Associations Between Short and Long Bouts of Physical Activity with Executive Function in Older Adults

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ORIGINAL ARTICLE

Associations Between Short and Long Bouts of Physical Activity with Executive Function in Older Adults

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Abstract

Greater amounts of moderate-to-vigorous physical activity (MVPA) are frequently associated with better cognitive function in older adults. The 2008 US physical activity guidelines recommended obtaining activity in at least 10-min bouts to achieve health benefits. In the context of brain health, the parameters of MVPA that are necessary to achieve and optimize cognitive benefits are not well understood. Here, we examined whether the association between MVPA and executive function in older adults varied as a function of whether activity was primarily obtained by engaging in MVPA bouts lasting < 10 min compared to engaging in MVPA bouts lasting ≥ 10 min. We collected data on 96 community-dwelling adults aged 55–86 years (mean $= 65.77 \pm 7.97$) without dementia. Executive function was assessed by performance on Stroop and Flanker tasks. MVPA was measured using a multi-sensor SenseWear armband. Consistent with prior literature, after controlling for age, gender, race, body mass index, and time wearing the armband, greater amounts of MVPA were associated with lower Stroop and Flanker interference (all p values $\leq .018$). After dividing the MVPA into bouts, we found that MVPA accumulated in bouts of ≥ 10 min was negatively associated with Stroop and Flanker incongruent RT and Stroop interference (all p values $\leq .029$). When examining MVPA accumulated in bouts that were < 10 min in duration, we found a negative association with Flanker incongruent condition response time ($p = .011$). However, in both of these analyses, after controlling for total accumulated minutes of MVPA, only the association between MVPA in bouts of < 10 min was with Flanker incongruent RT ($p = .019$). These results suggest that total accumulated minutes of MVPA, independent of the duration of the bout, may be most important in relation to cognitive performance in older adults. Our results may have important implications for physical activity recommendations in older adults and support that accumulating MVPA in bouts < 10 min in duration may also have significant cognitive benefits.

Keywords Physical activity · Executive function · Older adults · Exercise

Introduction

Physical activity influences neurocognitive functioning in late adulthood. Observational studies and randomized interventions find that engaging in more moderate-to-vigorous physical activity (MVPA) is associated with better performance on a variety of neurocognitive tasks, especially those involving executive functioning (EF) (Coetsee and Terblanche 2017; Colcombe and Kramer 2003; Eggermont et al. 2009; Etnier et al. 1997; Guiney and Machado 2013; Hillman et al. 2004). These effects are found across populations, including individuals who are cognitively normal and those with neurodegenerative diseases (Heyn et al. 2004; Hillman et al. 2008; Lautenschlager et al. 2008; Smith et al. 2010; Yu et al. 2017; see Carvalho et al. 2014 for review). For example, prospective observational studies find that older adults who participate in greater amounts of MVPA have a lower risk of experiencing future cognitive impairment and are less likely to convert to mild cognitive impairment or dementia (Baker et al. 2010; Laurin et al. 2001; Smith et al. 2010; see Bherer et al. 2013 for review). Randomized controlled trials have also shown that MVPA improves

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neurocognitive functioning, especially for EF, over periods of time ranging from one to 12 months (Colcombe and Kramer 2003; Kramer et al. 1999; Smiley-Oyen et al. 2008). This literature has shown that physical activity is associated with better performance on a number of EF tasks, including the Stroop and the Flanker tasks, both of which measure inhibitory control (Coetsee and Terblanche 2017; Giles et al. 2017; Hillman et al. 2006).

