HHS Public Access
Author manuscript
Psychol Aging. Author manuscript; available in PMC 2021 December 01.

Published in final edited form as:
Psychol Aging. 2020 December ; 35(8): 1154–1169. doi:10.1037/pag0000580.

Sensor-measured sedentariness and physical activity are differentially related to fluid and crystallized abilities in aging

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Abstract

Aerobic exercise and physical activity (PA) are known to benefit cognition in adulthood. However, a typical older adult spends most of the day sedentary or in light PA, behaviors that are typically poorly captured by questionnaires. To better understand the associations between time spent in different intensities of lifestyle PA and cognition, we measured average time spent daily in sedentariness, light, and moderate to vigorous PA using hip-worn sensors (Actigraph accelerometers). We studied baseline data from 228 cognitively normal adults (age 60–80) who took part in a clinical trial (NCT01472744). Fluid (processing speed, memory, and reasoning) and crystallized abilities (vocabulary knowledge) were assessed with the Virginia Cognitive Aging Battery. Adjusting for age, sex, and several modifiable socioeconomic, physical and functional health factors, time spent daily in moderate to vigorous PA was positively related with fluid abilities (perceptual speed and reasoning). Furthermore, we found that those spending more time

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The authors declare no competing financial interests.

sedentary performed better on vocabulary knowledge and reasoning tasks. In contrast, time spent in light PA was not related to either fluid or crystallized abilities. Our results add to the previous literature by providing the first sensor-based evidence that crystallized and fluid abilities in older age may be associated with engagement in different intensities of daily activity. Moreover, our findings suggest that the behavior of moderate to vigorous PA is at least as important in relation to cognition as the desirable long-term physiological effects of higher-intensity PA and exercise.

Keywords

sedentariness; physical activity; cognition; cardiorespiratory fitness; aging

Normative adult cognitive development is bidirectional (Baltes, 1987): it includes age-related declines in general *fluid abilities* and gains in *crystallized abilities* (Baltes et al., 1999; Cattell, 1971; Wolman & Stricker, 1982). Fluid abilities, which include reasoning and problem solving and are associated with processing speed, executive functioning, and memory (Baltes, 1993; Salthouse et al., 2003; Schretlen et al., 2000) deteriorate in older age (Hedden & Gabrieli, 2004). On the other hand, crystallized abilities, often represented by verbal knowledge, accumulate as a result of life experience and are preserved or improve until older age (Horn, 1982; Horn & Cattell, 1967; Horn & Hofer, 1992; Singh-Manoux et al., 2012).

Importantly, the cognitive aging process is malleable within and variable across persons (Hertzog et al., 2009), partly due to lifestyle choices people make throughout their lives (Lindenberger, 2014). For example, physical activity (PA), intellectual, and social engagement may help maximize cognitive function and mitigate losses (Hertzog et al., 2009). On one hand, PA, in particular, exercise, is related to better fluid abilities in older age such as speed, executive function and working memory (Hillman et al., 2008; Kramer et al., 1999; Voss, Erickson, et al., 2013). This is thought to occur via a variety of physiological and neuronal mechanisms, such as upregulation of neurotrophic factors, cardiorespiratory fitness, and decreased risk of hypertension (Bherer et al., 2013; Voss et al., 2014). On the other hand, most social and cognitive activities known as proxies of cognitive reserve associated with better cognitive function in older age are sedentary (Clare et al., 2017; Stern, 2009; Stern et al., 1994, 2018), such as structured education (Guerra-Carrillo et al., 2017), cognitively stimulating occupational work (Bonsang et al., 2012; Rohwedder & Willis, 2010), and cognitively stimulating leisure activities such as reading, solving riddles or playing games (Hertzog et al., 2008). Yet, excessive sedentariness has negative impacts on general health (Tremblay et al., 2010) and evidence is emerging for its negative associations with cognitive and brain health (Burzynska et al., 2014; Falck et al., 2017; Voss et al., 2014). Furthermore, there is increasing recognition for the general (Varma, Tan, et al., 2014) and brain health benefits of light PA (specifically, low-intensity walking) in older age (Varma, Chuang, et al., 2014). Therefore, the aim of the current study was to examine the still poorly understood associations between daily engagement in all levels of lifestyle PA, including sedentary behaviors, light, moderate, and vigorous PA, and cognition in cognitively healthy older adults.

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Most evidence relating PA to cognitive benefits in older age focuses on participation in exercise or moderate to vigorous PA. Exercise is defined as planned, structured, and repetitive PA with an objective of the improvement of physical fitness (Caspersen et al., 1985). This includes, for example, running, swimming, or participation in fitness classes (Bherer et al., 2013; Erickson & Kramer, 2009; Hillman et al., 2008). Moderate to vigorous PA is a broader term and includes both exercise as well as other high-intensity everyday life activities, such as walking or biking for transportation, climbing stairs, or strenuous housework. Moderate and vigorous PA involves elevated energy expenditure (3–6 and 6+ metabolic equivalents, respectively), and, therefore, is the most effective PA intensity to increase cardiorespiratory fitness (Helgerud et al., 2007). Exercise-induced increases in cardiorespiratory fitness have been proposed as a crucial factor underlying exercise-related benefits in fluid abilities (Clark et al., 1992; Colcombe et al., 2003, 2004; Colcombe & Kramer, 2003; Erickson et al., 2011; Hillman et al., 2008; Kramer et al., 1999; Pase et al., 2016; Raz & Daugherty, 2017; Voss, Erickson, et al., 2013; Voss, Vivar, et al., 2013). However, for most of the day, older adults engage in sedentary behaviors and light PA (Craft et al., 2012; Dunstan et al., 2012). Sedentary behavior is defined by a seated or reclined body posture and low energy expenditure (≤1.5 metabolic equivalents) and light PA includes low-intensity activities such as low-intensity walking, housework, or gardening (1.5–3 metabolic equivalents (Copeland et al., 2015; M. G. Davis et al., 2011; Rhodes et al., 2012). Therefore, given that most adults do not meet the minimum American College of Sports Medicine recommendations of engaging in moderate or vigorous PA, understanding how sedentary behavior and light PA relate to cognitive function is key for developing recommendations and interventions that will complement those focused on moderate to vigorous PA.

