitive risk factors of falling in older adults—a randomized controlled trial. PLoS ONE 10(12):e0145161. https://doi.org/10.1371/journal.pone.0145161

Sedentary Behaviour Research Network (2012) Letter to the editor: standardized use of the terms "sedentary" and "sedentary behaviours". Appl Physiol Nutr Metab Physiologie appliquee, nutrition et metabolisme 37(3):540–542. https://doi.org/10.1139/h2012-024

Sewell KR, Rainey-Smith SR, Peiffer J, Sohrabi HR, Doecke J, Frost NJ, Markovic SJ, Erickson K, Brown BM (2023) The influence of baseline sleep on exercise-induced cognitive change in cognitively unimpaired older adults: a randomised clinical trial. Int J Geriatr Psychiatry 38(10):e6016. https://doi.org/10.1002/gps.6016

Sharma P, Dunham A (2024) Pharmacy Calculations. https://www.ncbi.nlm.nih.gov/books/NBK560924. Accessed June 22 2025.

Shi K, Chen Z, Sun W, Hu W (2024) Measuring regularity of human physical activities with entropy models. J Big Data. https://doi.org/10.1186/s40537-024-00891-z

Shirzad M, Tari B, Dalton C, van Riesen J, Marsala MJ, Heath M (2022) Passive exercise increases cerebral blood flow velocity and supports a postexercise executive function benefit. Psychophysiol 59(12):e14132. https://doi.org/10.1111/psyp.14132

Smagula SF (2016) Opportunities for clinical applications of rest-activity rhythms in detecting and preventing mood disorders. Curr Opin Psychiatry 29(6):389–396. https://doi.org/10.1097/YCO.0000000000000283

Smagula SF, Gujral S, Capps CS, Krafty RT (2019) A systematic review of evidence for a role of rest-activity rhythms in dementia. Front Psych 10:778. https://doi.org/10.3389/fpsyt.2019.00778

Smagula SF, Chahine L, Metti A, Rangarajan A, Aizenstein HJ, Tian Q, Rosano C (2020) Regional gray matter volume links rest-activity rhythm fragmentation with past cognitive decline. Am J Geriatr Psychiatry 28(2):248–251. https://doi.org/10.1016/j.jagp.2019.07.009

Solis-Urra P, Fernandez-Gamez B, Liu-Ambrose T, Erickson KI, Ortega FB, Esteban-Cornejo I (2024) Exercise as medicine for the brain: moving towards precise and personalised recommendations. Br J Sports Med. https://doi.org/10.1136/bjsports-2024-108158

Song J, Paul SS, Caetano MJD, Smith S, Dibble LE, Love R, Schoene D, Menant JC, Sherrington C, Lord SR, Canning CG, Allen NE (2018) Home-based step training using videogame technology in people with Parkinson's disease: a single-blinded randomised controlled trial. Clin Rehabil 32(3):299–311. https://doi.org/10.1177/0269215517721593

Stamatakis E, Huang B-H, Maher C, Thøgersen-Ntoumani C, Stathi A, Dempsey PC, Johnson N, Holtermann A, Chau JY, Sherrington C, Daley AJ, Hamer M, Murphy MH, Tudor-Locke C, Gibala

MJ (2020) Untapping the health enhancing potential of vigorous intermittent lifestyle physical activity (VILPA): rationale, scoping review, and a 4-pillar research framework. Sports Med. https://doi.org/10.1007/s40279-020-01368-8

Stamatakis E, Ahmadi MN, Gill JMR, Thøgersen-Ntoumani C, Gibala MJ, Doherty A, Hamer M (2022) Association of wearable device-measured vigorous intermittent lifestyle physical activity with mortality. Nat Med. https://doi.org/10.1038/s41591-022-02100-x

Stamatakis E, Ahmadi MN, Friedenreich CM, Blodgett JM, Koster A, Holtermann A, Atkin A, Rangul V, Sherar LB, Teixeira-Pinto A, Ekelund U, Lee I-M, Hamer M (2023) Vigorous intermittent lifestyle physical activity and cancer incidence among nonexercising adults: the UK Biobank Accelerometry Study. JAMA Oncol. https://doi.org/10.1001/jamaoncol.2023.1830

Stamatakis E, Ahmadi MN, Elphick T-L, Huang B-H, Paudel S, Teixeira-Pinto A, Chen L-J, Del Cruz BP, Lai Y-J, Holtermann A, Ku P-W (2024) Occupational physical activity, all-cause, cardiovascular disease, and cancer mortality in 349,248 adults: Prospective and longitudinal analyses of the MJ Cohort. J Sport Health Sci. https://doi.org/10.1016/j.jshs.2024.03.002