Although the protective effects of physical activity on neurocognitive functioning have been well established, the parameters for how MVPA is accumulated for maximal gain to cognitive function have not been explored. Specifically, the 2008 U.S. federal physical activity guidelines emphasize that MVPA should occur in bouts, or periods of time, that last for ≥ 10 min (Committee 2008). However, despite this recommendation, there is mixed evidence regarding whether the duration of MVPA bouts is the primary factor influencing health outcomes or whether simply the total accumulated amount of activity is more important than the duration of any bout. For example, some cross-sectional studies find that bouts of ≥ 10 min are more beneficial to some metabolic and cardiovascular health outcomes (e.g., obesity, hypertension) than bouts of activity that are < 10 min (Di Blasio et al. 2014; Strath et al. 2008). Other studies have found that bouts of MVPA lasting < 10 min were more beneficial to other health outcomes (e.g., blood pressure, blood glucose) than bouts of longer duration (Ayabe et al. 2012, 2013; Gay et al. 2016; Glazer et al. 2013; White et al. 2015; Wolff-Hughes et al. 2015). Yet, other studies have found no meaningful differences for health outcomes (e.g., body mass index, all-cause mortality) between MVPA accumulated in bouts < 10 min in duration compared to bouts of ≥ 10 min (Cameron et al. 2017; Clarke and Janssen 2014; Fan et al. 2013; Jefferis et al. 2016; Saint-Maurice et al. 2018). Most importantly for this study, there is a lack of published work that has examined whether there are differential associations between MVPA and cognitive benefits when the MVPA is accumulated in shorter (< 10 min) or longer (≥ 10 min) bouts. There is myriad support that physical activity is related to cognitive functioning, and specifically EF (e.g., see Voelcker-Rehage et al. 2010). This relationship suggests that MVPA accumulated in bouts of varying duration may be differentially related to EF. However, no research to date has directly examined this relationship. This study addresses this scientific gap.

The primary purpose of the present study was to examine if MVPA accumulated with different bout durations (bouts of < 10 vs. ≥ 10 min) has differential associations with executive functioning. Given the evidence from prior scientific literature, the hypotheses of this study were twofold: (1) greater volume of accumulated MVPA would be associated with better EF task performance, and (2) bouts of MVPA accumulated in durations of ≥ 10 min would be more strongly associated with EF than bouts of MVPA of shorter duration.

Methods

Participants

One hundred and four older adults were recruited for a cross-sectional study examining the relationship between habitual physical activity and neurocognitive performance. Participants were eligible if they were between the ages of 55 and 90, English-speaking, and obtained a score of 24 or higher on the Mini-Mental Status Examination, a brief screening for cognitive impairment. Exclusion criteria included history of blindness or color blindness, head trauma, brain surgery, or a neurological disorder (e.g., dementia, stroke). Participants were recruited through community advertisements in western Pennsylvania and Pitt+Me, a website from the University of Pittsburgh's Clinical and Translational Science Institute dedicated to connecting potential research participants with specific studies. All participants signed an informed consent approved by the University of Pittsburgh and in accordance with the Declaration of Helsinki.

Physical Activity Assessment

All participants were provided with a multi-sensor SenseWear armband (BodyMedia, Pittsburgh, PA; Drenowatz and Eisenmann 2011; St-Onge et al. 2007) and were instructed to wear this device on their non-dominant arm for approximately one week. Participants were instructed to wear the armband continuously during this period of time, except when engaging in activities involving water. All participants wore the armband for at least three days and > 70% of the time that it was in their possession. To control for variability in the time of wearing the armband, the total duration that the device was worn was included in all analyses.

MVPA was defined as any interval when activity level reached an intensity of a metabolic equivalent (MET) greater than or equal to 3.0 (Pate et al. 1995). The SenseWear armband recorded data for each minute that it was worn. Any minute of MVPA that followed a minute of non-MVPA was the first minute of a bout. Any minute of MVPA that preceded a minute of non-MVPA was the last minute of a bout. The number of, and minutes accumulated from, bouts in each category (i.e., < 10 or ≥ 10 min) were then counted for each individual and included in analyses described below. MVPA was then transformed into multiple variables: total number of bouts, number of bouts lasting < 10 min, number of bouts lasting ≥ 10 min, total volume of MVPA in minutes, minutes of MVPA accumulated from bouts < 10 min in duration, and minutes of MVPA accumulated from bouts ≥ 10 min in duration.

