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Opinion

A neurobiological taxonomy of sedentary behavior for brain health

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Growing evidence documents that the influence of sedentary behaviors on brain health is not universally beneficial or detrimental but rather context-dependent and nuanced. More specifically, recent findings suggest that mentally active sedentary behavior, such as video gaming, may benefit brain health, whereas mentally passive sedentary behavior, such as television viewing, may not convey such benefits. However, traditional classification approaches do not fully recognize the importance of content relevance. In this opinion article, we propose a neurobiological, dual-axis framework combining mental activation and content relevance to distinguish effects of specific sedentary behavior types on brain health-related outcomes. This refined sedentary behavior taxonomy may open novel perspectives to clarify mechanisms and the roles of key moderators (e.g., age and life context) in future brain health research for enhanced public health strategies and more personalized lifestyle recommendations.

Highlights

There is a growing interest in understanding the influence of sedentary behavior on brain health, especially of moderators such as its dosage.

A dual-axis model, including mental engagement and relevance as dimensions, is proposed to improve the differentiation between types of sedentary behavior, allowing determination of the dosage with higher precision.

Neurobiological evidence supporting the proposed differentiation of sedentary behavior types is discussed, and future research avenues are mapped.

Opinion

Sedentary behavior and brain health

'Sedentary behavior' refers to any awake behavior in a sitting, reclining, or lying posture with an energy expenditure of <1.5 metabolic equivalents [1], and it has become an integral part of modern daily life in industrialized societies [2]. It is typically characterized by widespread use of screen-based devices (e.g., smartphones and television) and has recently garnered growing research interest, especially concerning its influence on brain health [3,4]. Systematic reviews further reveal that specific sedentary behavior types (e.g., television viewing) are associated with poorer cognitive performance – a critical brain health marker – in both children [5] and older adults [6]. Notably, the common assumption that all sedentary behavior types are detrimental to brain health has been challenged by recent studies emphasizing the moderating role of mental activation, referring to the extent to which a given sedentary behavior engages specific cognitive processes [3,4]. This distinction, commonly captured as 'mentally active' (i.e., synonymous with cognitively active) and 'mentally passive' (i.e., synonymous with cognitively passive) sedentary behavior, reflects the level of cognitive resources required to conduct a specific type of sedentary activity or task [4]. Indeed, emerging evidence supports the notion that mentally active sedentary behavior (e.g., reading) tends to be positively associated with behavioral outcomes of brain health, including cognitive performance [7,8], whereas mentally passive sedentary behavior (e.g., television viewing) may not confer such benefits and may even elevate the risk for disorders (e.g., dementia) [8,9].

While the moderating role of mental activation has been increasingly recognized, the dimension of relevance [10–12], as considered in frameworks related to physical activity, has received relatively

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little attention in the context of sedentary behavior research. If mental activation captures the quantity of cognitive resources engaged during sedentary behavior, then a critical missing piece concerns the quality and direction of that engagement. We propose that the content of a specific type of sedentary behavior – particularly, its relevance to the cognitive domain of interest – plays a vital role in determining its brain health-related effects. In this context, in alignment with a taxonomy proposed for physical activity [10,11], 'relevance' is defined as the degree to which a specific type of sedentary behavior requires the same cognitive processes or targets the same functional systems as the desired outcome (e.g., math reasoning, verbal fluency, memory retention), drawing on well-established principles in cognitive psychology and transfer of learning (Box 1) [13,14].

To bridge this gap, this opinion article aims to introduce a new taxonomy of sedentary behavior, which is rooted in neurobiology and also relevant to public health concerns. We first present a dual-axis framework that classifies sedentary behavior according to (i) the degree of mental activation and (ii) the content relevance to specific cognitive outcomes. Next, we summarize the existing evidence on associations between sedentary behavior types and brain health and critically discuss how this taxonomy aligns with neurobiological evidence, considering different levels of analysis. Finally, we delineate a research roadmap and methodological considerations for investigating different types of sedentary behavior through the lens of the proposed taxonomy.