Stillman CM, Cohen J, Lehman ME, Erickson KI (2016) Mediators of physical activity on neurocognitive function: a review at multiple levels of analysis. Front Hum Neurosci 10:626. https://doi.org/10.3389/fnhum.2016.00626

Stillman CM, Esteban-Cornejo I, Brown B, Bender CM, Erickson KI (2020) Effects of exercise on brain and cognition across age groups and health states. Trends Neurosci 43(7):533–543. https://doi.org/10.1016/j.tins.2020.04.010

Stimpson NJ, Davison G, Javadi A-H (2018) Joggin' the Noggin. Towards a physiological understanding of exercise-induced cognitive benefits. Neurosci Biobehav Rev 88:177–186. https://doi.org/10.1016/j.neubiorev.2018.03.018

Strath SJ, Kaminsky LA, Ainsworth BE, Ekelund U, Freedson PS, Gary RA, Richardson CR, Smith DT, Swartz AM (2013) Guide to the assessment of physical activity: clinical and research applications: a scientific statement from the American Heart Association. Circulation 128(20):2259–2279. https://doi.org/10.1161/01.cir.0000435708.67487.da

Sun X, Yu W, Wang M, Hu J, Li Y (2023) Association between rest-activity rhythm and cognitive function in the elderly: The U.S. National Health and Nutrition Examination Survey, 2011–2014. Front Endocrinol 14:1135085. https://doi.org/10.3389/fendo.2023.1135085

Symons IK, Bruce L, Main LC (2023) Impact of overtraining on cognitive function in endurance athletes: a systematic review. Sports Med Open 9(1):69. https://doi.org/10.1186/s40798-023-00614-3

Taher M, Leen WG, Wevers RA, Willemsen MA (2016) Lactate and its many faces. Eur J Paediatr Neurol EJPN 20(1):3–10. https://doi.org/10.1016/j.ejpn.2015.09.008

Takeuchi M, Sano Y (2024) Burstiness of human physical activities and their characterisation. J Comput Soc Sc 7(1):625–641. https://doi.org/10.1007/s42001-024-00247-w

Targa ADS, Benítez ID, Dakterzada F, Fontenele-Araujo J, Minguez O, Zetterberg H, Blennow K, Barbé F, Piñol-Ripoll G (2021) The circadian rest-activity pattern predicts cognitive decline among mild-moderate Alzheimer's disease patients. Alzheimer's Res Ther 13(1):161. https://doi.org/10.1186/s13195-021-00903-7

Tari B, Vanhie JJ, Belfry GR, Shoemaker JK, Heath M (2020) Increased cerebral blood flow supports a single-bout postexercise benefit to executive function: evidence from hypercapnia. J Neurophysiol 124(3):930–940. https://doi.org/10.1152/jn.00240.2020

Thøgersen-Ntoumani C, Grunseit A, Holtermann A, Steiner S, Tudor-Locke C, Koster A, Johnson N, Maher C, Ahmadi M, Chau JY, Stamatakis E (2024) Promoting vigorous intermittent lifestyle physical activity (vilpa) in middle-aged adults: an evaluation of the movsnax mobile app. BMC Public Health 24(1):2182. https://doi.org/10.1186/s12889-024-19549-9

Tian S, Mou H, Qiu F (2021) Sustained Effects of High-Intensity Interval Exercise and Moderate-Intensity Continuous Exercise on Inhibitory Control. IJERPH 18(5):2687. https://doi.org/10.3390/ijerph18052687

Timm I, Reichert M, Ebner-Priemer UW, Giurgiu M (2023) Momentary within-subject associations of affective states and physical behavior are moderated by weather conditions in real life: an ambulatory assessment study. Int J Behav Nutr Phys Activ 20(1):117. https://doi.org/10.1186/s12966-023-01507-0

Toigo M, Boutellier U (2006) New fundamental resistance exercise determinants of molecular and cellular muscle adaptations. Eur J Appl Physiol 97(6):643–663. https://doi.org/10.1007/s00421-006-0238-1

Tomoo K, Suga T, Sugimoto T, Tanaka D, Shimoho K, Dora K, Mok E, Matsumoto S, Tsukamoto H, Takada S, Hashimoto T, Isaka T (2020) Work volume is an important variable in determining the degree of inhibitory control improvements following resistance exercise. Physiol Rep 8(15):e14527. https://doi.org/10.14814/phy2.14527