Executive Functioning Assessment

Participants completed computerized versions of the Stroop task (Stroop 1935) and a modified Flanker task (Eriksen and Eriksen 1974) to measure inhibitory control, a subdomain of EF. The Flanker task was added to the protocol after the start of the study, so only 63 participants had complete Flanker data. We report both response time (RT) and accuracy results for each task in Table 4, but our hypotheses and hypothesis testing focused on the interference and RT measures (Salthouse 2000).

The Stroop task required participants to indicate the color of a word presented on the computer screen, regardless of the meaning of the word. The task consisted of 165 trials (54 congruent, 48 incongruent, and 63 neutral) where the stimuli were presented on the screen for 1000 ms and participants had up to 2500 ms to respond, with an inter-stimulus interval of 1000 ms. In the congruent condition, the word presented to the participant matched the color of the text that it was written in (e.g., "red" written in red ink). In the incongruent condition, the word presented did not match the color of the text (e.g., red written in green ink). In the neutral condition, the word presented was not a color name (e.g., "table" written in red ink). Stroop interference, the hallmark measure of inhibitory function in the Stroop task, was calculated by the equation: (incongruent RT − congruent RT) / congruent RT (Van der Elst et al. 2006). Only response times from accurate trials were included in the calculation of Stroop interference.

A subset of participants ($n = 63$) completed a modified Flanker task, which asked participants to respond to a target stimulus that was centered between incongruent distractor stimuli. Participants saw the stimulus on the screen for 1000 ms and had up to 2000 ms to respond, with 2000 ms between stimuli presentation. In this task, the target and distractor stimuli were arrows. The Flanker task consisted of 200 trials split evenly between congruent and incongruent conditions. In the congruent condition, the center arrow points in the same direction as the flanking arrows. In the incongruent condition, the center arrow points in the opposite direction of the flanking arrows. Participants were asked to respond only to the direction of the target arrow by pressing one of two buttons on a standard keyboard—a left button if the center arrow was pointing left and a right button if the center arrow was pointing right. Like the Stroop task described above, interference scores were calculated based on RT of accurate trials: (incongruent − congruent) / congruent.

Statistical Analyses

Demographic and EF variables were all normally distributed. The relationships between physical activity, EF, age, gender, race, body mass index (BMI), and education were examined using bivariate correlations. Age and gender were included as covariates in all analyses due to evidence that these demographic factors may influence EF and the amount of physical activity individuals engage in (Troiano et al. 2008). Due to the significant associations between race and BMI with MVPA and EF, these variables were included as covariates in all analyses reported below. The number of minutes each participant wore the armband was also included as a covariate in all analyses to reduce the influence of the variability in wear time on the results. To determine if less wear time altered our findings, participants with fewer than 5 days of armband data ($n = 5$) were removed from analyses. Removing these individuals did not change our results; therefore, results from the full sample are reported below.

We confirmed Stroop and Flanker interference effects using paired t tests between incongruent and congruent conditions. Hierarchical linear regression models examined the relationships between the minutes of MVPA accumulated from each category of bouts (i.e., < 10 or ≥ 10 min), the number of bouts in each category, and Stroop and Flanker task performance. All regression models first included age, gender, race, and BMI as covariates, as well as total minutes wearing the multi-sensor armband to control for individual differences in the amount of time wearing the armband. Finally, we conducted three separate models to test our hypotheses: in model (1), total minutes of MVPA were included to understand the association between volume of MVPA and Stroop and Flanker performance. Model 1 tested our first hypothesis that the total amount of MVPA would be associated with Stroop and Flanker performance. In model (2), the accumulation of MVPA minutes from bouts lasting < 10 and ≥ 10 min were included to evaluate whether the duration of bouts has a differential association with Stroop and Flanker performance. Model 2 tested our second hypothesis that greater volume of MVPA minutes from longer bouts would be associated with Stroop and Flanker performance more strongly than MVPA accumulated from shorter bouts of activity. In model (3), total minutes of MVPA were included as an additional covariate to model (2). This final model tested whether any association between the MVPA accumulated from bouts of different durations and Stroop and Flanker performance could be simply explained by the total volume of MVPA (see Fig. 1). Models 2 and 3 were also run using the number of bouts in each category (i.e., number of bouts $<$ 10 min and number of bouts ≥ 10 min) to examine any differences between the count of bouts and the MVPA accumulated from those bouts relative to EF.