A nuanced taxonomy of sedentary behavior type

The proposed dual-axis taxonomy (Figure 1) crosses mental activation (high/low) with content relevance (high/low) to a specified cognitive outcome. In the following examples, to illustrate each category, we focus on mathematical reasoning skill: (i) active and relevant: completing arithmetic or algebra problems while seated, directly exercising mathematical reasoning; (ii) passive and relevant: listening to a teacher's worked example without performing calculations, which provides exposure to target content but with limited cognitive involvement; (iii) active and low relevance: playing Sudoku, which engages logic and working memory but does not train advanced mathematical procedures; and (iv) passive and low relevance: watching an entertainment television program that requires little cognitive effort and is unrelated to mathematics.

Neurobiological mechanisms of the effects of mental activation on brain health outcomes

We propose that, comparable to physical activity research [15,16], the neurobiological mechanisms underlying the associations between different types of sedentary behavior and brain

Box 1. Transfer theory in sedentary behavior research

Cognition is not a unitary construct; it comprises multiple components such as attention, memory, and executive function [74,80]. Considerable variability in cognitive outcomes has been observed even among sedentary behaviors that qualify as 'mentally active,' which aligns with the broader principle in cognitive neuroscience that improvements tend to be domain-specific, with cognitive benefits often constrained to the trained functions [81–83]. Meta-analyses examining the impact of a variety of mentally active sedentary behaviors (e.g., chess, music, different types of purposefully designed cognitive training platforms, certain types of video games) tend to show that the largest impacts of training are on tasks that are similar to the trained tasks or use similar cognitive functions (i.e., 'near transfer'), while transfer that is further away from the trained tasks is more difficult to produce [84–86]. For example, a meta-analysis focused on executive and working memory training observed large positive benefits of training on performance on nearby cognitive tasks (e.g., if individuals were training on the N-Back working memory task, then the Operation Span working memory task would be a near-transfer task) but much smaller effects on tasks that were less similar (e.g., if training involved a working memory task, a reasoning task would be a far transfer) [84]. Even among sedentary behaviors that appear to produce broader benefits, the magnitude of the benefits still appears to be a function of the extent to which the cognitive functions are tapped by the experience. For instance, meta-analyses have shown that training with highly complex action video games (i.e., first- and third-person shooter video games) produces larger improvements in perceptual, attentional, and multitasking skills (high demands in such games) than verbal skills (low demands in such games) [84].

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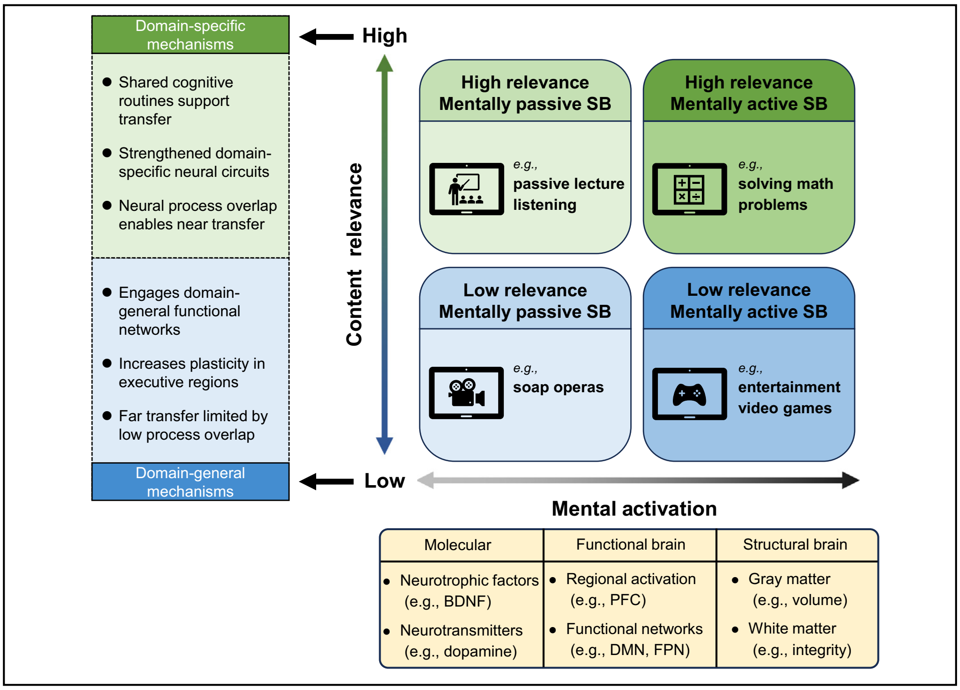