Tomoo K, Suga T, Dora K, Sugimoto T, Mok E, Tsukamoto H, Takada S, Hashimoto T, Isaka T (2021) Impact of inter-set short rest interval length on inhibitory control improvements following low-intensity resistance exercise in healthy young males. Front Physiol. https://doi.org/10.3389/fphys.2021.741966

Törpel A, Herold F, Hamacher D, Müller NG, Schega L (2018) Strengthening the brain-is resistance training with blood flow restriction an effective strategy for cognitive improvement? J Clin Med 7(10):377. https://doi.org/10.3390/jcm7100337

Tremblay MS, Aubert S, Barnes JD, Saunders TJ, Carson V, Latimer-Cheung AE, Chastin SFM, Altenburg TM, Chinapaw MJM (2017) Sedentary Behavior Research Network (SBRN)-Terminology Consensus Project process and outcome. Int J Behav Nutr Phys Activ 14(1):75. https://doi.org/10.1186/s12966-017-0525-8

Trull TJ, Ebner-Priemer U (2013) Ambulatory assessment. Annu Rev Clin Psychol 9:151–176. https://doi.org/10.1146/annurev-clinpsy-050212-185510

Tschakert G, Handl T, Weiner L, Birnbaumer P, Mueller A, Groeschl W, Hofmann P (2022) Exercise duration: Independent effects on acute physiologic responses and the need for an individualized prescription. Physiol Rep 10(3):e15168. https://doi.org/10.14814/phy2.15168

Tsukamoto H, Suga T, Takenaka S, Tanaka D, Takeuchi T, Hamaoka T, Isaka T, Hashimoto T (2016a) Greater impact of acute high-intensity interval exercise on post-exercise executive function compared to moderate-intensity continuous exercise. Physiol Behav 155:224–230. https://doi.org/10.1016/j.physbeh.2015.12.021

Tsukamoto H, Suga T, Takenaka S, Tanaka D, Takeuchi T, Hamaoka T, Isaka T, Ogoh S, Hashimoto T (2016b) Repeated high-intensity interval exercise shortens the positive effect on executive function during post-exercise recovery in healthy young males. Physiol Behav 160:26–34. https://doi.org/10.1016/j.physbeh.2016.03.029

Tymko MM, Ainslie PN, Smith KJ (2018) Evaluating the methods used for measuring cerebral blood flow at rest and during exercise in humans. Eur J Appl Physiol 118(8):1527–1538. https://doi.org/10.1007/s00421-018-3887-y

van Dongen EV, Kersten IHP, Wagner IC, Morris RGM, Fernandez G (2016) Physical exercise performed four hours after learning improves memory retention and increases hippocampal pattern similarity during retrieval. Curr Biol CB. https://doi.org/10.1016/j.cub.2016.04.071

van Egroo M, van Someren EJW, Grinberg LT, Bennett DA, Jacobs HIL (2024) Associations of 24-hour rest-activity rhythm fragmentation, cognitive decline, and postmortem locus coeruleus hypopigmentation in Alzheimer's disease. Ann Neurol. https://doi.org/10.1002/ana.26880

van Someren EJW, Oosterman JM, van Harten B, Vogels RL, Gouw AA, Weinstein HC, Poggesi A, Scheltens P, Scherder EJA (2019) Medial temporal lobe atrophy relates more strongly to sleep-wake rhythm fragmentation than to age or any other known risk. Neurobiol Learn Mem 160:132–138. https://doi.org/10.1016/j.nlm.2018.05.017

Velandia PP, Miller-Petrie MK, Chen C, Chakrabarti S, Chapin A, Hay S, Tsakalos G, Wimo A, Dieleman JL (2022) Global and regional spending on dementia care from 2000–2019 and expected future health spending scenarios from 2020–2050: an economic modelling exercise. EClinicalMedicine 45:101337. https://doi.org/10.1016/j.eclinm.2022.101337

Vetter C (2020) Circadian disruption: What do we actually mean? Eur J Neurosci 51(1):531–550. https://doi.org/10.1111/ejn.14255

von Haaren-Mack B, Kanning M, Ebner-Priemer UW, Reichert M (2022) "Capturing life as it is lived"—ambulatory assessment for physical activity, sport and exercise research. Ger J Exerc Sport Res 52(2):215–217. https://doi.org/10.1007/s12662-022-00824-z

Voss MW (2016) The chronic exercise-cognition interaction: fMRI research. In: McMorris T (ed) Exercise-cognition interaction. Elsevier, pp 187–209

