Associations of device-measured physical activity, sedentary behavior, and executive function in preadolescents: A latent profile approach

Running head: PHYSICAL ACTIVITY AND EXECUTIVE FUNCTION

Abstract

***Purpose*:** This study investigated the associations between physical activity (PA), sedentary behavior (SB) and executive function (EF) in preadolescents. ***Methods*:** One hundred and twenty preadolescents were recruited from two Hong Kong primary schools. PA and SB were recorded for seven consecutive days by accelerometer. EF performance, including inhibition (Stroop task, ST; Flanker task, FT) and working memory (Sternberg Paradigm task, SPT) were measured. Body mass index (BMI) and cardiorespiratory fitness (CRF, multi-stage fitness test) were tested. Latent profile analysis explored the profiles of PA and SB in preadolescents. ***Results*:** Three distinct profiles were identified: Low Activity, Average Activity, and High Activity. Participants in Low Activity performed worse in the accuracy of ST (vs. Average Activity, $P = 0.03$; vs. High activity, $P < 0.01$), FT (vs. Average Activity, $P = 0.02$; vs. High activity, $P < 0.001$), and SPT (vs. Average Activity, $P < 0.01$; vs. High activity, $P < 0.01$). No significant difference was observed between participants with Average

Activity and High Activity. No significant association was observed for profiles on BMI and CRF. ***Conclusion*****:** Supplementing the consensus of the literature that moderate-to-vigorous physical activity benefits cognition, we conclude that light physical activity enhances preadolescents' executive functioning.

Keywords: exercise; cognition; person-oriented approach; inhibition; working memory

Introduction

Executive function (EF) comprises a constellation of functions, including inhibitory control, cognitive flexibility, and updating information in working memory (9). EF is crucial for preadolescents' academic achievement and serves as the capstone for social behaviors expressed across the lifespan (9). Sedentary behavior (SB) refers to any waking behavior characterized by an energy expenditure ≤1.5 metabolic equivalents, such as in a sitting, reclining, or lying posture (42). For preadolescents, SB such as television viewing is negatively associated with EF development (43). Alternatively, physical activity (PA), which comprises all modes of movement caused by muscular activity resulting in increased energy expenditure (25), has been reported to “offset” the negative effect of SB on health (5). A review study has indicated that both light-intensity physical activity (LPA) and moderate-to-vigorous-intensity physical activity (MVPA) are associated with enhanced cognition (including EF) in 6–13-year-old children (14).

Given the impact of SB and PA on EF, schools have been criticized for minimizing opportunities for PA, and prolonging SB, in the school day (16). The reasons include emphasis placed on academic achievement in school, lack of active commuting to school and availability of electronic devices (16). The WHO guideline (2020) recommends that children and adolescents should engage in at least 60 minutes of MVPA per day (5). However, the Hong Kong Report Card (2018) showed that over 90% of school-aged children and adolescents do not participate adequately in PA (8). Considering that the counterbalance of PA and SB may predict preadolescents’ EF (48), low levels of PA and high amounts of SB in schools are of great concern.

Over the past decade, a number of reviews have been published on the relationships between PA, SB, and EF, concluding that PA is positively associated with EF (10,14). However, the evidence for the effects of PA on EF is inconclusive. In a recent review, it was found that only 48% of studies with high methodological quality observed a significant positive effect of PA intervention on EF (36). A meta-review showed no effect of classroom PA intervention on EF in school-aged children (46). Inconsistency also exists across multiple measures for the specific domain of EF. For example, several reviews reported a small to moderate effect of PA intervention on inhibition (1,14,19) and working memory (1,14), while another meta-review found that chronic PA had a small positive effect on inhibitory ability but had no effect on working memory in children (47). The inconsistent result therefore invites further investigation of the effect of PA on the specific domains of EF.

In addition to examining the variable-centered analysis of the effects of PA and SB on EF, researchers are beginning to take an interest in how PA profiles (a combination of time spent on different physical-related behaviors such as LPA, MVPA and SB) holistically affect EF. A complementary approach is to use latent profile analysis to identify subsets of individuals based on PA and SB patterns (34). By grouping the individuals into profiles based on the observed variables, this approach allows for identifying profiles/groups of individuals and examination of differences between these profiles. In particular, knowing whether the patterns of PA and SB are related to EF in preadolescents could inform interventions aimed at enhancing EF in this population.