Figure 1. A refined taxonomy of different types of sedentary behavior, classifying activities along two axes: mental activation (low to high) and content relevance (low to high). The gradient reflects that many behaviors exist on a spectrum rather than in discrete categories. The schematic illustration uses screen-based sedentary behaviors as an example. In this context, the following are worth noting. (i) We hypothesize that mentally active sedentary behavior with low relevance may still confer benefits; however, these benefits will tend to be smaller than directly training the cognitive domains of interest. For example, training of general cognitive abilities (e.g., core executive functions – 'lower' in the order in relation to relevance) may produce less benefits for math performance than directly training mathematics abilities (i.e., domain-specific skill [14]). (ii) The classification features (e.g., mentally passive versus active or low versus high relevance) are a continuum rather than binary classifiers. (iii) A more fine-grained differentiation can be achieved by also considering dimensions that contribute to the level of mental activation during sedentary behavior. Such dimensions (similarly developed for physical activity) may include level of choice (e.g., volitional or enforced activities; task demands, determined by elements such as novelty or variation in difficulty and social engagement, related to social interaction), the context in which sedentary behaviors occur (e.g., in the context of transportation, occupation, or leisure time), and the media used during sedentary behavior (e.g., non-screen-based or screen-based sedentary behavior). This perspective extends traditional cognitive training principles into ecologically valid, real-world sedentary activities, offering a unifying lens for both intervention science and lifestyle research [10,11]. Abbreviations: BDNF, brain-derived neurotrophic factor; DMN, default mode network; FPN, frontoparietal network; PFC, prefrontal cortex; SB, sedentary behavior.

health-related outcomes should be elucidated using a multilevel analytical approach, with assessments of changes on (i) molecular and cellular level [e.g., blood-based markers such as brain-derived neurotrophic factor (BDNF); see Box 2] and (ii) brain function [e.g., using functional near-IR spectroscopy [fNIRS] or electroencephalography (EEG)] and brain structure [e.g., using magnetic resonance imaging (MRI)]. Furthermore, changes in functional and structural brain patterns dovetail with theories of brain reserve (a structural buffer), brain maintenance (a slower trajectory of decline), and cognitive reserve (flexible network reallocation) [17]. Thus, engaging in mentally active sedentary behavior across the lifespan may build reserve early and support maintenance later [18].

Evidence from functional neuroimaging

At the level of functional brain changes, neuroimaging techniques such as functional MRI (fMRI), fNIRS, and EEG can be used to (i) quantify the level of mental activation provided by different

Box 2. Molecular pathways linking mental activation to neuroplasticity

One of the most well-characterized neuromodulators linking lifestyle factors to synaptic and neural network plasticity is brain-derived neurotrophic factor (BDNF), a protein that is upregulated in response to physical activity [87–90]. It has also been used increasingly in sedentary behavior research [91,92]. For example, a cross-sectional study in 250 adolescents with obesity found that higher total screen time, as mentally passive sedentary behavior, was associated with lower serum BDNF levels, specifically driven by television viewing rather than video games or computer use [92]. Such results are partially supported by previous intervention studies indicating that mentally active sedentary behavior, including cognitive training, can elevate BDNF levels in diverse populations [93–97]. For example, healthy older adults who completed 5-week computerized cognitive training showed a significant increase in serum BDNF levels, while participants in duration-matched physical exercise or mindfulness interventions did not exhibit such changes in this biomarker [93]. Similarly, 25 sessions of 40-min seated cognitive training significantly increased BDNF levels of older adults, which, in turn, mediated improvements in processing speed [97]. In another study, 44 older women with mild cognitive impairment were assigned participants in computer-based cognitive training, physical exercise, a combination of both, or a nonactive control group, three times per week for 8 weeks [95]. Compared with the control group, only the computer-based cognitive training group exhibited significant improvements in both working memory and processing speed, alongside a significant increase in BDNF levels, with BDNF changes significantly correlating with processing speed gains [95].