Walsh JJ, Tschakovsky ME (2018) Exercise and circulating BDNF: Mechanisms of release and implications for the design of exercise interventions. Appl Physiol Nutr Metab Physiologie Appliquee, Nutrition Et Metabolisme 43(11):1095–1104. https://doi.org/10.1139/apnm-2018-0192

Walsh EI, Smith L, Northey J, Rattray B, Cherbuin N (2020) Towards an understanding of the physical activity-BDNF-cognition triumvirate: a review of associations and dosage. Ageing Res Rev 60:101044. https://doi.org/10.1016/j.arr.2020.101044

Wang Y, Pan Y, Li H (2020) What is brain health and why is it important? BMJ (Clinical Research Ed) 371:m3683. https://doi.org/10.1136/bmj.m3683

Wang T, Laher I, Li S (2024) Exercise snacks and physical fitness in sedentary populations. Sports Med Health Sci. https://doi.org/10.1016/j.smhs.2024.02.006

Wanigatunga AA, Liu F, Wang H, Urbanek JK, An Y, Spira AP, Dougherty RJ, Tian Q, Moghekar A, Ferrucci L, Simonsick EM, Resnick SM, Schrack JA (2022) daily physical activity patterns as a window on cognitive diagnosis in the Baltimore longitudinal study of aging (BLSA). J Alzheimer's Dis JAD 88(2):459–469. https://doi.org/10.3233/JAD-215544

Warburton DER, Bredin SSD (2016) Reflections on physical activity and health: what should we recommend? Can J Cardiol 32(4):495–504. https://doi.org/10.1016/j.cjca.2016.01.024

Warburton DE, Bredin SS (2017) Health benefits of physical activity. Curr Opin Cardiol 32(5):541–556. https://doi.org/10.1097/HCO.0000000000000437

Warren JM, Ekelund U, Besson H, Mezzani A, Geladas N, Vanhees L (2010) Assessment of physical activity—a review of methodologies with reference to epidemiological research. A report of the exercise physiology section of the European Association of Cardiovascular Prevention and Rehabilitation. Eur J Cardiovasc Prev Rehabil 17(2):127–139. https://doi.org/10.1097/HJR.0b013e32832ed875

Wegner M, Amatriain-Fernández S, Kaulitzky A, Murillo-Rodriguez E, Machado S, Budde H (2020) Systematic review of meta-analyses: exercise effects on depression in children and adolescents. Front Psychiatry. https://doi.org/10.3389/fpsyt.2020.00081

Wheeler MJ, Green DJ, Ellis KA, Cerin E, Heinonen I, Naylor LH, Larsen R, Wennberg P, Boraxbekk C-J, Lewis J, Eikelis N, Lautenschlager NT, Kingwell BA, Lambert G, Owen N, Dunstan DW (2019) Distinct effects of acute exercise and breaks in sitting on working memory and executive function in older adults: a three-arm, randomised cross-over trial to evaluate the effects of exercise with and without breaks in sitting on cognition. Br J Sports Med. https://doi.org/10.1136/bjsports-2018-100168

Wilckens KA, Stillman CM, Waiwood AM, Kang C, Leckie RL, Peven JC, Foust JE, Fraundorf SH, Erickson KI (2020) Exercise interventions preserve hippocampal volume: a meta-analysis. Hippocampus. https://doi.org/10.1002/hipo.23292

Wimo A, Seeher K, Cataldi R, Cyhlarova E, Dielemann JL, Frisell O, Guerchet M, Jönsson L, Malaha AK, Nichols E, Pedroza P, Prince M, Knapp M, Dua T (2023) The worldwide costs of dementia in 2019. Alzheimer's Dement. https://doi.org/10.1002/alz.12901

World Health Organization (2019) Risk reduction of cognitive decline and dementia. WHO Guidelines. https://www.who.int/publications/i/item/9789241550543. Accessed June 22 2025

World Health Organization (2020) WHO guidelines on physical activity and sedentary behaviour. World Health Organization, Geneva

World Health Organization (2022) Global status report on physical activity 2022. https://www.who.int/publications/i/item/9789240059153. Accessed 22 June 2025

Wu J, Qiu P, Li Y (2024) The association between "weekend warrior", regular exercise, and cognitive function in elderly individuals with and without depressive symptoms: a cross-sectional analysis from NHANES 2011–2014. J Affect Disord. https://doi.org/10.1016/j.jad.2024.08.184