Results

Participant Characteristics

One hundred and four older adults were enrolled in the study. Of the 104 eligible participants, 8 were excluded due to:

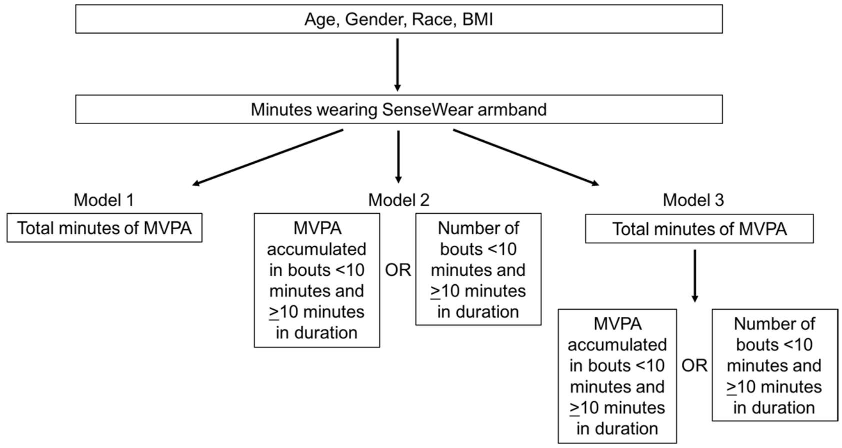

Fig. 1 Regression models

previous familiarity with the cognitive tests administered (1), computer data acquisition error (2), less than 70% adherence to wearing the armband (4), and technical error with retrieving the armband data (1). The final sample included 96 community-dwelling adults.

Participants' ages ranged between 55 and 86 years, with a mean of 65.77 years (SD = 7.97 years). The sample was 75% Caucasian, 45.8% male, and highly educated (mean years of education = 15.66 ± 2.88) (see Table 1 for details). Age, gender, and education were not significantly associated with neurocognitive task performance or physical activity variables (all p values ≥ .06). Race was significantly associated with RT in the Stroop and Flanker incongruent conditions, MVPA minutes accumulated in bouts ≥ 10 min in duration, and number of MVPA bouts ≥ 10 min in duration, such that Caucasian participants performed faster on the Stroop and Flanker tasks, accumulated more minutes in these bouts, and had more of these MVPA bouts than non-Caucasian participants. BMI was significantly associated with all MVPA variables, such that participants with higher BMI were engaging in lesser amounts of activity (see Table 2).

Physical Activity—Multi-Sensor Armband

Overall, participants wore the SenseWear armband for 6.56 days (mean = 6.56 ± 0.91 days) and an average of 22.62 h per day (mean = 22.62 ± 1.61 h). This was equivalent to 95% of the time that the device was in their possession (mean = 94.55 ± 5.95%). We controlled for the amount of time that the device was worn in our analyses. On average, participants engaged in 544.20 ± 615.94 min of MVPA across days that the device was worn. This is equivalent to 82.71 ± 87.84 min per day and 5.76% of the participants' time wearing the device spent participating in MVPA. However, there was a broad range of engagement in MVPA (range of approximately 8 to 4151 min) across the time that the armband was worn.

Participants engaged in an average of 164 bouts of MVPA of any duration across the period that the armband was worn. Of these bouts, 92.6% were < 10 min in duration, which accumulated to an average of 330 min of MVPA. Participants averaged 12 bouts (7.4%) of MVPA that were ≥ 10 min in duration that accumulated to an average of 231 min of MVPA (see Table 3 for details). The majority of participants (93 of 96) had fewer than 50 bouts that were ≥ 10 min in duration.