However, our understanding of the relationships between lifestyle PA and cognition is limited because the great majority of studies have relied on self-reports, daily activity logs or questionnaires, which have limited validity and reliability for measuring time spent in sedentary behavior and light PA or the time and intensity of typically short bouts of moderate to vigorous PA (Dogra et al., 2017; Rzewnicki et al., 2003; Sallis & Saelens, 2000; Shephard, 2003). Sensor-based tools, including accelerometers, provide more accurate estimates of sedentary behavior and light PA, which are hardest to capture with self-reports (De Carvalho Bastone et al., 2014; España-Romero et al., 2014; Gardiner et al., 2011; Gennuso et al., 2015; Healy et al., 2008; Jefferis et al., 2016; Pfister et al., 2017; Van Cauwenberg et al., 2014; Visser & Koster, 2013). For example, self-reported sedentariness (5.3 h/day) was shown to be significantly underestimated as compared with sensor-based sedentary behavior (9.4 h/day) in older populations (Heesch et al., 2018).

To date, few studies have investigated sensor-assessed PA in relation to cognition (gauging predominantly fluid abilities) in older adults. Among these, most studies focused on total PA (e.g., mean counts or steps/day) and found mostly positive associations with executive function (Barnes et al., 2008; Zeitzer et al., 2018), memory (Buchman et al., 2008; Hayes et al., 2015; Wilbur et al., 2012), greater maintenance of processing speed (Buchman et al., 2012), as well as general cognition (composite scores or short clinical assessments) (Barnes et al., 2008; Buchman et al., 2008), and reduced incidence of dementia. However, several studies reported no relationship between total PA and fluid abilities (memory,

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attention, speed) and crystallized abilities (verbal fluency) and general cognition (Brown et al., 2012; Halloway et al., 2017). To our knowledge, only ten studies have used sensors to measure levels of PA intensity in relation to cognition in cognitively normal older adults (Supplementary material I). Several studies reported positive associations between moderate to vigorous PA and fluid abilities such as visuospatial ability (Brown et al., 2012), memory (Wilbur et al., 2012; Zhu et al., 2017), executive function (Kerr et al., 2013; Zhu et al., 2017), general cognitive status (Stubbs et al., 2017), or crystallized ability measured as verbal fluency (Brown et al., 2012), but almost as many studies have reported non-significant associations with fluid abilities after adjusting for typical covariates such as age, sex, education, or BMI (Halloway et al., 2017, 2019; Iso-Markku et al., 2018; Johnson et al., 2016). Regarding sensor-measured light PA, several studies reported a positive association with fluid abilities including executive function (Johnson et al., 2016), perceptual speed (Kerr et al., 2013), semantic memory (Wilbur et al., 2012), general cognition (Iso-Markku et al., 2018), and cognitive status maintenance (Stubbs et al., 2017), but others found no associations (Halloway et al., 2017; Kerr et al., 2013; Zhu et al., 2017). Finally, more time spent sedentary correlated with poorer general cognition (Iso-Markku et al., 2018; Ku et al., 2017) and memory (Hayes et al., 2015), but others reported no associations with fluid abilities (Johnson et al., 2016; Zhu et al., 2017).

In sum, studies using sensors to differentiate levels of PA intensity in relation to cognition have yielded promising, yet inconsistent findings, which likely stem from differences in PA measurement and limited cognitive assessments (e.g., single tasks, short clinical assessments of cognitive status), insufficient to measure latent constructs or to contrast fluid and crystallized abilities (Supplementary material I). In addition, only age and sex have been consistently used as covariates, which is well justified by the age differences in cognition (Park et al., 2002), and age and sex differences in lifestyle PA (Bauman et al., 2012; Chodzko-Zajko et al., 2009; Hagströmer et al., 2007; Hansen et al., 2012; Hedden & Gabrieli, 2004; Janssen et al., 2016; Peters et al., 2010; Troiano et al., 2008). However, other modifiable health and socioeconomic factors need to be considered in exploring PA-cognition associations. For example, cardiorespiratory fitness is the desirable long-term benefit of engaging in moderate to vigorous PA, whereas excessive sedentariness and lack of PA are comorbid with cardiovascular and metabolic disorders such as hypertension, diabetes, and obesity (Ekelund et al., 2016; Ford et al., 1991), all of which are risk factors for cognitive decline in older age (Spiro & Brady, 2012). Furthermore, higher education and income have been associated with greater maintenance of cognitive function (Albert et al., 1995; Clare et al., 2017; Inouye et al., 1993; Stern, 2009; Stern et al., 1994) and PA engagement in older age (August & Sorkin, 2011; Birmingham et al., 1999; Bolen et al., 2000; Humphreys & Ruseski, 2006; Kari et al., 2015; Meltzer & Jena, 2010). Employment status among older adults is also important: transition to retirement is associated with declines in both PA (Feng et al., 2016) and cognitive functioning (Clouston & Denier, 2017). Finally, functional and physical health may influence the patterns of lifestyle PA (Gorman et al., 2014; Trost et al., 2002).

The current study was designed to revisit and extend previous findings linking lifestyle PA with cognition, using well-validated measures of fluid and crystallized cognitive abilities (Salthouse, 2004, 2010; Salthouse et al., 2004; Salthouse & Ferrer-Caja, 2003), sensor-

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measured lifestyle PA, and a comprehensive set of covariates, including, among others, cardiorespiratory fitness measured with gold-standard graded exercise test, cardiovascular risk history, blood pressure, income and education, and measures of functional fitness. We hypothesized that adults spending more time in moderate to vigorous PA would have better fluid abilities. At the same time, we predicted spending more time in sedentary behaviors would be negatively associated with fluid abilities but positively with crystallized abilities. We had less information to make a strong prediction regarding light PA, and so analyses for light PA are considered exploratory.