To date, latent profile analysis has been used to classify survey-based PA data (45), and explore its association with academic burnout (6), and healthy diet behavior (4) in children. The devices-measured PA in children was classified independently (without SB) (20), and were used to investigate the associations with mental status (38). To the best of our knowledge, no study has investigated the associations between PA and SB profiles (using a device-measured approach) and EF in preadolescents. Compared to the survey-based approach, device-measured PA is believed to provide more accurate estimates of energy expenditure and eliminates many of the issues of recall and response bias (31). Therefore, the current study examined the associations between accelerometry-derived day-to-day PA and SB profiles and their relations with EF performance in preadolescents. We hypothesized that profiles characterized by more MVPA and less SB were associated with better EF.

Method

Participants

A total of 184 right-handed students from two elementary school in Hong Kong were recruited using convenience sampling, of whom 120 completed the entire study (50.8% males, mean ± SD: age = 10.8 ± 0.5 yrs; body weight = 36.6 ± 9.1 kg; height = 144 ± 8 cm; body mass index (BMI) = 17.3 ± 3.1 kg/m^2). The remaining 64 individuals were excluded due to invalid data in accelerometers, EF, or CRF. Students who suffered from severe neurological diseases, dyslexia, color blindness, special needs, and sensory deficits were excluded from the study. Before the study, parents of the students signed the consent form. The ethics approval was obtained from the University Ethics Committee (No. 2017-2018-0404).

Experimental design

The present study was a cross-sectional study. Participants completed EF tests and PA recording within two weeks. During the trial day, EF was measured first to avoid the effect of exercise on EF task performance. The EF tests, including Stroop task (ST), Flanker task (FT), and Sternberg Paradigm task (SPT), were performed via the same battery which has been adopted in various studies (15,41,49). The EF tasks were conducted in a quiet classroom at school with a 22 ºC constant temperature. Participants were required to practice the entire testing battery twice on the trial day, to ensure they were familiar with the tasks. After a short break, a formal test was arranged. The sequence of EF tasks was consistent for all participants. The 15-m version of the multi-stage fitness test was performed, on an outdoor sports facility, to measure cardiorespiratory fitness. A 10-min standardized warm-up protocol (consisting of 400-m jogging and stretching) was adopted before completing the multi-stage fitness test. Finally, participants wore the accelerometer for one week to record SB and PA.

Measurements

Participants' PA and SB were objectively measured using the Actigraph accelerometer (GT3X, Pensacola, FL, USA). They were instructed to wear the accelerometer for seven consecutive days, removing it only for water-based activities (such as swimming, bathing or showering). Similar to previous studies (2,32), valid data were considered to be at least 480 min/day of wearing time for at least 2 weekdays (i.e., 9 a.m. to 5 p.m.) and 1 weekend day (i.e., 10 a.m. to 6 p.m.), corresponding to a reliability of 0.7 for three days measurement in a large population study of 11-year-olds (26). The Evenson cut-point has been chosen (SB = 0-99, LPA = 100-2295, and MVPA ≥ 2296 counts/min (12) which has shown to be useful for youth aged 5-15 years (44). The ActiLife package (version 6.13.4, Actigraph, Pensacola, FL, USA) was used for data analysis.

Cardiorespiratory fitness was measured using a 15-m version of the multi-stage fitness test (i.e., maximal oxygen consumption; $VO_{2\,max}$) (33). The protocol started at 8.0 km/h, which increased to 9.0 km/h and then increased 0.5 km/h every minute. Participants were required to shuttle run for 15-m following the audio instruction to the point of volitional exhaustion, or until they could no longer keep pace with the audio signal. The performance was recorded and analyzed using the Ramsbottom equation (33).