Executive Functioning and Physical Activity

Consistent with previous literature and our predictions, participants responded faster to the congruent versus incongruent conditions of both the Stroop and Flanker tasks (all p values < .001). Also, consistent with prior research, participants responded more accurately in the congruent versus incongruent conditions of both tasks (all p values < .001). RT and accuracy for both conditions of the Stroop and Flanker tasks are included in Table 4.

We predicted that higher levels of MVPA would be associated with better EF task performance as indicated by less Stroop and Flanker interference. Consistent with this hypothesis, we found that higher total MVPA accumulation was associated with less interference for the Stroop and Flanker tasks (all p values < .02) (see Table 5 for details).

We predicted that a greater volume of MVPA in bouts of ≥ 10 min in duration would be more strongly associated with EF than MVPA accumulated in bouts lasting < 10 min. Consistent

Table 1 Participant characteristics

	Mean	St. Dev.	Minimum	Maximum
Age	65.77	7.97	55	86
Education	15.66	2.88	8	22
BMI	28.04	5.54	18.73	42.76
Gender	45.8% Male			
Race	75% Caucasian			

St. Dev. standard deviation, *Education expressed in years; BMI body mass index expressed as kg/m^2*

Table 2 Bivariate correlations between demographic characteristics, physical activity, and EF. Correlations expressed as *r* (*p* value)

	Age	Gender	Education	Race	BMI
MVPA mins	.076 (.46)	− .053 (.61)	− .064 (.54)	− .198 (.06)	− .407 (< .001)**
Accum. of MVPA from bouts < 10 mins	− .007 (.94)	− .150 (.15)	− .121 (.24)	− .168 (.10)	− .422 (< .001)**
Accum. of MVPA from bouts ≥ 10 mins	.119 (.25)	.005 (.96)	− .024 (.82)	− .211 (.04)*	− .363 (< .001)**
Total no. of bouts	− .017 (.87)	− .131 (.20)	− .121 (.24)	− .174 (.09)	− .432 (< .001)**
No. of bouts < 10 mins	− .040 (.70)	− .153 (.14)	− .133 (.20)	− .160 (.12)	− .432 (< .001)**
No. of bouts ≥ 10 mins	.127 (.22)	.015 (.88)	− .020 (.84)	− .232 (.02)*	− .335 (< .001)**
Stroop INC RT	− .038 (.72)	.000 (1.0)	− .009 (.94)	.233 (.03)*	.120 (.26)
Stroop Effect	.110 (.30)	.189 (.07)	.169 (.11)	.033 (.76)	.112 (.29)
Flanker INC RT	.176 (.17)	− .120 (.35)	− .242 (.06)	.282 (.03)*	− .010 (.94)
Flanker INT RT	− .164 (.20)	− .066 (.61)	.089 (.49)	− .069 (.59)	.026 (.84)

Education expressed in years, *BMI* body mass index expressed in kg/m^2, *mins* minutes, *accum.* accumulation, *INC* incongruent condition, INT interference

*$p < .05$; **$p < .01$

with this hypothesis, more MVPA from bouts of ≥ 10 min was associated with less interference on the Stroop task ($\beta = -.529$, $p = .004$). The MVPA accumulated in either category of bouts was not associated with Flanker interference (see Table 5 for details). When examining the number of bouts of either < 10 or ≥ 10 min in duration, the same pattern of results was present, such that more bouts of ≥ 10 min in duration were associated with less Stroop task interference ($\beta = -.417$, $p < .001$), but not with Flanker interference.

Model 3 included total volume of MVPA as a covariate to test whether bouts of ≥ 10 min would be associated with EF independently of total minutes of MVPA. We found that, after controlling for total minutes of MVPA, only the MVPA accumulated in bouts < 10 min in duration was associated with Flanker incongruent RT ($\beta = 2.232$, $p = .019$). Neither the MVPA accumulated in bouts ≥ 10 nor < 10 min was associated with Stroop performance or Flanker interference (all *p*-values > .21). However, when we examined the number of bouts of < 10 min or ≥ 10 min in duration, neither category of bouts was significantly associated with any cognitive task performance (all *p* values > .06).