Method

Participants

The current study was conducted using the baseline data from a 6-month randomized controlled exercise trial (clinical study identifier NCT01472744). The study was approved by the University of Illinois institutional review board, written informed consent was obtained from all participants, and the study was performed in accordance with the 1964 Declaration of Helsinki. Healthy, low active older adults were recruited in Champaign county. Of the 1,119 participants recruited, 247 ($n = 169$ women) met inclusion criteria for the initial clinical trial, agreed to enroll in the study, and underwent a series of demographic, health, PA, neuroimaging, cognitive, and cardiorespiratory data collection at baseline. For more details on this clinical trial, its primary outcomes and neuroimaging data, refer to our earlier work (Baniqued et al., 2018; Burzynska et al., 2017; Ehlers et al., 2017; Fanning et al., 2017; Voss et al., 2019). Participants eligible to be enrolled in the initial clinical trial met the following criteria: (1) were between the ages of 60 and 80 years old, (2) were free from psychiatric and neurological illness and had no history of stroke, transient ischemic attack, or head trauma, (3) scored ≥ 23 on the Mini-Mental State Exam and >21 on a Telephone Interview of Cognitive Status questionnaire, (4) scored < 10 on the geriatric depression scale (GDS-15), (5) scored ≥ 75% right-handedness on the Edinburgh Handedness Questionnaire (a criterion related to functional MRI analyses), (6) demonstrated normal or corrected-to-normal vision of at least 20/40 and no color blindness, (7) were screened for safe participation in an MRI environment (e.g., no metallic implants that could interfere with the magnetic field or cause injury and no claustrophobia), and (8) reported to have participated in no more than two bouts of moderate exercise per week within the past 6-months. This last criterion was designed to target typically low-active older adults who do not exercise regularly and do not exceed the minimum recommendations of 150 moderate PA per week and, therefore, would benefit most from the aerobic exercise intervention. As previously reported (Voss et al., 2019), 33 participants of 247 reported taking anti-depressant medications; the majority (79%) of these participants were taking some form of a selective serotonin reuptake inhibitor and most others (12%) were taking drugs that block reuptake of norepinephrine and dopamine (e.g., bupropion). Finally, in addition to the general inclusion criteria, we applied a stricter cutoff regarding cognitive status (Mini-Mental State Exam score ≥ 26) for the analyses presented here to exclude the few participants with possible mild cognitive impairment. Table 1 defines our final sample with respect to age, sex, race, and ethnicity composition.

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Actigraphy

To reconcile previous findings with respect to measures of lifestyle PA, we used an ActiGraph device used in eight out of ten of the aforementioned studies using linking sensor-based PA measures to cognition (see Supplementary material I). Each participant was instructed to wear the accelerometer (Model GT1M or GT3X; ActiGraph, Pensacola, FL) on the non-dominant hip during waking hours for 7 consecutive days and record the time that they wore the device each day on a log. A valid measurement day consisted of at least 10 hours of valid wear-time, with a valid hour defined as no more than 60 consecutive minutes of zero counts with one-minute sampling epochs. Only data for individuals with a minimum of 3 valid days of wear time were included in analyses (Peterson et al., 2010; Troiano et al., 2008). These data were downloaded as activity counts, which represent raw accelerations that have been summed over a specific epoch length (e.g., 60s), and these counts vary based on frequency and intensity of the recorded acceleration (Fanning et al., 2017). Next, these data were processed using cut points designed specifically for older adults (Copeland & Esliger, 2009) such that 50 or fewer counts per minute corresponded with sedentary behavior, 51–1,040 counts per minute corresponded to light PA, and 1,041 counts or greater represented moderate to vigorous PA. All 234 participants had at least 3 days of valid PA data recording with on average 6.98±1.4 valid days of measurement (range 3–7). 90% of the sample (210 participants) had 6 or more valid days required to reliably measure sedentary behavior (Hart et al., 2011). Only 0.4% of the sample (9 participants) had less than 5 valid days of wear. The primary accelerometer-related variables were average daily time spent in sedentary behavior, light, and moderate to vigorous PA (Table 1). Wear time (total valid days) was used to examine the associations of wear time with sedentary behavior, light, and moderate to vigorous PA (Supplementary material III). Average daily counts (total counts/number of valid days) was used to report bivariate correlations for comparison with the existing literature (Supplementary material III). There were two outliers (>3SD) in moderate to vigorous PA and one in light PA and sedentary behavior, which were winsorized (i.e., assigned the highest number in the sample <3 SD). Our sample size was defined as the 228 out of 247 participants who had complete Actigraphy data.

Cognition: fluid and crystallized abilities

We administered a well-validated Virginia Cognitive Aging Project cognitive battery (Salthouse, 2004, 2010; Salthouse et al., 2004; Salthouse & Ferrer-Caja, 2003) consisting of 16 tasks that measure latent constructs of fluid abilities (reasoning, perceptual speed, episodic memory), and crystalized ability (vocabulary knowledge). The computer-based tasks were programmed in E-prime version 1.1 (Psychology Software Tools, Pittsburgh, PA) and administered on computers with 17″ cathode ray tube monitors. For more details on individual tasks and analysis see (Burzynska et al., 2015). First, to confirm validity of task structure as presented in (Salthouse, 2004), we performed factor analysis using principal component analysis with varimax rotation, with missing values replaced by sample mean. Next, we calculated standardized scores (z-scores) and winsorized values that were >3SD (two for digit symbol, letter comparison and WAIS vocabulary, three for pattern comparison, and one for form boards and picture vocabulary). Then, the z-scores were averaged according to the task groupings specified in Table 1, resulting in four component scores representing vocabulary knowledge, perceptual speed, memory and reasoning. Due to

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technical issues with saving computerized tasks, 30 participants had data for only one task within a construct of reasoning, therefore, the z-score of this task was used for the construct to maximize sample size. Note that the advantage of the current analyses was to measure latent constructs of perceptual speed, memory, reasoning, and vocabulary knowledge. For this reason, we did not include the two tasks measuring executive function (Task Switching) and working memory (Spatial Working Memory).

Modifiable socioeconomic and health factors

Socioeconomic factors included years of education and annual household income, which was dichotomized as <$40,000 and >40,000 to define low and high income in Illinois. Current cognitive activities were measured as participation in adult education (0: never participated, 1: took overall 1–2 classes, 2: took 3–5 classes, 3: took > 5 classes), employment status (dichotomized into those fully retired or unemployed 50%, n=114, and working full- or part-time), and comfort using a computer (as a proxy of time and skill, coded as 1: excellent, 2: very good, 3: good, 4: fair, 5: poor; Table 1).

We assessed cardiometabolic health with cardiorespiratory fitness, cardiovascular history score, body mass index, diabetes diagnosis, and mean arterial pressure (Table 2), namely, the main cardiometabolic diseases or risk factors comorbid with excessive sedentariness and lack of PA (Ekelund et al., 2016; Ford et al., 1991) and also linked to decreased cognitive performance in older age (Assuncao et al., 2018). Cardiorespiratory fitness was assessed as peak oxygen uptake (VO_{2peak}) during graded maximal exercise testing on a motor-driven treadmill. Participants received consent from their personal physician prior to cardiorespiratory fitness testing. Before the treadmill test, we collected resting systolic and diastolic blood pressure, body weight, and height. The protocol involves walking at a self-selected pace with incremental grade increases of 2–3% every two min. Measurements of oxygen uptake, heart rate and blood pressure were constantly monitored. $VO_{2\ peak}$ was measured from expired air samples taken at 30-s intervals until a peak oxygen uptake was attained; test termination was determined by symptom limitation, volitional exhaustion, and/or attainment of $VO_{2\ peak}$ as per American College of Sports Medicine guidelines (acsm.org). Due to technical problems cardiorespiratory fitness data were not collected from 2 participants, resulting in $n = 226$ for $VO_{2\ peak}$. Body mass index was calculated as kg body mass/m^2 of body height. Mean arterial pressure was calculated as (systolic blood pressure +(2 × diastolic blood pressure))/3 as a measure of systemic vascular resistance and general perfusion.