In addition to neurotrophins, dopaminergic signaling represents a key molecular mechanism through which physical activity [98] and thus potentially also different types of sedentary behavior may differentially influence brain health [99,100]. Evidence from intervention studies indicates that mentally active tasks performed in a seated position can elicit significant changes in dopamine transmission [101]. Another study using positron emission tomography to operationalize changes in the dopaminergic system showed that playing a 50-min video game increased dopamine level in the ventral striatum, which was correlated with cognitive performance improvements [102]. Furthermore, 5 weeks of seated working memory training enhanced dopamine release in the caudate nucleus and cognitive performance during high-load cognitive tasks [103]. These findings support the notion that dopaminergic modulation is not limited to physical activity [98] but can also be triggered by mentally active sedentary behavior [104]. Not all sedentary behaviors are neurobiologically equal, and those involving higher cognitive engagement may initiate adaptive molecular processes critical for brain health.

types of sedentary behavior (see Box 3) and (ii) investigate their influence on resting-state or task-based brain activation patterns. For example, a cross-sectional resting-state fMRI study in children examined how time spent on different types of sedentary behavior predicted functional connectivity from the visual word form area (VWFA), a key region for reading acquisition [19]. More time spent on mentally active sedentary behavior (i.e., book reading) was associated with

Box 3. Quantifying the level of mental activation during sedentary behavior

A growing, albeit limited, number of neuroimaging studies showed fundamentally distinct underlying patterns of functional brain activation patterns between different types of sedentary behavior [105–107]. For example, a within-subject fNIRS study involving 28 preschoolers (aged 3–6 years) compared brain activation during two sedentary tasks: (i) a live book-reading session and (ii) a screen-based story condition [106]. In the book-reading condition, an experimenter read aloud while the child viewed a physical book; in the screen condition, children listened to an audio narration while viewing images and text on a screen. Results indicated that significant activation in the right temporal parietal junction was only present during the book-reading condition. Furthermore, the inferior and middle frontal gyri, the superior and middle temporal gyri, and the temporal parietal junction brain responses during the book-reading condition were greater in right-lateralized regions than left-lateralized regions, while brain responses during the screen time condition were similar across left and right brain regions of interest [106].

In addition, another within-subject fNIRS study, comparing the neural signatures of different types of mentally active (i.e., gaming and social media use) and mentally passive sedentary behavior (i.e., television viewing) in a sample of 27 younger healthy adults observed the largest dorsolateral prefrontal cortex activation in the social media use condition, followed by gaming, with considerably less activation in this brain region crucial for executive and attentional control during the television viewing condition [107]. These observations imply that the cognitive demands of different types of sedentary behavior are paralleled by differences in brain activation patterns of mentally passive and active sedentary behavior. In particular, mentally active sedentary behaviors are metabolically demanding, requiring a greater localized increase in cerebral glucose use and blood flow – a phenomenon known as 'neurovascular coupling' [105,108]. For example, studies have shown increased aerobic glycolysis and glucose use within executive and attentional regions during complex cognitive processing [109,110], whereas passive sedentary behavior, such as television viewing or mind-wandering states, characterized by relatively low cognitive engagement, is associated with a lower metabolic activity within these task-positive networks and instead is accompanied by elevated metabolic activity within DMN regions [110]. Over prolonged periods, this pattern of reduced metabolic engagement and inefficient energy allocation may lead to underuse of networks critical for cognitive control and executive function, potentially explaining cognitive decline associated with passive sedentary lifestyles [111].

increased VWFA connectivity to language-related cortices (e.g., left Brodmann areas [BAs] 40, 42, 43, and 22), visual association areas (e.g., bilateral BA 19), and executive control hubs (e.g., left BAs 7 and 44), whereas more time spent on mentally passive sedentary behavior (i.e., screen exposure) correlated with reduced integration between the VWFA and both language (e.g., bilateral BAs 39 and 20) and control regions (e.g., BAs 24, 13, 25, and 47) [19]. In other cross-sectional fMRI studies among adults aged 18–50 years, mentally active sedentary behavior (e.g., arithmetic problem-solving, working memory challenges, or logic reasoning) was consistently associated with a pronounced activation of frontoparietal areas, including the dorsolateral prefrontal cortex, intraparietal sulcus, and anterior cingulate cortex [20], which was accompanied by concurrent suppression of the default mode network (DMN) [21]. Conversely, mentally passive sedentary behavior, such as eyes-open rest, television viewing, or passive listening, was associated with sustained DMN dominance and reduced task-positive network recruitment [22,23].