Discussion

We predicted that a higher volume of MVPA would be associated with better EF in older adults and that, consistent with the 2008 physical activity guidelines, bouts of ≥ 10 min would be associated with better EF and bouts of activity < 10 min in duration would not be associated with better EF. Consistent with our first hypothesis, we found that more MVPA was associated with better EF task performance even after controlling for demographic variables and the amount of time wearing the armband. Consistent with our second hypothesis, we found that a greater accumulation of MVPA minutes from, and number of, bouts ≥ 10 min in duration was associated with EF; however, these results did not remain significant when the total minutes of MVPA were included in the model. This

Table 3 Participants' physical activity characteristics

	Mean	St. Dev.	Minimum	Maximum
Total days worn	6.56	0.91	3.72	10.87
Total hours worn	22.62	1.61	15.30	24.00
On-body %	94.55	5.95	71.47	100.00
MVPA mins	544.20	615.94	9.00	4150.80
Accum. of MVPA from bouts < 10 mins	330.01	280.26	8.00	1527.00
Accum. of MVPA from bouts ≥ 10 mins	230.57	385.37	0.00	2623.00
Total no. of bouts	163.54	117.28	8.00	661.00
No. of bouts < 10 mins	151.68	100.94	8.00	534.00
No. of bouts ≥ 10 mins	12.11	19.26	0.00	127.00
Total light PA mins	1455.16	525.42	320.00	2797.00
Total sedentary mins	4921.86	1174.70	1210.00	11282.00

St. Dev. standard deviation, *mins* minutes, *accum.* accumulation *no.* number

Table 4 Executive functioning task performance

	Number	Mean	St. Dev.
Stroop			
CON RT	96	726.21	110.35
INC RT	96	894.67	169.47
Effect RT	96	0.23	0.13
CON ACC	96	0.95	0.09
INC ACC	96	0.82	0.20
Flanker			
CON RT	63	617.65	90.81
INC RT	63	728.86	99.76
INT RT	63	0.18	0.07
CON ACC	63	0.99	0.02
INC ACC	63	0.96	0.05

St. Dev. standard deviation, *CON* congruent condition, *INC* incongruent condition, *Effect* Stroop effect, *INT* interference score, *RT* response time measured in milliseconds, *ACC* accuracy

indicates that the total volume of MVPA may be a more important predictor of executive functioning than the duration or number of individual bouts of activity.

Our results from model 1 are consistent with prior literature showing that greater volumes of MVPA are associated with better EF (Coetsee and Terblanche 2017; Colcombe and Kramer 2003; Eggermont et al. 2009; Etnier et al. 1997; Guiney and Machado 2013; Hillman et al. 2004). This replication of previous findings allowed us to probe this relationship further by examining the effects of bouts < 10 and ≥ 10 min for the first time in the context of cognitive outcomes. The 2008 Physical Activity Guidelines (Committee 2008) suggest that bouts of MVPA lasting ≥ 10 min should be "counted" towards the recommended volume of activity of 150–300 min per week. Based on these guidelines, we predicted that more accumulation of MVPA from bouts of ≥ 10 min, and more of these ≥ 10-min bouts overall, would be associated with better cognitive performance, while the volume from and number of < 10-min bouts would not be associated with cognitive performance. When we examined the MVPA accumulated from each of these bout categories (i.e., model 2), we found evidence to support that achieving both a higher volume of minutes from, and number of, ≥ 10-min bouts was associated with better EF performance. These results are consistent with prior literature showing that minutes of MVPA accumulated in bouts of this duration were associated with a variety of enhanced health outcomes (Di Blasio et al. 2014; Strath et al. 2008). The results of this current study also support the notion that more MVPA accumulated in bouts that are ≥ 10 min in duration is beneficial to neurocognitive outcomes.

However, when we controlled for the total minutes of MVPA (i.e., model 3), only one association between MVPA accumulated in bouts < 10 min in duration and EF remained significant. This means that bout duration may only be significant outside of the consideration of the total volume of MVPA obtained. These results suggest that bouts lasting ≥ 10 min may not be different than bouts lasting < 10 min relative to EF measures. Instead, individuals who achieve higher volumes of MVPA—regardless of the duration of the bout—are achieving better cognitive performance.