Self-rated health was measured on scale 1 to 5. 15% of participants described their health as excellent, 45% as very good, 36 % as good, and 4% as fair. Physical health status was also measured with the physical component score of the 12-Item Short Form Health Survey (Ware et al., 1996), with higher scores indicating better health status. The functional fitness test (Rikli & Jones, 2013) included time to walk stairs up and down, chair stand test, chair sit and reach test, arm curl test, back scratch, 8ft up and go, left leg, right leg, and dominant leg stand time (Supplementary material II). Functional fitness composite score was calculated as a sum of z-scores of all individual tests. Bivariate correlations between variables from Table 1 are presented in Supplementary material III.

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Statistical analyses

All analyses were carried out using SPSS v. 26. Our aim was to test whether time spent in different intensities of lifestyle PA (i.e., sedentary behavior, light, and moderate to vigorous PA) was associated with cognitive ability across several domains. In testing these associations, we adjusted for multiple demographic, socioeconomic, and health variables. The demographic covariates included age and sex. Next, to identify a parsimonious set of predictors of each cognitive construct and to maximize degrees of freedom in our moderately-sized sample, we used backward elimination regression on the socioeconomic and health variables from Table 1. Days of accelerometer wear were excluded as they were not related to measures of lifestyle PA or cognition (Supplementary material IV). In brief, backward elimination starts with a global linear regression model with all variables included, and removes nonsignificant predictors from the model one-by-one until all are significant with a *p*-value criterion of 0.1 (Heinze et al., 2018; Heinze & Dunkler, 2017). Then, we carried out four multiple regression models (one for each cognitive construct as a dependent variable), with the sedentary time, light and moderate to vigorous PA, age, sex, and the selected socioeconomic and health factors as independent variables. The alpha levels for overall model fit were adjusted using Bonferroni correction (0.05/4=0.0125). The assumptions of linearity, normality of distributed errors, and uncorrelated errors were tested and fulfilled by all regression models.

Results

First, using backward elimination regression, we identified the following predictors of cognitive abilities that should be considered as covariates in the main analyses. These were the comfort at a computer, employment status, and mean arterial pressure for perceptual speed, education and adult education for vocabulary knowledge, comfort at a computer and perceived health for memory, and education, comfort at a computer, and cardiorespiratory fitness for reasoning (Table 2).

Next, multiple linear regression analysis adjusting for age, sex, education, adult education, light, and moderate to vigorous PA revealed a positive association between sedentary behavior and vocabulary knowledge (R^2=.235, $F_{change}(7/220) = 9.7$, $p < 0.001$, Table 3), of a small effect size (Figure 1). Education and adult education were also positively associated with vocabulary knowledge, with moderate and small effect sizes (Cohen J., 1988), respectively.

Moderate to vigorous PA was positively associated with perceptual speed in a fully adjusted model (R^2=.243, $F_{change}(8/217) = 8.7$, $p < 0.001$, Table 4, Figure 1). Being younger, female, employed, having greater comfort at a computer and greater mean arterial pressure was also associated with faster perceptual speed, with small effect sizes.

Both time in sedentary behavior and moderate to vigorous PA were positively associated with reasoning in a fully adjusted model (R^2=.236, $F_{change}(8/217) = 8.4$, $p < 0.001$, Table 5, Figure 1). In addition, comfort at a computer and cardiorespiratory fitness showed also a positive association; all effect sizes were small. The effect of sex was statistically significant but the effect size was negligible.

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Finally, the overall model predicting memory was also significant (R^2=.207, F_{change}(7/219) = 8.1, $p < 0.001$), but no lifestyle PA significantly contributed to the model. Female sex and comfort at a computer were associated with better memory, with small effect sizes (Table 6). The effect of perceived health was statistically significant but of negligible effect size.

Discussion

We investigated the relationships between time spent in different intensities of sensor-measured lifestyle PA and cognition in healthy older adults. Our main finding was that time in both moderate to vigorous PA and sedentary time were positively associated with cognition, after adjusting for multiple demographic, socioeconomic, and health covariates. Furthermore, there was a dissociation between PA intensity and cognitive performance. Namely, we found that older adults who spent more time in sedentary behavior performed better on vocabulary knowledge and reasoning tasks, whereas spending more time in moderate to vigorous PA correlated with better perceptual speed and reasoning. We discuss our findings in the light of models of cognitive aging and the existing literature. Then, we discuss implications of our results for future research and lifestyle guidelines.

Positive associations of sedentary behavior with crystallized and fluid abilities

We found that sedentary time was positively associated with vocabulary knowledge, even when adjusting for education and adult education, the well-known correlates of crystallized abilities (Ackerman, 1996). This result is consistent with our hypothesis related to the fact that most cognitive activities related to acquiring knowledge and expanding vocabulary are sedentary (Seider et al., 2016), but novel in demonstrating such relationships using sensor-measured sedentary behavior. Contrary to our hypothesis, we found a positive association between sedentary time and reasoning ability, in addition to positive correlations of reasoning with moderate to vigorous PA and cardiorespiratory fitness (discussed below).

It is tempting to speculate that the time spent sedentary was related to engaging in cognitively stimulating sedentary activities. For example, earlier studies linked computer activities, reading, playing games, craft activities, viewing educational TV or DVDs with better verbal memory and performance on Trail Making Test-B, global cognitive function, reduced subjective cognitive complaints, and decreased odds of mild cognitive impairment (Barnes et al., 2013; Geda et al., 2011; Kesse-Guyot et al., 2012; Nemoto et al., 2018). However, a bidirectional or third variable relationship is equally plausible in our cross-sectional dataset. For example, there is a well-established association between fluid abilities and educational attainment (Deary et al., 2007), whereas educational attainment and socioeconomic status is associated with more time spent reading (Smith, 1990), using a computer (Chu et al., 2009), but less time watching TV (Molina et al., 2016). In this vein, adults with higher socioeconomic status may partake in more cognitively enriching leisure activities or those with higher educational and occupational attainment may continue to engage in more cognitively stimulating sedentary activities post-retirement. Thus, future studies should combine sensor-based measures of sedentary time with 24-hour recalls (Matthews et al., 2018) and real-time assessments such as the Experience Sampling Method (Csikszentmihalyi & Larson, 2014) or Ecological Momentary Assessment (Shiffman et al.,

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2008) to assess the nature and context (e.g., educational content and cognitive challenge) of both leisure and occupational sedentary activities with less recall bias and greater ecological validity than standard questionnaires. For instance, watching TV, in general, is considered less cognitively stimulating and of lower energy expenditure than reading, typing, playing piano or playing board games (Ainsworth et al., 2011; Shields & Tremblay, 2008). Conversely, focused in-class training of reasoning strategies and problem solving resulted in immediate and long-term improvement of fluid ability in older adults (the ACTIVE trial, (Rebok et al., 2014). After key characteristics of sedentary activities are identified, the time-ordered or causal relationships will need to be established in observational longitudinal or experimental studies, such as by comparing vocabulary knowledge acquisition and long-term retention of selected sedentary activities (Grabe et al., 2009).