More robust evidence comes from a randomized controlled trial conducted among children aged 8–11 years, who were assigned either to a working memory training group, receiving 20 sessions of home-based computerized working memory exercises with increasing task difficulty, or to an active control group that completed a nonadaptive version of the same program [24]. Only the intervention group showed significant improvements in working memory performance, and these gains were significantly correlated with increases in resting-state functional connectivity (measured via magnetoencephalography) between the bilateral frontoparietal network and both the left superior parietal lobule and the left inferior temporal cortex [24].

Evidence from structural neuroimaging

Numerous neuroimaging studies demonstrate that different types of sedentary behavior are associated with distinct trajectories of structural brain development, particularly during sensitive periods, referring to specific developmental stages that are marked by heightened neuroplasticity, in which the brain is sensitive to specific experiences or environmental stimuli [25]. In early youth, for example, a cross-sectional analysis of 8125 adolescents from the ABCD cohort compared reading and television viewing, revealing how their distinct cognitive demands differentially associated with cognitive performance and cortical development [26]. Findings revealed opposing effects: more time spent on mentally active sedentary behavior was significantly associated with better performance in all cognitive tests and greater cortical surface area across dorsolateral and inferior frontal lobes, bilateral temporal lobes, and cingulate gyrus. Conversely, more time spent on mentally passive sedentary behavior was significantly associated with diminished cognitive performance and thinner cortical thickness, most prominently in the lateral temporal cortex, temporoparietal junction, and orbitofrontal cortex [26]. Such results are partially supported by neuroimaging evidence on mentally stimulating screen-based behaviors such as video gaming, particularly those involving problem-solving that have been shown to exert beneficial effects on brain structure and cognitive performance in healthy young adults [27,28].

Notably, the direction of structural changes is not always consistent across studies or developmental periods. For example, in a longitudinal cohort study of Japanese youth (aged 6–18 years at baseline), longer duration of mentally passive sedentary behavior (i.e., television viewing) was associated with greater regional gray matter volume (e.g., the frontopolar cortex and visual cortices) at follow-up approximately 3 years later [29]. Crucially, the increased regional gray matter volume in the frontopolar region was negatively associated with verbal intelligence quotient, which possibly reflects a detrimental rather than beneficial brain development [29]. This interpretation is supported by evidence suggesting that a cortical thinning of the frontopolar cortex is typically observed during development [30,31] and that greater regional gray matter volume in this region is associated with lower cognitive performance across children, adolescents, and younger adults [32]. Additionally, in a recent longitudinal analysis of over 18 000 middle-aged to older adults, mentally passive sedentary behavior (i.e., greater daily television viewing) was significantly associated with increased risk of incident dementia and declined neurite density (indexed by intracellular volume fraction) across bilateral temporal, fusiform, insular, and frontal regions, even after adjusting for physical activity and other lifestyle factors (e.g., sleep duration) [33]. Unlike the cortical surface area reductions observed in youths, the intracellular volume fraction declines seen in older adults are likely to represent ongoing neurite degeneration and synaptic loss [34,35], characteristic of age-related neurodegenerative trajectories and lower brain health [36]. Thus, engaging in a moderate level of mentally active sedentary behavior may benefit the brain health of older adults. For example, a systematic review of 22 neuroimaging studies [37] indicated that video game training interventions, particularly with 3D platforms and cognitively demanding genres, frequently resulted in increased gray matter volume in the hippocampus and prefrontal cortex in older adults. These structural changes were often paralleled by cognitive improvements, most consistently in the domains of visuospatial processing and attentional control [37].

Neurobiological mechanisms underlying the effects of content relevance on brain health outcomes

Mental activation level alone is insufficient to fully account for the observed variability in brain health-related outcomes, especially those related to brain structure (e.g., differences related to content or cognitive strategy [37,38]). For instance, longitudinal experiments demonstrated that action video game training, as mentally active sedentary behavior, significantly reduced hippocampal gray matter in individuals using response-based strategies but increased it in those adopting spatial strategies [39]. These two strategies reflect distinct cognitive modes: response learners rely on fixed stimulus–response sequences (e.g., 'turn right after two steps'), engaging habit-based procedural systems primarily involving the striatum; spatial learners, by contrast, construct cognitive maps based on environmental cues and landmarks, a process heavily dependent on the hippocampus [39]. Beyond strategy differences within the same game, genre also matters, with 3D platform games being associated with significant growth in the hippocampus and entorhinal cortex across learners [39]. These findings demonstrate that both strategy and genre modulate neural plasticity, underscoring that content determines which neural circuits are engaged. This interpretation is consistent with evidence that the brain comprises domain-specific representational systems (e.g., supramarginal and angular gyri for phonological or semantic information) alongside domain-general control networks (e.g., prefrontal and parietal cortices) that flexibly coordinate processing [40–42]. Thus, whether mentally active sedentary behavior yields adaptive or maladaptive brain changes critically depends on the relevance of its content – namely, whether the cognitive operations required by the activity overlap with those that support the targeted outcomes.