Although there is evidence to suggest that MVPA accumulated in bouts that are ≥ 10 min in length are more beneficial that MVPA accumulated in bouts of shorter duration for a variety of health outcomes, there is also evidence to the contrary (Cameron et al. 2017; Clarke and Janssen 2014; Fan et al. 2013; Jefferis et al. 2016). The novel finding of this current study is that with regard to executive function, the total volume of MVPA, rather than the duration of the bouts in which the MVPA is accumulated, appears to be important to emphasize.

It is possible that there is a difference in the underlying mechanisms by which bouts of short versus long duration influence physiology. For example, a greater volume of

Table 5 Models 1 and 2—the relationships between executive functioning and (1) total volume of MVPA in minutes, (2) minutes of MVPA accumulated from bouts of < 10 or ≥ 10 min, and (3) number of bouts < 10 or ≥ 10 min

	Stroop INC			Stroop Effect			Flanker INC			Flanker INT		
	β	p	R^2	β	p	R^2	β	p	R^2	β	p	R^2
MVPA mins	*− .271*	*.018**	*.130*	*− .417*	*< .001***	*.232*	.058	.698	.131	*− .562*	*< .001***	*.326*
Accum. of MVPA from bouts < 10 mins	.215	.276	*.160*	− .036	.535	*.257*	*.636*	*.011**	*.226*	− .411	.074	*.326*
Accum. of MVPA from bouts ≥ 10 mins	*− .471*	*.015**		*− .529*	*.004***		*− .512*	*.029**		− .176	.413	
No. of bouts < 10 mins	.176	.380	*.138*	.240	.198	*.261*	*.588*	*.010**	*.229*	− .273	.193	*.313*
No. of bouts ≥ 10 mins	*− .399*	*.038**		*− .609*	*.001***		*− .432*	*.034**		− .289	.129	

All analyses controlled for age, gender, race, BMI, and minutes wearing the multi-sensor armband. The values for the accumulation of MVPA and number of bouts in each category are reported *without* controlling for total volume of MVPA. Values in italics indicate statistical significance

INC incongruent, *INT* interference, *mins* minutes, *accum.* accumulation, *no.* number

*p<.05; **p<.01

MVPA accumulated in bouts of ≥ 10 min may be related to increased cardiorespiratory fitness (CRF) levels (Warburton et al. 2006), and higher CRF is associated with more efficient resting cerebral blood flow (Brown et al. 2010). Better cerebrovascular functioning is associated with better neurocognitive functioning, particularly in older adults (Lucas et al. 2012). MVPA accumulated in bouts < 10 min in duration, however, may be sufficient to induce cardiometabolic or related phenotypic changes, such as reduced blood pressure, glucose regulation, insulin pathways, or adipose tissue. However, the design of this study did not allow for these potential mechanisms to be examined.

Additionally, certain factors may mediate the relationship between MVPA and inhibitory control. The current study did not employ any neuroimaging techniques, though there is evidence that changes in brain volume, connectivity, or other metrics may be mediating the relationship between MVPA and cognition (for review, see Stillman et al. 2016). One example of this is that increasing MVPA improved regional connectivity in frontal networks associated with executive functioning in a 12-month aerobic exercise intervention of older adults (Voss et al. 2010). These results suggest that accumulating more MVPA is associated with more efficient neural functioning. It is also possible that other modifiable lifestyle factors mediate this relationship. One such possibility is the effect of diet on executive functioning. Maintaining a healthy diet is associated with better cognitive task performance and reduced risk of dementia over time (Lourida et al. 2013). It is possible that those individuals obtaining greater amounts of activity are also engaging in healthier diets. Without a dietary assessment, we are not able to test whether a modifiable factor such as this could play a causal role in the relationship between inhibitory control and MVPA.