Wunsch K, Eckert T, Fiedler J, Woll A (2022) Just-in-time adaptive interventions in mobile physical activity interventions - A synthesis of frameworks and future directions. Eur Health Psycholog 22(4):834–842

Xiao Q, Sampson JN, Lacroix AZ, Shadyab AH, Zeitzer JM, Ancoli-Israel S, Yaffe K, Stone K (2022) Nonparametric parameters of 24-hour rest-activity rhythms and long-term cognitive decline and incident cognitive impairment in older men. J Gerontol Ser Biol Sci Med Sci 77(2):250–258. https://doi.org/10.1093/gerona/glab275

Yamada Y, Frith EM, Wong V, Spitz RW, Bell ZW, Chatakondi RN, Abe T, Loenneke JP (2021) Acute exercise and cognition: A review with testable questions for future research into cognitive enhancement with blood flow restriction. Med Hypotheses 151:110586. https://doi.org/10.1016/j.mehy.2021.110586

Yang L, Cao C, Kantor ED, Nguyen LH, Zheng X, Park Y, Giovannucci EL, Matthews CE, Colditz GA, Cao Y (2019) Trends in Sedentary Behavior Among the US Population, 2001–2016. JAMA 321(16):1587–1597. https://doi.org/10.1001/jama.2019.3636

Yu Q, Herold F, Ludyga S, Cheval B, Zhang Z, Mücke M, Kramer AF, Li J, Kong Z, Zou L (2022) Neurobehavioral mechanisms underlying the effects of physical exercise break on episodic memory during prolonged sitting. Complement Ther Clin Pract 48:101553. https://doi.org/10.1016/j.ctcp.2022.101553

Zenko Z, Hall EE, Bixby WR (2024) The effects of affect-guided interval training on pleasure, enjoyment, and autonomy: a registered report. Psychol Sport Exerc 73:102611. https://doi.org/10.1016/j.psychsport.2024.102611

Zhang M, Chi N-C, Gardner SE, Moon C (2024) Rest-activity rhythm and cognitive function in older adults: A scoping review and integrative framework. Geriatr Nurs (New York, N.y.) 61:80–90. https://doi.org/10.1016/j.gerinurse.2024.10.074

Zou L, Herold F, Ludyga S, Kamijo K, Müller NG, Pontifex MB, Heath M, Kuwamizu R, Soya H, Hillman CH, Ando S, Alderman BL, Cheval B, Kramer AF (2023) Look into my eyes: what can eye-based measures tell us about the relationship between physical activity and cognitive performance? J Sport Health Sci 12(5):568–591. https://doi.org/10.1016/j.jshs.2023.04.003

Zou L, Herold F, Cheval B, Wheeler MJ, Pindus DM, Erickson KI, Raichlen DA, Alexander GE, Müller NG, Dunstan DW, Kramer AF, Hillman CH, Hallgren M, Ekelund U, Maltagliati S, Owen N

(2024) Sedentary behavior and lifespan brain health. Trends Cogn Sci 28(4):369–382. https://doi.org/10.1016/j.tics.2024.02.003

Zubin Maslov P, Schulman A, Lavie CJ, Narula J (2018) Personalized exercise dose prescription. Eur Heart J 39(25):2346–2355. https://doi.org/10.1093/eurheartj/ehx686

Zuurbier LA, Ikram MA, Luik AI, Hofman A, van Someren EJW, Vernooij MW, Tiemeier H (2015) Cerebral small vessel disease is related to disturbed 24-h activity rhythms: a population-based study. Eur J Neurol 22(11):1482–1487. https://doi.org/10.1111/ene.12775

Authors and Affiliations

Fabian Herold[1,2,3] · **Liye Zou**[4] · **Paula Theobald**[3] · **Patrick Manser**[5,6] · **Ryan S. Falck**[7,8,9,10] · **Qian Yu**[4] · **Teresa Liu-Ambrose**[8,9,10] · **Arthur F. Kramer**[11,12,13] · **Kirk I. Erickson**[14,15,16] · **Boris Cheval**[17,18] · **Yanxia Chen**[4] · **Matthew Heath**[19,20,21] · **Zhihao Zhang**[4] · **Toru Ishihara**[22] · **Keita Kamijo**[23] · **Soichi Ando**[24] · **Joseph T. Costello**[25] · **Mats Hallgren**[26,27] · **David Moreau**[28] · **Vahid Farrahi**[29] · **David A. Raichlen**[30,31] · **Emmanuel Stamatakis**[32,33] · **Michael J. Wheeler**[27,34] · **Neville Owen**[34,35] · **Sebastian Ludyga**[36] · **Henning Budde**[37] · **Thomas Gronwald**[2,38]

