A daily process analysis of physical activity, sedentary behavior, and perceived cognitive abilities

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Abstract:

Objectives This study evaluated the role of both physical activity and sedentary behavior in daily perceptions of cognitive abilities and whether these relations exist within-person, between-person, or both.

Design Non-experimental, intensive longitudinal research using ecological momentary assessments.

Method College students wore accelerometers and provided end-of-day reports on physical activity, sedentary behavior, and perceived cognitive abilities for 14 days.

Results Across self-reports and objective measures of behavior, daily deviations in physical activity were positively associated with perceived cognitive abilities. Daily deviations in self-reported, but not objectively-assessed, sedentary behavior also were negatively associated with perceived cognitive abilities. Contrary to previous research, overall levels of physical activity and sedentary behaviors were not associated with perceived cognitive abilities.

Conclusions These findings indicate that physical activity has a within- rather than between-person association with perceived cognitive abilities although between-person associations effects may require longer monitoring periods to manifest. Further research is needed to establish the direction of causality and resolve whether the nature (rather than quantity) of sedentary activities influences cognition.

Keywords: Exercise | Sitting | Intraindividual | Memory | Concentration

Article:

Physical activity offers many mental health benefits including enhanced executive functioning (Ahn & Fedewa, 2011; Colcombe & Kramer, 2003). These benefits for executive function have been documented across the lifespan with the greatest evidence at the young and old extremes (Guiney & Machado, 2013); however, little is known about how sedentary behavior affects executive function. Given that sedentary behavior has distinct physical health consequences from insufficient levels of physical activity (Owen, Healy, Matthews, & Dunstan, 2010), it may also have distinct consequences for cognitive performance. In this study, we focused on perceived cognitive abilities because perceptible daily fluctuations in cognitive performance are important and clinically-meaningful outcomes. Moreover, if linked with physical activity or sedentary behavior, those perceptions may influence emerging outcome expectations for those behaviors. This study also builds on the fact that previous research has focused on identifying *who* differs cognitively (e.g., people who are more vs. less fit or more vs. less active) and less is known about *when* such differences exist or *why*. Information about the dynamics of health behaviors, such as physical activity or sedentary behavior, and cognition may lead to improved strategies for improving cognition as well as a clearer understanding of the consequences of health behaviors.

COGNITION AND PHYSICAL ACTIVITY IN DAILY LIFE

Cognition refers to how people process sensory information and includes a number of functions, such as attention, memory, and reasoning, which are required for daily activities (Neisser, 1967). These abilities develop from birth and tend to diminish in older adulthood (Hillman et al., 2006; Strout & Howard, 2012). Although cognitive development is often viewed as a slow-changing process over extended time periods, day-to-day fluctuations in cognition occur and may influence one's ability to complete daily tasks (Neupert, Almeida, Mroczek, & Spiro, 2006). These day-to-day shifts in cognition have been linked to daily fluctuations in affect and stress but not to specific behavioral antecedents (Brose, Schmiedek, Lövdén, & Lindenberger, 2012; Neupert et al., 2006). Physical activity also varies on a daily basis (Behrens & Dinger, 2003, 2005; Conroy, Elavsky, Hyde, & Doerksen, 2011; Conroy, Elavsky, Maher, & Doerksen, 2013) and has been linked with daily affect and stress (Gerber et al., 2013; Hyde, Conroy, Pincus, & Ram, 2011) so it is plausible that fluctuations in physical activity may influence day-to-day cognitive performance.