There are several limitations that may influence the results of this study. First, the neuropsychological battery used was limited and does not allow us to make claims about other domains of cognition that are sensitive to the aging process (e.g., memory). It is possible that the effects of MVPA on inhibitory control are not relevant for other areas of cognition that are less sensitive to the effects of aging (e.g., language). Second, this study was cross-sectional, and therefore, we are limited in making casual claims about MVPA, duration of bouts, and EF. It is possible that our results are due to a bidirectional relationship between MVPA and EF, such that individuals who perform better on these cognitive tasks are also leading healthier, more active lifestyles. Third, many variables that may be related to MVPA and/or executive functioning were not measured. It is possible that these third variables mediate or moderate the relationship between MVPA and EF. Fourth, very few of the total bouts measured from all participants were ≥ 10 min long. That is, the majority of participants who were getting MVPA were getting their activity in bouts shorter than 10 min in duration. This makes it difficult to discern whether there is a threshold for MVPA to have beneficial effects on EF since few participants had a large number of bouts that exceeded 10 min.

It is important to note that our statistical models did not consider the effects of CRF in this study. However, CRF and habitual PA are related, and this study only examined the relationship between EF and MVPA bouts in an older adult population. While it is possible that individuals in our sample with higher CRF were those who demonstrated the highest levels of inhibitory control, it is also likely that those individuals with the highest levels of CRF were also those engaging in the most MVPA. Future research needs to examine these possible associations with CRF.

Importantly, this study did not systematically manipulate the total dose, duration of MVPA bouts, or number of MVPA bouts. In some models, the total volume of MVPA was included as a covariate, but deciphering the impact of bouts versus that of total activity is challenging in this type of design in which those individuals getting a higher volume of MVPA from and number of bouts in intervals ≥ 10 min are also the individuals achieving the most activity. Yet, despite this challenge, we believe our results speak to the important issue of the parameters of activity that are needed to achieve cognitive benefits. Based on our results, it appears that bout duration may be less important than the total amount of MVPA obtained. Although we used different regression models to test our hypotheses, thoroughly examining these effects in a cross-sectional design limits the strength and type of interpretations we can make. Future studies should recruit larger sample sizes with more variability in both the number of bouts and the amount of total activity, in addition to randomized trials that systematically manipulate bouts versus total activity levels.

Additionally, it is possible that our participants took short breaks during their MVPA bouts that led to an increase in the accumulation of MVPA during bouts < 10 min rather than during bouts ≥ 10 min. MVPA can be strenuous, and it is reasonable for older adults to take breaks. However, we were not able to determine if there is a differential effect on cognition between, for example, a 1-min versus 4-min break in MVPA. Addressing this in future work would be beneficial for understanding the mechanisms by which MVPA influences cognition.

Despite these limitations, this study obtained a sample of participants with a wide range of MVPA that is likely representative of the general population. With this variability in activity levels, we were able to examine the associations between bouts < 10 or ≥ 10 min on EF. To our knowledge, this is the first study to test these relationships. Given the current recommendations for healthy adults to reach 150 min of MVPA per week in bouts of ≥ 10 min, we were able to provide evidence that the amount of MVPA overall seems to be important regardless of the duration of the bout.

This was the first examination of the effects of the duration of bouts of MVPA on neurocognitive outcomes. We found evidence that the total volume of MVPA was more influential on EF than the breakdown of longer (i.e., ≥ 10 min) or shorter (i.e., < 10 min) bouts of activity. These results may inform future physical activity interventions that seek to understand the mechanisms that underlie how MVPA benefits executive functioning. Importantly, these results serve as additional support for prescribing physical activity as an intervention to enhance neurocognitive function in older adults. Rather than requiring older adults to exercise for long periods of time, our results show that shorter bouts of activity may be just as beneficial to cognitive functioning. Shorter bouts of activity are likely more attainable for many people and especially for older adults. Notably, older adults who are physically active and achieving short bouts of activity may be significantly reducing their risk of cognitive impairment. Future work should examine the relationship between long and short bouts of MVPA and other domains of neurocognitive functioning, in addition to understanding any mechanistic differences that come from different durations of activity.

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