Finally, we did not find the hypothesized negative association between sedentary time and cognitive function. Importantly, the few existing studies that reported such negative associations with sensor-measured sedentariness used only short dementia screening assessments (Iso-Markku et al., 2018; Ku et al., 2017) or identified such relationships with fluid abilities only in post-hoc analyses (Hayes et al., 2015). Thus, future studies combining blood metabolic profiles with biomarkers of brain health (Voss et al., 2014) are needed to reconcile the negative metabolic effects of excessive sedentariness (Dunstan et al., 2012; Tremblay et al., 2010) with the positive associations with fluid and crystallized abilities. Of note, the lack of association of sedentary time with memory and perceptual speed is consistent with the two aforementioned studies that reported null correlations with processing speed (Johnson et al., 2016) and memory (Zhu et al. 2017).

Positive associations of moderate to vigorous PA with fluid abilities

As we hypothesized, we found positive associations between daily time in moderate to vigorous PA and fluid abilities, specifically, perceptual speed and reasoning. Those associations, although of small effect sizes, are important, because declines in processing speed, reasoning, and executive function are the hallmarks of cognitive aging (Finkel et al., 2007; Salthouse, 2010). Note that reasoning can be considered a higher-order executive function as it relies on working memory, cognitive flexibility and inhibitory control (Diamond, 2013). In line with literature, perceptual speed and reasoning showed the most negative correlation with age among the four cognitive constructs in our sample (see bivariate correlations in Supplementary material III). Our findings are an important extension of limited and inconsistent evidence linking sensor-based moderate to vigorous PA to fluid abilities, including executive function, reasoning, and perceptual speed, as outlined in the introduction. Specifically, one previous study linked peak daily PA intensity to reasoning assessed with a single task of visuospatial ability (Brown et al., 2012), whereas moderate to vigorous PA correlated with Trail Making Test-B performance assessing executive function in one study (Johnson et al., 2016) but not in another (Kerr et al., 2013). The three studies that measured perceptual speed reported non-significant correlations with moderate to vigorous PA (Halloway et al., 2017; Johnson et al., 2016; Wilbur et al., 2012).

Although our cross-sectional results cannot establish causality, several possible explanations need to be considered for future research. Processing speed largely relies on the integrity

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of myelinated axons within the brain's white matter (Fields, 2008). In our earlier work, we have shown that white matter microstructure declines with age (Burzynska et al., 2009) and with fluid cognitive abilities (Burzynska et al., 2017; Madden et al., 2012). We also demonstrated that older adults spending more time in moderate to vigorous PA had lower volume of white matter lesions (Burzynska et al., 2014) and lesser 6-month decline in the prefrontal white matter (Burzynska et al., 2017). Therefore, preservation of white matter integrity could be one of the mechanisms linking moderate to vigorous PA with processing speed and reasoning, consistent with the "cortical disconnection" (Bartzokis, 2004) and the "processing speed" theories of cognitive aging (Li et al., 2004; Salthouse, 1996).

Unfortunately, we do not have sufficient information on the type of moderate to vigorous PA that our participants engaged in, which could give more insights into the observed associations. For instance, interceptive sports such as tennis may help train perceptual speed (Voss et al., 2010); however, one of the inclusion criteria was participating in two or less bouts of moderate exercise (and no vigorous exercise) per week within the past 6-months, making such explanation unlikely. Thus, future studies should supplement actigraphy with assessments of the type and context to identify the types of moderate or vigorous PA that best correlate with perceptual speed and reasoning among sedentary older adults, similar as we suggested in the previous section on sedentary activities. It is also important to acknowledge an equally possible bidirectional association, in which older adults with better fluid abilities are more comfortable in engaging in higher-intensity PA. For example, poorer performance on processing speed is the most consistent predictor of future falls and injuries (J. C. Davis et al., 2017).

Furthermore, we confirmed our predictions regarding the associations of cardiometabolic health with fluid abilities. Namely, we found that cardiorespiratory fitness was positively associated with reasoning, which agrees with and extends earlier research on executive function including control, speed, and visuospatial abilities (Colcombe & Kramer, 2003; Hillman et al., 2008). Perceptual speed was positively associated with mean arterial pressure, an index of systemic vascular resistance and blood perfusion. Although indirectly, this result converges with a recent report linking greater global cerebral perfusion with lesser declines in processing speed (Staffaroni et al., 2019).

Our data showed that cardiorespiratory fitness was not a significant predictor of perceptual speed and memory. Furthermore, the moderate-to-vigorous PA was positively associated with reasoning, after accounting for the significant positive association of cardiorespiratory fitness with reasoning. Similarly, moderate-to-vigorous PA was positively associated with perceptual speed, after accounting for the significant positive association of mean arterial pressure with speed. This suggests that engaging in moderate to vigorous PA, a behavior, is as important in relation with cognition as the long-term physiological benefits of moderate to vigorous PA, such as cardiorespiratory fitness and vascular health. This partial dissociation between moderate to vigorous PA and cardiorespiratory fitness for processing speed and reasoning is consistent with the fact that up to 50% of cardiorespiratory fitness may be determined genetically (Bouchard et al., 2011), and, therefore, may not be related to PA behavior. This finding also agrees with our earlier report on a nonagenarian track-and-field athlete who engaged in above average moderate to vigorous PA and outperformed

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her peers on processing speed, despite relatively low cardiorespiratory fitness (Burzynska et al., 2016). Thus, our findings motivate future research aimed at teasing apart the differential cognitive effects of engaging in structured aerobic exercise, increasing time spent in moderate to vigorous PA, and gains in cardiorespiratory fitness. Individual differences in baseline characteristics and genetics, contamination of randomized controlled trials by outside PA engagement (Ehlers et al., 2016), and mixed support for cognitive benefits of exercise interventions (Young et al., 2015) support the need for future research examining change in moderate to vigorous PA behavior and cardiorespiratory fitness separately. The results of an ongoing clinical trial comparing the effects of aerobic walking 150min/week with 225min/week on cognitive and brain health bear a great promise in elucidating the dose-response relationships between moderate to vigorous PA and cognition (Erickson et al., 2019). As of today, the recommended minimum engagement in moderate to vigorous PA for benefits in fluid abilities remains to be defined.