Building on evidence from domain-specific systems (e.g., working memory), a broader body of developmental neuroscience research also supports the notion that the brain's plastic responses to cognitive engagement are strongly modulated by the type of information and skills involved [43]. A systematic review of 71 neuroimaging studies in youths revealed that training-induced plasticity is highly content-sensitive, with different types of tasks (e.g., cognitive and academic interventions) producing distinct neural changes across regions and MRI modalities [43]. This architectural division between specialized representational areas and shared control systems reinforces the notion that the brain organizes cognition around both content-specific and cross-domain demands. In this light, content relevance, the degree to which a sedentary activity engages neural systems that are functionally and anatomically aligned with the cognitive domain being targeted, emerges as a critical determinant of brain activation patterns and plasticity.

Another compelling area of evidence supporting the importance of content relevance comes from studies on cognitive transfer (see Box 1). If a specific type of sedentary behavior meaningfully enhances cognitive function, such benefits should generalize beyond the trained task, but only when the neural systems recruited during training overlap with those required by the target outcome [44,45]. For instance, an experimental study demonstrated that transfer from working memory training to an untrained three-back task occurred only when both tasks recruited the same striatal region, whereas no transfer occurred when this neural overlap was absent [46]. Near transfer occurs with high content overlap (e.g., memory tasks), whereas far transfer to reasoning is rare without shared processes. Although computational models of working memory posit shared, domain-general neural resources, the translation of these mechanisms into real-world improvements appears largely domain-specific [42]. Transfer is not automatic; rather, it requires the development of new cognitive routines that are tightly coupled to the functional demands of the trained task. This shift from regional overlap to procedural compatibility further reinforces our argument that content relevance is about not merely neural coactivation but functionally meaningful engagement with the systems required for future performance. In the context of sedentary behavior, this implies that only when the cognitive content of an activity trains the same systems involved in the target domain can meaningful, transferable gains occur. Thus, the taxonomy's relevance axis predicts brain integrity–related and cognitive benefits based on functional alignment.

Research roadmap and methodological considerations for the dual-axis taxonomy

Standardizing mental activation and content relevance

The current classification of mental activation and content relevance in sedentary behavior research is often based on subjective judgment, limiting comparability across studies [47]. To empirically advance the dual-axis framework proposed in this article, it is imperative to develop psychometrically validated tools for quantifying the mental activation of sedentary behaviors, especially given the limitations of current classification approaches. Notably, supraordinate categories of different types of sedentary behavior – such as 'video game play' – are insufficiently precise to allow classification into an appropriate quadrant [48]. For instance, there is strong evidence that variety is key in keeping mental activation high and engendering broad generalization of learning [49] (e.g., by reducing the extent to which performance is automated and thus no longer demanding). As such, a serious mathematics game may very well be mentally passive if there is insufficient variety to keep mental activity high in a sustained manner through time. Similarly, entertainment-based video games can be either mentally active or mentally passive, depending on whether they are designed with sufficient variety to keep high loads on cognition through time [50,51].

The challenges to assess the level of cognitive engagement of a specific sedentary behavior type with high precision are exacerbated by the nature of emerging sedentary behavior types (e.g., smartphone and social media use), which are often characterized by rapidly fluctuating patterns of cognitive engagement due to its relation to complex, algorithm-driven streams of social and emotional content [52]. Such features not only obscure the boundaries between passive and active cognitive engagement but also require assessment tools that can dynamically capture both the temporal fragmentation of attention and the multidimensional affective and social interactions inherent to these activities. Thus, rating scales should be developed to assess cognitive features (e.g., attentional demand, task novelty) that can be applied to both real-world and experimental tasks associated with common types of sedentary behavior and that can be complemented with objective neurobiological markers (e.g., pupil dilation, brain activation) to ensure construct validity [53–55]. These measures could be further supplemented by context-sensitive methods such as ecological momentary assessment to enhance ecological validity [56].