✉ Thomas Gronwald
Thomas.Gronwald@medicalschool-hamburg.de

1 Department of Physiology, Faculty of Medicine, HMU Health and Medical University Erfurt, Erfurt, Germany

2 Institute of Interdisciplinary Exercise Science and Sports Medicine, MSH Medical School Hamburg, Am Kaiserkai 1, 20457 Hamburg, Germany

3 Research Group Degenerative and Chronic Diseases, Movement, Faculty of Health Sciences Brandenburg, University of Potsdam, Potsdam, Germany

4 Body-Brain-Mind Laboratory, Shenzhen University, Shenzhen, China

5 Motor Control and Learning Group, Department of Health Sciences and Technology, Institute of Human Movement Sciences and Sport, ETH Zurich, Zurich, Switzerland

6 Division of Physiotherapy, Department of Neurobiology, Care Sciences and Society, Karolinska Institute, Stockholm, Sweden

7 School of Biomedical Engineering, The University of British Columbia, Vancouver, BC, Canada

8 Aging, Mobility, and Cognitive Health Laboratory, Department of Physical Therapy, The University of British Columbia, Vancouver, BC, Canada

9 Djavad Mowafaghian Centre for Brain Health, Vancouver Coastal Health Research Institute, Vancouver, BC, Canada

10 Centre for Aging Solutions for Mobility, Activity, Rehabilitation and Technology (SMART) at Vancouver Coastal Health, Vancouver Coastal Health Research Institute, Vancouver, BC, Canada

11 Center for Cognitive and Brain Health, Northeastern University, Boston, MA, USA

12 Department of Psychology, Northeastern University, Boston, MA, USA

13 Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, IL, USA

14 Department of Neuroscience, AdventHealth Research Institute, AdventHealth, Orlando, FL, USA

15 Department of Psychology, University of Pittsburgh, Pittsburgh, PA, USA

16 Center for the Neural Basis of Cognition, University of Pittsburgh, Pittsburgh, PA, USA

17 Department of Sport Sciences and Physical Education, Ecole Normale Supérieure Rennes, Bruz, France

18 Laboratory VIPS2, University of Rennes, Rennes, France

19 School of Kinesiology, Faculty of Health Sciences, University of Western Ontario, London, ON N6A 3K7, Canada

20 Canadian Centre for Activity and Aging, University of Western Ontario, London, ON N6A 3K7, Canada

21 Graduate Program in Neuroscience, University of Western Ontario, London, ON N6A 3K7, Canada

22 Graduate School of Human Development and Environment, Kobe University, Kobe, Japan

23 Faculty of Liberal Arts and Sciences, Chukyo University, Nagoya, Japan

24 Graduate School of Informatics and Engineering, The University of Electro-Communications, Tokyo, Japan

25 Extreme Environments Laboratory, School of Psychology, Sport and Health Sciences, University of Portsmouth, Portsmouth, UK

26 Epidemiology of Psychiatric Conditions, Substance Use and Social Environment (EPiCSS), Department of Public Health Sciences, Karolinska Institute, Solna, Sweden

27 Institute for Physical Activity and Nutrition (IPAN), School of Exercise and Nutrition Sciences, Deakin University, Geelong, Australia

28 School of Psychology and Centre for Brain Research, University of Auckland, Auckland, New Zealand

29 Institute for Sport and Sport Science, TU Dortmund University, Dortmund, Germany

30 Human and Evolutionary Biology Section, Department of Biological Sciences, University of Southern California, Los Angeles, CA 90089, USA

31 Department of Anthropology, University of Southern California, Los Angeles, CA 90089, USA

[32] Mackenzie Wearables Research Hub, Charles Perkins Centre, University of Sydney, Sydney, NSW, Australia

[33] Faculty of Medicine and Health, School of Health Sciences, University of Sydney, Sydney, NSW, Australia

[34] Physical Activity Laboratory, Baker Heart & Diabetes Institute, Melbourne, VIC, Australia

[35] School of Health Sciences, Swinburne University of Technology, Melbourne, VIC, Australia

[36] Department of Sport, Exercise and Health, University of Basel, Basel, Switzerland

[37] Institute for Systems Medicine (ISM), MSH Medical School Hamburg, Hamburg, Germany

[38] G-Lab, Faculty of Applied Sport Sciences and Personality, BSP Business and Law School, Berlin, Germany