Contrary to our prediction, moderate to vigorous PA was not associated with episodic memory. However, we should highlight here that the existing evidence linking sensor-measured moderate to vigorous PA to memory is inconsistent and based only on several tasks of semantic memory and word list recall (Halloway et al., 2017; Wilbur et al., 2012; Zhu et al., 2017). Therefore, our non-significant results with regard to memory are not contradicting previous findings, but warrant further investigations with a broader array of tasks gauging different memory sub-processes.

Finally, with regard to secondary predictors of fluid abilities identified in our analyses, employment status is consistent with continued employment around retirement age being related to better cognition in older age (Bonsang et al., 2012; Rohwedder & Willis, 2010) and computer use has been linked with better general cognitive function across the adulthood (Tun & Lachman, 2010; Wu et al., 2019), specifically in older samples (Wu et al., 2019).

No associations of light PA with cognition

Our exploratory analyses suggested no significant associations of light PA with cognition. Thus, our null result converges with several previous studies reporting no relationships between sensor-measured light PA and performance on fluid abilities including episodic memory (Wilbur et al. 2012), processing speed, executive function, visual, and verbal memory (Kerr et al., 2017; Halloway et al., 2017; Hayes et al., 2015; Zhu et al., 2017). Moreover, the previously reported significant associations of sensor-measured light PA to cognition pertain to single tasks of fluid abilities, for example, semantic memory (Wilbur et al. 2012), processing speed (Kerr et al., 2013), executive function (Johnson et al., 2016), or short screenings for cognitive status (Iso-Markku et al. 2018) and self-rated cognition (Stubbs et al., 2017). In addition, although researchers have demonstrated that replacing sedentary time with light PA may improve a number of cardiometabolic outcomes (Buman et al., 2014), our earlier study found no benefits of increasing time in light PA over 6 months on fluid abilities measured with task switching and spatial working memory (Fanning et al., 2016). Although benefits of low-intensity walking have been reported for general, mental, and structural brain health (Varma, Chuang, et al., 2014; Varma, Tan, et al., 2014),

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it is possible that light PA is less beneficial for cognition than initially predicted. Yet, longitudinal studies will be needed to establish such temporal or casual associations (or lack thereof). As noted above, complimenting sensor-based data with real-time measurements or 24-hour recalls may help identify light activities that obscure the possibly existing relationships.

Limitations

Our cross-sectional study cannot establish causal associations between lifestyle activities and cognition, nor does it enable any time-ordered interpretation of the reported correlations. However, such correlational studies are critical for identifying associations that can then be further explored in observational and experimental longitudinal studies to establish time order or causality, respectively.

There is an ongoing debate on the validity and reliability of measuring sedentary behavior and PA with different types of sensors (Heesch et al., 2018). Thus, our results should be replicated using other devices that use different placements (wrist, thigh or ankle), sampling methods, intensity thresholds, and are worn continuously over the measurement period to capture a wider range of aerobic activities such as swimming, cycling, and resistance training (Wullems et al., 2017). In particular, different PA intensity cut points may need to be explored within the group of older adults, as differences in fitness level, stride length, and other factors, may contribute to some classification error at low to moderate ranges.

Ideally, real-time measurements of the type of the activity, its subjective intensity and cognitive stimulation using Experience Sampling Method (Csikszentmihalyi & Larson, 2014), Ecological Momentary Assessment (Shiffman et al., 2008) or 24-hour recalls (Matthews et al., 2018) should complement the sensor-based measurements. In addition, future studies should include a more detailed battery of processing speed and reaction time tasks, memory and executive function sub-domains, and tasks testing general knowledge beyond vocabulary and language skills.

We acknowledge that our sample was not well balanced with respect to race and ethnicity, and thus we were unable to examine differences in lifestyle PA-cognition associations between racial and ethnic groups. Future research should explore these associations in larger and more diverse samples, particularly given cultural differences that may exist towards health behaviors (August & Sorkin, 2011; Dave et al., 2015). Similarly, our results may have limited generalizability to the general older population due to relatively strict inclusion criteria. Our sample was possibly healthier, fitter, and of higher socioeconomic status, and, therefore, more homogenous than the general older population. Thus, our findings need to be tested in more diverse samples with regard to health, cognitive, and socioeconomic status. In addition, broader age ranges, including middle age and the oldest-old (the fastest growing segment of the population) are needed to probe developmental trends.

It is also important to note that the effect sizes of the associations between lifestyle PA and cognition were small, which does not mean they are not consequential. In other words, the observed correlations of lifestyle PA sampled over one week can be seemingly small, but they can be practically significant across adulthood as lifestyle behaviors repeat over time

(Funder & Ozer, 2019). This needs to be tested in larger and independent samples, and in longitudinal designs.

Also, the fact that we did not observe a relationship between comfort at using a computer and vocabulary knowledge or sedentary time may be because this question was initially designed to ensure comfort when solving computer-based tasks, and not to measure time spent working at a computer or objective proficiency.

Conclusions

The value of our approach lies in quantifying daily time in different intensities of lifestyle PA using sensors and assessing crystallized and fluid abilities as separate cognitive constructs. This unique study design provided the first evidence that crystallized and fluid abilities may have distinct lifestyle correlates. The positive associations of sensor-measured moderate to vigorous PA with fluid abilities (perceptual speed and reasoning) extend the existing evidence linking exercise and cardiorespiratory fitness with cognitive and brain health. Namely, our results suggest that, in correlations with cognition, time spent in the behavior of moderate to vigorous PA is at least as important as the desirable long-term physiological benefits of exercise, such as cardiorespiratory fitness or vascular health. This may have an important practical application in helping identify those at risk of decline in fluid abilities by measuring their lifestyle levels of moderate to vigorous PA. Given the accessibility and popularity of PA trackers and cognitive assessments on phones and tablets, it is possible that such data already exist. Furthermore, we contributed new findings of positive associations between sensor-based sedentary behavior, vocabulary knowledge, and reasoning. These findings may have important implications for developing suggestions on how to increase cognitive stimulation during sedentary time. Given the disproportionate time older adults spent sitting each day, our results could inform lifestyle intervention and prevention programs on how to make the best of sedentary activities, including their context and optimal daily ratio to moderate to vigorous PA. For example, training specific fluid abilities (Rebok et al., 2014) or improving crystallized abilities (Stern et al., 2018) could help offset losses in other domains, postponing overall cognitive impairment (Horn, 1970).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by the National Institute on Aging at the National Institutes of Health (R37 AG025667) and funding from Abbott Nutrition through the Center for Nutrition, Learning, and Memory at the University of Illinois. We would also like to thank Anya Knecht, Susan Houseworth, Nancy Dodge, Holly Tracy, and all of the Lifelong Brain and Cognition and Exercise Psychology Laboratory graduate students and staff for their help in participant recruitment and data collection.