A positive association between physical activity and cognition has been documented in numerous studies contrasting high and low fit people as well as more and less active people (Guiney & Machado, 2013; Hillman, Buck, Themanson, Pontifex, & Castelli, 2009). In these studies, cognition has frequently been operationalized in terms of specific executive functions (e.g., attention, inhibition, task switching, working memory) or general academic achievement (Carlson et al., 2008; Castelli, Hillman, Buck, & Erwin, 2007; Coe, Pivarnik, Womack, Reeves, & Malina, 2006; McNaughten & Gabbard, 1993; Ruscheweyh et al., 2011; Wu et al., 2011). Although neurocognitive and performance-based measures are considered gold standards for assessing cognition, self-reports of perceived cognitive abilities have been linked with performance on a variety of measures of cognitive function (e.g., learning, memory, processing speed, flexibility; Becker, Stuifbergen, & Morrison, 2012; Benedict et al., 2003). Moreover, assessing patient-reported outcomes, such as self-reported cognitive abilities, informs understanding of a person's perceived capabilities, limitations and needs, and can drive help-seeking behavior and openness to intervention (Centers for Disease Control and Prevention, 2000; Donaldson, 2008; Greenhalgh, 2009). Even small fluctuations in these perceptions over time may reveal clinically-meaningful changes in individual functioning because these measures center on the person's experience (Deshpande, Rajan, Sudeepthi, & Abdul Nazir, 2011). From a motivational standpoint, perceived cognitive abilities provide a basis for individuals to form outcome expectations for antecedent behaviors. To the best of our knowledge, none of the studies cited above have sampled cognition intensively over time so this study was designed to focus on the dynamics of perceived cognitive abilities and establish links with putative behavioral antecedents.

The extant literature has emphasized between-person differences in physical activity and cognition that are presumably mediated by adaptations in brain volume, cerebral blood flow, and cerebrovascular reserve (Colcombe et al., 2006; Davenport, Hogan, Eskes, Longman, & Poulin, 2012; Erickson et al., 2009; Voss, Carr, Clark, & Weng, 2014). These mechanisms reflect both long- and short-term adaptations to physical activity so it is possible that the effects of physical activity on cognition may reflect differences in people's overall physical activity, daily physical activity, or both. It is also possible that the mechanisms linking physical activity and cognition are age-dependent. Overall physical activity (as a precursor of fitness) may be most valuable for stemming age-related decline in older adults (Colcombe & Kramer, 2003). In contrast, most college students are emerging or young adults and have experienced limited age-related cognitive or vascular decline. For this population, overall physical activity levels may not impact brain volume or cerebrovascular reserve substantially, and one might anticipate that any cognitive effects would be derived from daily physical activity which impacts cerebral blood flow directly. Before investigating any of the proposed psychological or physiological mechanisms, it is necessary to evaluate whether perceived cognitive abilities are linked with overall physical activity (reflecting a between-person process), daily physical activity (reflecting a within-person process), or both.

SEDENTARY BEHAVIOR AND COGNITION

The aforementioned research focused on physical activity and largely neglected the potential confound of sedentary behavior. Whereas physical activity refers to any bodily movement produced by skeletal muscle that requires energy expenditure, sedentary behavior refers to activities that do not increase energy expenditure substantially above the resting level (e.g., sitting, lying down, watching television; Caspersen, Powell, & Christenson, 1985; Sedentary Behaviour Research Network, 2012). This distinction between physical activity and sedentary behavior is critical for two reasons. First, sedentary behavior can displace physical activity and confound interpretations of associations between physical activity and cognitive abilities. Only by differentiating these behaviors is it possible to evaluate whether the observed link is due to insufficient physical activity or excessive sedentary behavior. Likewise, differentiating between these behaviors can inform theorizing about possible mechanisms (e.g., increased vs. decreased cerebral blood flow). Second, many health consequences of insufficient physical activity and excessive sedentary behavior are independent and additive (Owen et al., 2010; Thorp, Owen, Neuhaus, & Dunstan, 2011) so it is possible that each behavior has a unique effect on cognitive abilities. If relations are due to a single behavior, future interventions should focus on that behavior alone. In contrast, independent additive relations would imply that multiple health behaviors should be changed to improve cognitive abilities maximally.