Recent work has demonstrated that neuroimaging methods can be used to objectively assess mental activation during different types of sedentary behavior. For example, convolutional neural networks trained on fNIRS signals have successfully classified mental workload levels based on prefrontal activity, supporting the feasibility of automated and scalable mental activation level detection [57]. Similarly, EEG-based time-frequency analysis combined with a bidirectional long short-term memory classifier demonstrates its robustness as an objective indicator of mental activation, achieving high accuracy when distinguishing levels of cognitive load during short mental arithmetic tasks [58].

Additionally, the relevance of an activity's content to a targeted cognitive domain is often assumed rather than measured. For example, video gaming might be labeled as irrelevant for academic achievement without considering whether the game involves logical reasoning, memory updating, or language processing [27]. Thus, researchers should develop coding systems that map the cognitive demands of a task onto specific outcome domains (e.g., language, math, memory), informed by cognitive task analysis or neural overlap models derived from meta-analytic databases [59]. Combining expert ratings and/or participant descriptions, behavioral performance correlations, and neuroimaging evidence would allow more precise classification of different types of sedentary behavior in terms of their likely influence on specific measures of brain health.

Experimental and study design considerations

Most evidence supporting the dual-axis taxonomy comes from observational research, including both cross-sectional and longitudinal designs [60]. Large-scale cohorts such as the UK Biobank and ABCD studies have provided valuable insights into long-term patterns and potential temporal relationships between sedentary behavior and brain health (e.g., risk trajectories for neurodegenerative diseases) [26,33]. However, without experimental manipulation, these studies cannot directly test causal effects or determine how such effects vary across behavioral or contextual conditions. Notably, randomized controlled trials in this domain remain rare, largely due to ethical and practical constraints: deliberately increasing sedentary behavior over extended periods poses potential health risks, rendering such interventions less feasible than those that promote physical activity [61]. As a result, the majority of intervention studies have prioritized reducing sedentary time, typically employing strategies such as interrupting prolonged sitting [62]. However, this focus on total sedentary time overlooks the potential differential effects of specific sedentary behavior types. To advance the field, future research should aim not only to reduce sedentary time but also to systematically manipulate the content of sedentary activities. For example, interventions could manipulate the content of sedentary behavior by assigning participants to mentally active behaviors (e.g., reading) or passive behaviors (e.g., screen viewing) during sedentary episodes and then comparing their cognitive and neurobiological outcomes.

Building on these advances in behavioral tracking and experimental design, it would become possible to model sedentary behavior in a more nuanced, multidimensional manner. This need is underscored by the fact that, even when sedentary activities are mentally active, prolonged uninterrupted sitting can reduce cerebral blood flow and may accelerate cortical thinning [63,64]. Compared with the well-established use of specific variables to describe the dosage characteristics of physical activity (i.e., frequency, intensity, time, and type, also known as the 'FITT principle') as well as relevant extensions of these variables (e.g., density) [65,66], the application of such variables to quantify the dose and dosage characteristics of sedentary behavior remains limited [67]. Most studies investigating the influence of sedentary behaviors on brain health have relied solely on total daily time spent on sedentary behaviors as the primary exposure variable [5,6], overlooking other key parameters that may meaningfully moderate the association between sedentary behaviors and brain health. However, recent findings suggest that not only the quantity but also the temporal distribution of that sedentary behavior matters [68]. Three critical dose-related dimensions are emerging as especially relevant to gain a more comprehensive understanding of the influence of different types of sedentary behavior on brain health, namely (i) the frequency of sedentary episodes throughout the day, (ii) the total accumulated sedentary time per day, and (iii) the average or maximum duration of uninterrupted sedentary bouts [68]. These parameters may have distinct effects on neurobiological processes related to brain health. For example, prolonged uninterrupted sedentary bouts have been linked to suppressed cerebrovascular function, independent of total sedentary time, whereas physical activity breaks during prolonged sitting may attenuate these effects [54].