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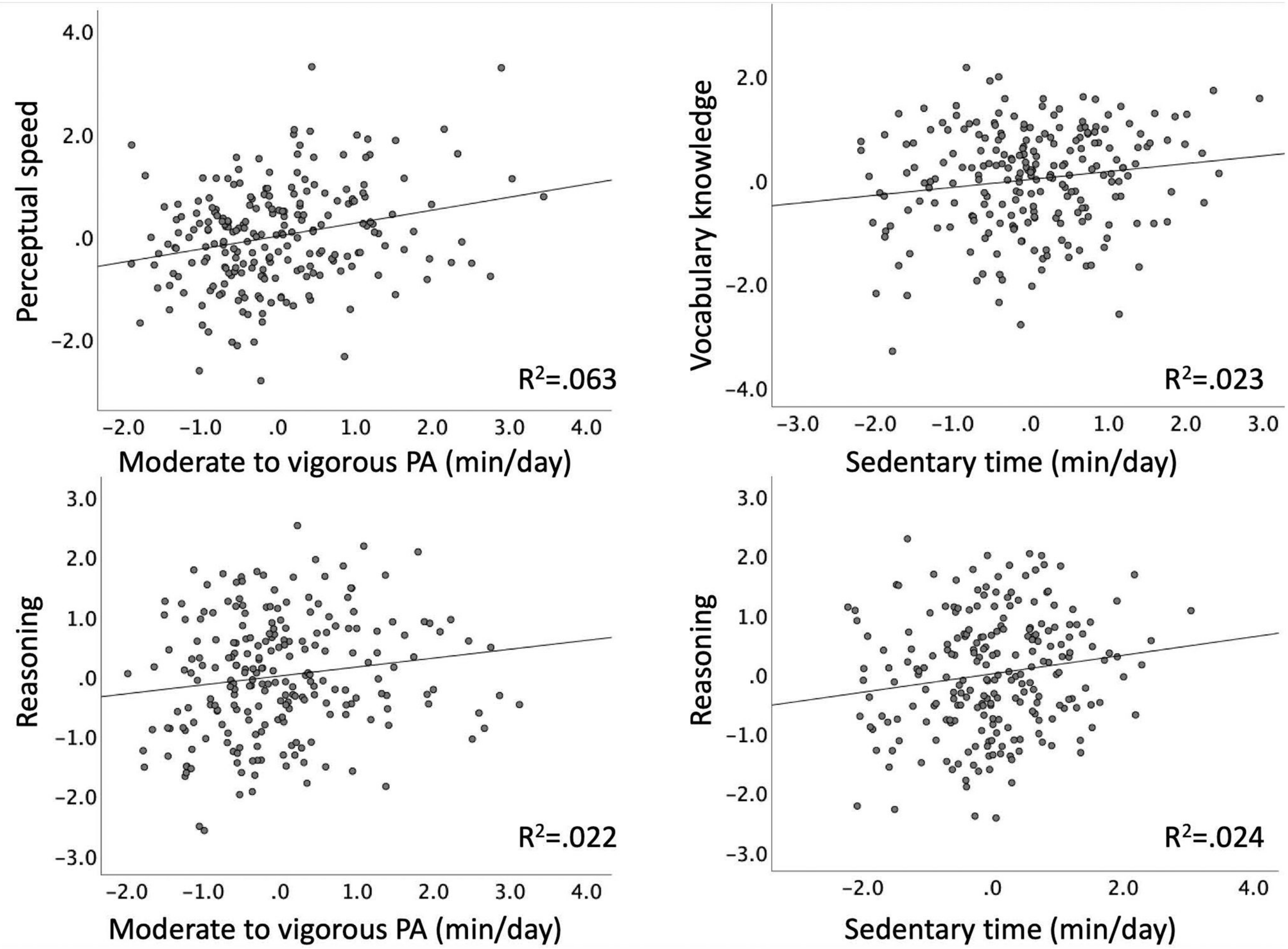

Figure 1.

Partial regression plots showing associations of sensor-measured lifestyle PA and cognition shown in Tables 3–5. The residuals of both predictor variables (lifestyle PA) and dependent (cognition) were obtained by regressing the variable against the remaining independent variables in each model. To calculate the residuals for perceptual speed and moderate to vigorous PA (top left), age, sex, employment status, comfort at a computer, mean arterial pressure, and light PA were partialled out (Table 4); vocabulary knowledge and sedentary time residuals (top right) were created by partialling out age, sex, education, adult education, light and moderate to vigorous PA (Table 3); reasoning and moderate to vigorous PA residuals (bottom left) were calculated by regressing out age, sex, education, comfort at a computer, cardiorespiratory fitness, sedentary behavior and light PA (Table 5); reasoning and sedentary time residuals (bottom right) were created by regressing out age, sex, education, comfort at a computer, cardiorespiratory fitness, light, and moderate to vigorous PA (Table 5).

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Table 1

Sample characteristics

	N	Minimum	Maximum	*M*	*SD*
Age	228	60	78	65.3	4.5
Sex (female)	155	68%			
Race & Ethnicity					
White	196	86%			
Black	26	11.4%			
Asian	6	2.6%			
Non-Hispanic	224	98.2%			
Hispanic	3	1.3%			
Socioeconomic factors					
Household annual income:					
<40,000	54	23.7%			
>40,000	134	58.8%			
Not known	40	17.5%			
Years of education	234	12	26	15.9	3.0
Employment status:					
Full time >35 h/week	51	22%			
Part time <35h/week	30	13%			
Retired, part time	33	15%			
Retired, not working	107	47%			
Unemployed or other	7	3 %			
Comfort using a computer[*]	228	1	5	3.5	1.2
Adult education[**]	228	0	3	.4	.7
Cardiometabolic health					
VO_2 peak [ml/kg/min]	226	6.5	34.2	19.7	4.7
Mean arterial pressure	226	75	119	97	8
Cardiovascular History score	228	0	9	3.7	2.0
Body mass index	226	15	51	31	6
Diabetes (positive)	32	14%			
Functional health					
Self-rated health[***]	227	1	4	2 (median)	.76
Physical health score	228	22	63	47	9
Functional fitness[****]	227	−1.12	1.04	−.0017	.36
Cognition[*****]					
Perceptual Speed					
Digit symbol	227	15	110	65.4	14.5
Pattern comparison	228	8	26	15	2.9
Letter comparison	228	4.5	18	9.6	2.0
Memory					