Findings on sedentary behavior and cognition have been limited and mixed (for a review, see Voss et al., 2014). In a sample of older adults, computer usage was positively associated with executive function, but television watching was negatively associated with executive function (Kesse-Guyot et al., 2012). Another study indicated that directly-measured sedentary behavior was not associated with children's academic performance but self-reported sitting time was positively associated (Syväoja et al., 2013). Worksite interventions that use standing or treadmill workstations to reduce sitting time have shown no adverse effects on employees' cognition; however those findings can be difficult to interpret because standing and physical activity are often confounded (Alderman, Olson, & Mattina, in press; Ohlinger, Horn, Berg, & Cox, 2011). Based on the limited available literature, we hypothesized that sitting time (which is not differentiated by the type of task) would be associated with lower perceived cognitive abilities.

THE PRESENT STUDY

This study was designed to fill two key gaps in the literature. First, we sought to extend research establishing between-person associations between physical activity and cognition by examining whether fluctuating levels of physical activity also have within-person associations with daily cognitive abilities. Second, we sought to evaluate both between- and within-person links between sedentary behavior and daily cognitive abilities. To assess cognitive abilities and behavior in the natural context of people's daily lives, we used an ecological momentary assessment research design with self-reports of daily cognitive abilities at the end of each day serving as our primary outcome. Behavior was measured using both self-report and direct measures of physical activity and sedentary behavior. In the absence of literature on within-person associations between these behaviors and cognition, our hypotheses were identical for the between- and within-person levels of analysis. Specifically, physical activity and sedentary behavior were expected to exhibit positive and negative associations, respectively, with daily cognitive abilities. We also conducted exploratory analyses to evaluate whether cognitive abilities were associated with an interaction between physical activity and sedentary behavior.

METHOD

Participants

Participants were a convenience sample of college students enrolled in undergraduate courses that participated in a daily diary study as part of a class project. All but one participant indicated that they were capable of performing normal physical activity. Another participant did not give permission to use his data for research purposes. Those two participants were excluded from analyses, resulting in a sample of 75 women and 53 men (N = 128). The mean age of participants was 21.3 years (SD = 1.1; range = 18–25). The sample consisted of predominately White (87%), non-Hispanic (96%) women (58%) in their third (16%) or fourth (78%) year of college.

Measures

Perceived cognitive abilities

Perceived cognitive ability was assessed using the four-item Applied Cognition – Abilities Scale from the Patient Reported Outcomes Measurement Information System (Becker et al., 2012; Cella et al., 2010) adapted for daily use. In developing this measure, item-response theory analyses informed selections from an item bank to represent the full range of the construct (Cella et al., 2010). Scores are positively associated with performance on neurocognitive tests that assess learning, memory, processing speed, flexibility, complex scanning, and visual tracking (Becker et al., 2012). Participants reported how much they agreed with statements such as, "Today I have been able to keep track of what I am doing, even if I was interrupted" on a slider scale ranging from 1 (*not at all*) to 100 (*very much*). Along with this question, content from the other three items focused on cognitive flexibility, working memory and inhibition. Responses exhibited strong longitudinal factorial invariance from day 1 to day 14 (i.e., invariant item-factor regression coefficients and factor means) with coefficients in the expected directions. This level of invariance is considered sufficient for temporal comparisons of scale scores across time (Bontempo & Hofer, 2007). Daily hierarchical reliability (ω) estimates ranged from .91 to .97 (M = .95) and a general factor explained an average of 93% of the common variance across the 14 days (range = .86–.96). Responses were averaged to create a single score for each day.

Physical activity

The International Physical Activity Questionnaire (IPAQ) (Booth, 2000) was used to self-report physical activity. Craig et al. (2003) validated IPAQ scores as measures of adult physical activity and we followed the recommendation of Matthews, Moore, George, Sampson, and Bowles (2012) to increase score validity by shortening the recall period to a single day. Questions focused on the amount of time spent in 10+ min bouts of vigorous physical activity, moderate physical activity, and walking. Responses were scored using established data screening and weighting procedures to create a single physical activity (MET·min) scores (Sjöström et al., 2002, 2005).