Equally important, the influence of mentally active sedentary behavior on brain health may follow nonlinear dose–response patterns. In a cross-sectional study, daily reading (i.e., up to 4 h) was positively associated with cognitive performance, but no additional benefit was observed beyond this point [26]. These findings raise critical questions about whether there are lower and upper limits to the benefits of mentally active sedentary behavior and whether prolonged engagement in mentally active sedentary behavior may diminish or even reverse the positive effects. Evidence has shown that accumulating time spent on mentally active sedentary behavior may result in mental fatigue and/or reduce the time that can be spent on other activities important for brain health, such as physical activity or sleep [69,70]. Similarly, cognitive performance, especially cognitive flexibility and social cognition, improved with moderate video gaming in youths but began to decline when daily or weekly playtime exceeded 4 h [71] or 17–20 h [72], respectively. These diminishing returns may be attributed partly to the adverse impact of problematic gaming on sleep, because meta-analytic evidence has linked excessive gaming to shorter sleep duration, lower sleep quality, and greater daytime sleepiness [73]. Future research should move toward modeling sedentary dose in a multidimensional fashion, incorporating factors related not only to quantity but also to timing and distribution of sedentary behavior, and explicitly test for nonlinear and interaction effects between parameters determining the dose of specific types of sedentary behavior and brain health-related outcomes.

Developmental and sociocultural moderators of sedentary behavior effects

The associations between different types of sedentary behavior and specific brain health-related outcomes can be influenced by a range of developmental and sociocultural factors [3]. Among those factors, age remains a fundamental moderator, because different life stages are characterized by distinct patterns of brain development, behavioral needs, and environmental constraints, all of which influence the type, content, and function of sedentary behaviors [3]. For example, childhood and adolescence are characterized by rapid neurodevelopment, particularly in executive control, memory, and attentional systems [74,75]. During different life stages, the engagement in different types of sedentary behavior can change tremendously. Particularly, while in early periods of life individuals typically engage in high amounts of mentally active sedentary behavior (i.e., in the context of formal education), in late adulthood the amount of mentally passive sedentary behavior (e.g., television viewing) often increases [76]. Furthermore, sedentary behaviors that are both mentally active and content-relevant [e.g., academic tasks or strategic (nonviolent) games] may yield greater developmental gains in younger populations with heightened levels of neural plasticity [77]. However, there is likely to be a sweet spot in younger years, especially when there are high baseline exposures (e.g., formal education) to such activities in education settings, so that additional after-school tutoring classes may yield diminishing returns because they may increase cognitive load and mental fatigue related to academic burnout [78]. Moreover, emerging evidence suggests that the impacts of sedentary behaviors can be moderated not only by age but also by sociocultural factors, including ethnicity, socioeconomic status, and cultural context [26,79]. Collectively, these findings highlight the necessity of considering both developmental and sociocultural moderators when evaluating the effects of sedentary behaviors to avoid overgeneralization, ensuring that interventions are equitable and broadly applicable. Future studies should test the framework across varied ages, cultures, and health conditions to strengthen generalizability.

Concluding remarks

In this opinion article, we aimed to (i) critically examine the relevant concepts and current state of evidence concerning different types of sedentary behavior and its associations with brain health outcomes; (ii) introduce a novel, more fine-grained taxonomy for differentiating types of sedentary behavior based on the levels of mental activation and relevance; and (iii) propose an approach for examining the underlying neurobiological mechanisms and factors linking different types of sedentary behavior to brain health. Additionally, we provide methodological recommendations concerning their assessment and highlight the importance of both longitudinal studies and ethically optimized randomized controlled trials to clarify long-term effects and causal relationships. We hope that future research avenues yield a more nuanced understanding of how specific types of sedentary behavior influence aspects of brain health (see Outstanding questions). Further investigation is a key prerequisite to refining and personalizing lifestyle guidelines by providing evidence-based and tailored advice for different age groups.

Outstanding questions

Does the cognitive benefit of mentally active sedentary behavior follow a dose–response relationship, and is there a threshold beyond which additional time spent on such activities ceases to provide benefits?

How does the impact of sedentary behavior on brain health vary across different life stages, such as childhood versus late adulthood?

How can researchers objectively and reliably quantify the 'mental activation' and 'content relevance' of real-world sedentary behaviors, and what tools or biomarkers are needed to standardize these classifications across studies?

What are the specific neural circuits and molecular pathways that differentiate the effects of mentally active versus passive sedentary behaviors, and how do these interact with individual differences such as genetic risk or baseline cognitive capacity?

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Declaration of interests

D.R. and G.E.A. are coinventors on a patent application for a method to predict disease risk using physical activity measures. The other authors declare no competing interests.

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