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	N	Minimum	Maximum	*M*	*SD*
Word recall	228	19	65	44	8.8
Logical memory	228	18	63	43.7	8.6
Paired associates (correct items averaged across 12 word pairs)	223	0	1	0.34	0.25
Reasoning					
Shipley abstract	228	3	20	12	3.3
Form board total	195	0	21	5.7	3.7
Letter set total	196	4	15	11.1	2.7
Matrix reasoning total	197	1	16	8.1	3.0
Paper folding total	198	1	11	5.4	2.5
Spatial relations	198	0	20	8.0	4.6
Vocabulary					
WIAS vocabulary total	228	9	61	46.1	10.3
Picture vocabulary total	228	4	29	20.0	4.8
Synonym total	197	0	10	6.9	2.7
Antonym total	198	0	10	6.0	3.1
Mini Mental Status Exam	228	26	30	28.7	1.2
Physical activity					
Sedentary Time (min/day)	228	295	810	537	83
Light PA (min/day)	228	147	528	276	69
Moderate to vigorous PA (min/day)	228	4.7	139	40[******]	37[******]
Wear time (days)	228	3	17	7	1
Average Counts (counts/day)	228	49035	553117	181121	80040

Note.

[*] 1: low to 5: proficient;

[**] 0: never participated, 1: 1–2 classes, 2: 3–5 classes, 3: > 5 classes;

[***] 1: Excellent, 2: Very Good, 3: Good, 4: Fair, 5: Poor;

[****] Descriptive statistics for the nine tasks from the functional fitness test are presented in the Supplementary material II;

[*****] Units refer to correct responses unless specified otherwise;

[******] Due to skewness, median and interquartile range are presented instead of mean and SD.

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Table 2

Backward elimination regression: secondary predictors of cognition

	Speed				**Vocab.**				**Memory**				**Reasoning**			
	Std.β	***t***	***p***	**VIF**	**Std.β**	***t***	***p***	**VIF**	**Std.β**	***t***	***p***	**VIF**	**Std.β**	***t***	***p***	**VIF**
Income																
Education					.344	5.0	<.000	1.0					.145	2.0	.047	1.1
Employment	−.159	−2.2	.026	1.1												
Computer	.300	4.3	<.001	1.1					.208	2.9	.004	1.1	.276	3.9	<.001	1.1
Adult Edu.					.163	2.4	.018	1.0								
Mean arterial pressure	.138	2.0	.045	1.0												
Cardiovascular History																
VO_{2peak}													.143	2.0	.048	1.1
Body mass index																
Diabetes																
Health									−.183	−2.5	.012	1.1				
Physical health																
Functional fitness																

Note. VIF: variance inflation factor

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Table 3.

Associations with vocabulary knowledge

IV	Std. β	*SE*	*t*	*p*	f^2	LB	UP	VIF
Age	−.006	.012	−.1	.915	<.02	−.024	.022	1.0
Sex	.091	.120	1.4	.157	<.02	−.066	.406	1.2
Education	.364	.018	5.9	**<.001**	**.16**	.072	.144	1.1
Adult Education	.144	.074	2.4	**.018**	**.026**	.031	.323	1.0
Sedentary behavior	.170	.001	2.3	**.023**	**.024**	.000	.003	1.6
Light PA	−.136	.001	−1.8	.075	<.02	−.004	.000	1.7
Moderate to vigorous PA	.072	.002	.99	.325	<.02	−.002	.006	1.5

VIF: variance inflation factor. LB and UP: lower and upper bounds of 95% confidence intervals.

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Table 4.

Associations with perceptual speed

IV	Std. β	*SE*	*t*	*p*	f^2	LB	UP	VIF
Age	−.129	.011	−2.2	.033	<.02	−.045	.002	1.0
Sex	.169	.111	2.7	**.008**	**.033**	.079	.518	1.1
Employment status	−.166	.034	−2.6	**.009**	**.032**	−.159	−.023	1.1
Comfort at a computer	.205	.043	3.3	**.001**	**.050**	.057	.227	1.1
Mean arterial pressure	.150	.006	2.5	**.013**	**.033**	.003	.027	1.0
Sedentary behavior	−.009	.001	−.1	.900	<.02	−.002	.001	1.6
Light PA	−.020	.001	−.3	.799	<.02	−.002	.002	1.7
Moderate to vigorous PA	.280	.002	3.8	**<.001**	**.067**	.004	.012	1.5

VIF: variance inflation factor.

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Table 5.

Associations with reasoning

IV	Std. β	*SE*	*t*	*p*	f^2	95% LB	95% UB	VIF
Age	−.104	.011	−1.7	.088	<.02	−.040	.003	1.0
Sex	.137	.118	2.0	.047	.018	.004	.470	1.3
Education	.112	.017	1.8	.079	<.02	−.004	.065	1.1
Comfort at a computer	.274	.042	4.4	**<.001**	**.089**	.102	.269	1.1
Cardiorespiratory fitness	.162	.013	2.1	**.036**	**.025**	.002	.054	1.7
Sedentary behavior	.174	.001	2.3	**.021**	**.025**	.000	.003	1.6
Light PA	−.025	.001	−.3	.746	<.02	−.002	.002	1.7
Moderate to vigorous PA	.177	.002	2.2	**.028**	**.024**	.001	.009	1.8

VIF: variance inflation factor.

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Table 6.

Associations with memory

IV	Std. β	*SE*	*t*	*p*	f^2	LB	UB	VIF
Age	−.102	.011	−1.7	.097	<.02	−.041	.003	1.0
Sex	.333	.116	5.1	**<.001**	**.13**	.361	.818	1.2
Comfort at a computer	.200	.043	3.2	**.002**	**.05**	.053	.222	1.1
Perceived health	−.137	.068	−2.2	.030	.018	−.283	−.015	1.1
Sedentary behavior	.088	.001	1.2	.245	<.02	−.001	.002	1.6
Light PA	−.139	.001	−1.8	.075	<.02	−.004	.000	1.7
Moderate to vigorous PA	.098	.002	1.3	.193	<.02	−.001	.007	1.6

VIF: variance inflation factor.