Daily physical activity was measured directly using a triaxial accelerometer (Actigraph model GT3X, Pensacola, FL). Activity counts were aggregated into one minute epochs and processed using the Actilife data analysis software from Actigraph (versions 5.1.5). The software screened the data to identify valid days (i.e., days with 10+ hours of valid wear time). Daily activity counts were also adjusted for variability in the number of valid hours of wear time (hours with at least 10% non-zero activity counts), by dividing the total daily activity counts by the number of valid hours. This modification eliminates the potential confound of high activity counts being the result of increased wear time as opposed to increased activity.

Sedentary behavior

Sedentary behavior was measured using the sitting item from the IPAQ (Booth, 2000). The IPAQ-based weekly measure of sitting time was found to be a reliable measure of sedentary behavior (Rosenberg, Bull, Marshall, Sallis, & Bauman, 2008). To reduce recall errors, bias and reliance on heuristics that compromise the validity of self-reports, we modified that item to focus on daily sitting time (Matthews et al., 2012). Participants recorded the amount of sitting based on total amount of time for that day in hours and minutes; responses were transformed into the total number of minutes.

Daily sedentary behavior was also measured directly using a triaxial accelerometer (Actigraph model GT3X, Pensacola, FL). Sedentary behavior was characterized as the number of min/day with <100 counts·min^{-1} (Freedson, Melanson, & Sirard, 1998).

Procedures

Participants provided informed consent and permission to use their data for research purposes, and then completed a questionnaire to provide demographic information. A research assistant measured the participant's height and weight (twice each with a third measure taken when recordings differed by 0.4 cm or 0.3 kg). Research assistants instructed participants on how to access a secure website at the end of every day (7 pm–4 am) over the course of the 14-day study. They were instructed to complete a brief questionnaire about their daily physical activity, sedentary behaviors, and perceived cognitive abilities as close to bedtime as possible. Participants were also instructed to wear an accelerometer during all waking hours for the duration of the study except while engaging in water-related activities (e.g., showering) or high-contact activities that could damage the accelerometer (e.g., football). Research assistants trained participants to place the accelerometer on their right hip, over the midline of the knee.

Data analyses

Study hypotheses were tested with a hierarchical linear regression model implemented in SAS 9.3 PROC MIXED (Littell, Milliken, Stroup, & Wolfinger, 1996) to account for the nested data structure (days nested within people). Maximum likelihood estimation was used to handle the small amount of missing data. Data was missing for 67 of the total possible 1664 person days (96% complete). Both self-report and accelerometer physical activity scores were rescaled (simple division by 1000) to facilitate interpretation of model coefficients. To estimate both the overall (between-person) and daily (within-person) effects, physical activity and sedentary behaviors variability was separated into between- and within-person components (Snijders & Bosker, 1999). Scores for overall physical activity and sedentary behavior were calculated as the within-person mean score for self-reports or activity counts across the 14 days between lab visits $\left(\text{Overall Physical Activity}_i = 1/d\sum_{d=1}^{14}\text{Physical Activity}_{di}\right)$. Individual scores for daily physical activity and sedentary behavior were calculated as the daily deviations from corresponding within-person means. For example, deviations in physical activity on day *d*for individual *i* (Daily Physical Activity$_{di}$) were calculated as the difference between observed physical activity on day *d* for individual *i* and the mean level of physical activity observed for individual *i* (=Physical Activity$_{di}$ − Overall Physical Activity$_i$). In that way, a positive daily physical activity score indicated that the person was more active than usual on that day, and a negative daily physical activity score indicated that the person was less active than usual on that day.

In the model, daily ratings of perceived cognitive abilities were regressed on overall and daily physical activity and sedentary behaviors, and interaction terms between physical activity and sedentary behaviors at the overall and daily levels. Positive coefficients for overall physical activity would indicate that participants who reported greater cognitive abilities on average would be those who engaged in greater overall physical activity across the 14 days; positive coefficients for daily physical activity would indicate that participants reported greater cognitive abilities on days when they were more active than usual (within-person association). These models also controlled for sex (0 = female, 1 = male) and body mass index (BMI) related differences in cognitive abilities which might confound interpretations of the behavioral coefficients. The model is presented in Eqs. (1)–(3).

Level-1:

$$\text{Cognitive Abilities}_{di} = \beta_{0i} + \beta_{1i}(\text{Daily Physical Activity}_{di}) + \beta_{2i}(\text{Daily Sedentary Behavior}_{di}) + \beta_{3i}(\text{Daily Physical Activity}_{di} \times \text{Daily Sedentary Behavior}_{di}) + e_{di} \quad (1)$$

Level-2:

$$\beta_{0i} = \gamma_{00} + \gamma_{01}(\text{Overall Physical Activity}_i) + \gamma_{02}(\text{Overall Sedentary Behavior}_i) + \gamma_{03}(\text{Overall Physical Activity}_i \times \text{Sedentary Behavior}_i) + \gamma_{04}(\text{Sex}_i) + \gamma_{05}(\text{BMI}_i) + u_{0i} \quad (2)$$

$$\beta_{(1-3)i} = \gamma_{(1-3)0} + u_{(1-2)i} \quad (3)$$

Eqn. (1) represents the within-person model of perceived cognitive abilities on day *d* for individual *i*, where β_{0i} represents a person-specific intercept, β_{1i} represents the person-specific association between daily physical activity and cognitive abilities, β_{2i} represents the person-specific association between daily sedentary behavior and cognitive abilities, β_{3i}represents the person-specific interaction between daily physical activity, daily sedentary behavior, and cognitive abilities, and e_{di} represents time-specific residuals (i.e., unexplained within-person variance). This within-person model was constrained by the between-person model components expressed in Eqs. (2) and (3). Eqn. (2) regresses overall perceived cognitive abilities (i.e., person-specific intercepts from Eqn. (1)) on overall physical activity and sedentary behavior (γ_{01} and γ_{02}, respectively), the interaction between the overall levels of those behaviors (γ_{03}), sex (γ_{04}), and BMI (γ_{05}). Eqn. (3) represents the average within-person coefficients linking daily perceived cognitive abilities with daily deviations in physical activity (γ_{10}), sedentary behavior (γ_{20}), and their interaction (γ_{30}). Unexplained between-person variation in these models is represented by $u_{(0-2)i}$. These models were estimated separately for self-reported and direct measures of (in)activity.

RESULTS

Participants provided self-report data for a total of 1653 of the 1792 possible days (93% response rate) and 88 of the participants (69%) provided data on 13 days of the 14 study days (Median = 14 days, Mean = 12.9, SD = 1.4). Participants also had valid accelerometer data on

1485 of the 1782 possible days (83% compliance rate); 71 (56%) provided data on 12 or more days of the 14 day study (Median = 13 days, Mean = 11.7, SD = 2.9).

Table 1 presents (a) descriptive statistics, (b) bivariate correlations describing associations between perceived cognitive abilities, physical activity, sedentary behavior, sex and BMI, and (c) intraclass correlations describing the proportion of between-person variation in each variable with repeated measures. Two types of bivariate correlations were estimated. The within-person correlations shown above the diagonal were estimated based on daily scores, which disregard the nesting of scores within people across occasions. The between-person correlations shown below the diagonal were estimated based on within-person mean scores and disregard daily fluctuations in scores over time. Because of the limitations of each correlation coefficient, these estimates are interpreted descriptively rather than inferentially. At both the within- and between-person levels of analysis, physical activity exhibited weak positive correlations with perceived cognitive abilities, whereas sedentary behaviors exhibited weak negative correlations with perceived cognitive abilities. There was also a weak positive correlation with cognitive abilities at the within-person but not the between-person level of analysis for accelerometer-measured data. Cognitive abilities had negligible within- and between-person correlations with directly-measured sedentary behavior. Intraclass correlations suggested that variance in perceived cognitive ability, physical activity and sedentary behavior was distributed both between- and within-people in similar proportions; this finding reinforced the need to test for both between- and within-person associations between these variables.

Table 1
Descriptive statistics and correlations of perceived cognitive abilities, physical activity and sedentary behavior.

	M	SD	1	2	3	4	5
1. Perceived cognitive abilities	70.89	20.71	(.50)	.03	.06	−.02	.04
2. Physical activity (self-report; MET-min/day)	645.41	504.68	.07	(.47)	.17	−.28	−.36
3. Physical activity (direct; counts/hour)	28,483.12	13,900.10	.13	.33	(.30)	−.19	−.53
4. Sedentary behavior (self-report; min)	365.54	155.10	−.07	−.29	−.25	(.48)	.25
5. Sedentary behavior (direct; % waking time)	66.73	8.65	−.06	−.37	−.54	.33	(.28)
6. Sex	0.41	.49	−.09	.06	.04	.05	.06
7. BMI (kg/m^2)	24.64	3.87	−.06	.04	−.04	.05	−.05

Note. Intraclass correlations for variables that were assessed in an intensive longitudinal manner appear along the diagonal of the matrix. Between-person correlations (based on within-person means for intensively assessed variables) appear on the bottom half of the matrix. Within-person correlations appear on the top half of the matrix. Sex was dummy coded (0 = female, 1 = male).

Table 2 summarizes coefficients from the hierarchical linear models that test the study hypotheses using behavioral data from self-reports (left column) and accelerometers (right column). With respect to self-reported behavior, after controlling for all other variables in the model, participants reported greater perceived cognitive ability on days when they reported being more active than usual (γ_{10}) and on days when they reported being less sedentary than usual (γ_{20}). Random effects revealed significant residual variability in both of these within-person associations as well as in daily perceived cognitive abilities. Cognitive ability did not differ, on average, as a function of participants' sex, BMI, overall physical activity, overall sedentary behavior, or the interaction of those behaviors. The pseudo-R^2 effect size indicated that this model with self-reported behaviors accounted for 13% of the variance in perceived cognitive abilities; daily physical activity and sedentary behavior accounted 43% and 37% of that variance, respectively.

Table 2
Coefficients from hierarchical linear model regressing perceived cognitive abilities on physical activity and sedentary behavior.

	Self-reported behavior	Directly-measured behavior
	Parameter estimate (SE)	Parameter estimate (SE)
Fixed effects		
Intercept, γ_{00}	88.23 (8.71)	84.99 (11.04)
Overall physical activity, γ_{01}	4.61 (4.46)	0.13 (0.22)
Daily physical activity, γ_{10}	5.77* (1.40)	0.17* (0.04)
Overall sedentary behavior, γ_{02}	−0.03 (0.02)	0.03 (0.66)
Daily sedentary behavior, γ_{20}	−0.01* (0.004)	−0.12 (0.08)
Overall physical activity × Overall sedentary behavior, γ_{03}	0.05 (0.03)	−0.001 (0.02)
Daily physical activity × Daily sedentary behavior, γ_{30}	0.02 (0.01)	0.005 (0.004)
Sex, γ_{04}	−1.92 (2.85)	−1.40 (2.97)
BMI, γ_{05}	−0.69 (0.36)	−0.60 (0.37)
Random effects		
Variance intercept, u_0	217.47* (29.69)	218.81* (30.75)
Variance physical activity, u_1	76.95* (24.93)	0.03 (0.03)
Variance sedentary behavior, u_2	0.0007* (0.0003)	0.27* (0.10)
Residual, e_{di}	187.80 (7.19)	187.34 (8.09)

Note. SE = standard error. Unstandardized estimates based on 100 posterior simulations, $^{*}p < .05$.

In the model based on accelerometer data, participants reported greater perceived cognitive ability on days when they reported being more active than usual (γ_{10}) but not on days when they were more sedentary than usual (γ_{20}). The latter, but not the former, association varied significantly across participants indicating that the association between daily sedentary behavior and perceived cognitive abilities varied across participants (u_2) whereas the association between daily physical activity and perceived cognitive abilities was more uniform (u_1). Cognitive ability did not differ, on average, as a function of participants' sex, BMI, overall physical activity, overall sedentary behavior, or the interaction of those behaviors. The pseudo-R^2 effect size indicated that this model with objectively-measured behaviors accounted for 13% of the variance in perceived cognitive abilities; daily physical activity accounted 64% of that variance (sedentary behavior was not a significant predictor so we assumed it made a negligible contribution to the pseudo-R^2).

DISCUSSION

This study investigated relations between daily cognitive abilities, physical activity, and sedentary behavior. An interesting initial observation from the study was that perceived cognitive abilities varied considerably from day to day. Whereas previous studies on physical activity and cognition have often invoked either explicit or implicit assumptions about the relative stability of cognitive ability and executive functions, the present study relaxed that assumption and we found that perceived cognitive abilities varied approximately as much within person over time as they did between people. This result corresponds with other daily studies of cognition (Brose et al., 2012; Neupert et al., 2006). It is possible that such fluctuations are limited to self-reported cognitive abilities and it is not clear whether performance-based measures of cognition and executive function will vary as much over time. It is also not clear how much fluctuating cognitive abilities impact daily performance for the college student population and this question warrants further research. With respect to the present study, the daily fluctuations in cognition reinforced the value of intensive longitudinal assessments of (in)activity for our investigation.

Previous research on physical activity and cognition has focused on differences between people who are more vs. less active or fit. Whereas more active and more fit people have exhibited greater executive function and academic performance in those studies (Colcombe & Kramer, 2003; Guiney & Machado, 2013), no such association was observed in the present study. This result may reflect a sampling difference because, unlike the present study, the majority of the literature which has supported a between-person association between physical activity and cognition has been based on samples of children and older adults (Guiney & Machado, 2013). The mechanisms underlying relations between physical activity and cognition may differ in healthy, young adult populations who have yet to experience substantial age-related cognitive decline. Thus, a quadratic age function may moderate relations between overall physical activity and cognitive function such that the between-person associations are strongest at the young and old extremes of the lifespan. Few studies have employed a lifespan developmental perspective in this area or even sampled from across the adult lifespan (for a notable exception see; Hillman et al., 2006) and that perspective would be valuable for clarifying how relations between overall physical activity and cognition vary across the lifespan.

Another possible explanation for the null relations with overall physical activity is that the self-report measure of cognitive abilities was too sensitive to daily fluctuations and did not provide a reliable estimate of individual differences in cognition. In previous research, this measure has been sensitive to computer-based cognitive training and exhibited positive correlations with established neurocognitive measures (Becker et al., 2012). The magnitude of those convergent validity coefficients was modest but deemed acceptable given the need for measures that reduced burden on participants and facilitated comparison across studies. It is also possible that this measure assessed cognitive abilities which are not impacted by adaptations to high levels of overall physical activity and fitness. If that is the case, the present coefficients may have underestimated relations with the cognitive abilities which are more impacted by adaptations to physical activity and fitness.

In contrast to the null associations at the between-person level of analysis, a positive association was observed between physical activity and cognitive abilities at the within-person level of analysis. This result extends the literature by providing (to the best of our knowledge) the first evidence of a within-person process linking daily physical activity and cognition. Whether this result generalizes beyond the college population is an open question; however it is worth noting that the within-person association did not vary significantly between people in this study. Although the present research design was not experimental and required strong assumptions about causality, it appears reasonable to recommend that college students seek ways to engage in physical activity on days when they need greater cognitive abilities (e.g., go for a longer-than-usual morning run when one has an exam scheduled later in the day). Alternatively, it may be that enhanced cognitive abilities on a given day increase one's likelihood of planning physical activity, resisting temptations for alternatives, and engaging in the planned activity (e.g., Hall, Elias, & Crossley, 2006).

Future work will need to evaluate mechanisms of this within-person association. One plausible mechanism involves acute physiological responses (e.g., increased cerebral blood flow) which lead to changes in subjective experiences (e.g., increased pleasant-activated feeling states, decreased perceived stress) and subsequent changes in cognition. This mechanism is consistent with previous findings about affective responses to physical activity as well as the broaden-and-build theory of positive emotions which posits that positive emotional states broaden thought-action repertoires (i.e., more global and flexible information processing) in service of long-term personal resource development (Fredrickson, 1998, 2004). This connection provides an example of how daily physical activity may serve to enhance fitness (in an evolutionary rather than a strictly physiological sense).

This study clearly indicated that the amount of overall sedentary time was not associated with people's cognitive abilities. These findings are consistent with studies of workplace standing interventions which have shown that treadmill desks and standing workstations do not alter job-related performance (Alderman et al., in press; Ohlinger et al., 2011). Such interventions often confound reductions in sedentary behavior with increases in physical activity so the present research adds to the literature by disentangling those influences on perceived cognitive abilities. Strategies for reducing sedentary behavior appear to exact no cognitive cost; however, it would be worthwhile to re-evaluate that hypothesis with other measures of cognitive performance before drawing strong conclusions.

At the within-person level, results were mixed because a significant negative association emerged from self-reports and a non-significant association emerged from the direct measure of sedentary time. The non-significant association trended in the expected direction but the effect was too small to be detected in the analyses. The significant variability in each of these coefficients was noteworthy because it suggests that daily sedentary time has no association with cognitive abilities for some people and a negative association for others. The nature of sedentary activities – for example, whether one watches television or works on a computer – may influence the association between daily sedentary time and cognitive abilities (Kesse-Guyot et al., 2012). Future research would benefit from capturing the quality as well as the quantity of sedentary behavior to resolve these mixed results.

Although longitudinal, the research design for this study was not experimental and cannot distinguish the causal direction of associations between (in)activity and cognitive abilities. Based on previous work showing cognitive adaptations to exercise interventions (Colcombe & Kramer, 2003; Guiney & Machado, 2013), we assumed that (in)activity influenced daily cognitive abilities. It is possible that the observed relations were due to cognitive abilities influencing (in)activity or that the process is recursive. This alternative causal pathway is supported by work linking individual differences in executive function with subsequent physical activity either directly or indirectly through enhanced self-regulation (Hall, Fong, Epp, & Elias, 2008; Hall, Zehr, Ng, & Zanna, 2012; McAuley et al., 2011). Future research with experimental designs that manipulate either (in)activity or executive function will be valuable for clarifying the causal direction of these relations. It will also be important for future research to control for potential confounding variables in peoples' daily lives which may impact relations between behavior and cognitive abilities (e.g., affect, stress).

Other limitations of this study included the narrow sample which was young, healthy, and well-educated relative to the population at large. Conclusions should not be generalized broadly to other populations pending further research. The sample size also limited our ability to detect small between-person associations between cognitive abilities and overall physical activity. Cognitive abilities were assessed using self-reports and it is unclear how those perceptions correspond with specific executive functions in young adults or whether they attenuated relations with behaviors. Of course, the alternative interpretation of this limitation is that perceived cognitive abilities provide unique insight from a patient-reported perspective which cannot be gained from performance-based measures and has implications for help-seeking, openness to intervention and outcome expectations for health behaviors. Even modest changes in these outcomes are noteworthy because they have crossed the threshold of being noticed by the person experiencing the change. Our measures of overall physical activity and sedentary behavior were based on the average daily levels of those behaviors over a two-week period. Although this monitoring period should provide a valid estimate of individual differences in behavior (Tudor-Locke et al., 2005), it may not provide a valid estimate of differences in fitness-based adaptations that underlie some differences in cognition. Finally, the physical activity and sedentary behavior measures were relatively molar and insensitive to differences in the type of behavior.

In summary, this study revealed that daily physical activity was associated with greater perceived cognitive abilities. Links between daily sedentary behavior and perceived cognitive abilities were mixed and warrant further research with more fine-grained measures of sedentary behavior. This study extended the literature by documenting within-person processes linking (in)activity and cognition for the first time. Although knowledge of the cognitive consequences of (in)activity is unlikely to suffice for behavior change, such knowledge may facilitate intention formation as a precursor to behavior change. Given the need to increase activity and decrease inactivity during the transition into adulthood (Haase, Steptoe, Sallis, & Wardle, 2004), the daily cognitive benefits of physical activity merit consideration for dissemination in public health campaigns that target college students.

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