For the EF tests, ST (40) and FT (11) were used to measure attention and inhibitory control. SPT (39) was used to measure working memory. Each task comprised two sections: the practice section (to have the participants get familiar with the task) and the main section (where the participants' performance was recorded and scored). Before each main task, participants practiced in 3-6 stimuli with feedback. After the main task began, no feedback was provided. The three main tasks took 12-15 minutes to complete (i.e., ~2 min for ST, ~3 min for FT and ~5 min for SPT). The corrected reaction time and accuracy were recorded for analysis.

The ST consists of 60 stimuli with 20 congruent and 40 incongruent stimuli. Congruent stimulation occurs when the meaning of a word and its font color is the same. Participants were tasked with pressing the color of the word. Incongruent stimulation is the opposite: the meaning of the word and the color on the screen do not align. Participants were asked to press the color of the word instead of reading the word itself. FT includes the two stimulations as ST, but with an equal number of congruent and incongruent stimuli for a total of 60 stimuli presented in a randomized order. The congruent condition refers to the arrows showing the same direction as the central one, and the incongruent condition refers to the arrows pointing in a different direction than the central arrow. Participants were asked to press the right or left arrow on the keyboard to respond.

Regarding SPT, participants were instructed to remember a series listed number with a random sequence. The task consists of three ascending levels with the beginning of the one-item level and then three- and five-item levels. At the beginning of each level, participants are assigned a target number or letter that they should remember. During the test, a number or letter appears on the screen, and participants should select whether it is one of the assigned letters or a number by pressing the right arrow key, or whether it is a distraction by pressing the left arrow key. The correct answer was counterbalanced between the left and right arrows for each level.

Statistical analysis

Statistical analyses were conducted in Mplus Version 8.1. All SB, LPA, and MVPA were subjected to a robust maximum likelihood estimation of latent profile analysis. In the analysis, 1000 random starting values were used to ensure the validity of each class solution. The number of latent classes (groups) was determined as follows. Beginning with a single latent class, additional classes were added in sequence, until a model was found that met optimal selection criteria. In the present study, the optimal statistical number of classes was determined using the Bayesian Information Criterion (BIC), the sample-size Adjusted BIC (ABIC), the Lo-Mendell-Rubin likelihood ratio test (LRT), and the Adjusted LRT (ALRT). Lower BIC and ABIC values indicate a better model. The LRT and the ALRT test a model with K classes versus a model with K-1 classes. A significant P value indicates that the model with K classes is better than the model with K-1 classes. A non-significant P value indicates that the model with K classes does not improve the model with K-1 classes. Although entropy is generally not used to determine the model with the optimal number of classes, it is useful as it summarizes classification accuracy (whether individuals are classified neatly into one and only one category). Entropy varies from 0 to 1, with values closer to 1 indicating fewer classification errors. The final model was chosen based on both statistical results and interpretation.

The relations between profiles and constructs related to EF (i.e., ST, FT, SPT) and fitness (i.e., predicted VO_{2max}, BMI) were examined by Wald chi-square tests (i.e., Bolck, Croon, and Hagenaars [BCH] method). The BCH procedure is the most robust and recommended method for examining relationships between classes and continuous variables (3).

Results

To identify the optimum number of profiles of PA and SB, we computed models with 1 to 5 profiles. Table 1 provides the BIC, ABIC, LRT, ALRT and entropy for these models. Both the BIC and ABIC decreased sequentially from the 1- to 2- to 3- to 4-profiles. The BIC value for the 4-profiles model was slightly lower than that of the 3-profiles model (ΔBIC = -4.92), and the ABIC value for the 4-profiles was lower than the 3-profiles model (ΔABIC = -17.56). The BIC was negligibly higher in the 5-profiles model than the 4-profiles model (ΔBIC = 3.12), and the ABIC was lower in the 5-class model than the 4-class model (ΔABIC

= -9.54). The LRT value for the 2-profiles LPA solution was significant at P < 0.001. The ALRT values for the 2-, 3- and 4-profiles LPA solutions were significant at P < 0.001. These values were not significant for the 5-profiles model. Collectively, these findings do not support the 5-profiles model, and it is not necessary to test models with more profiles. The overall classification accuracy (Entropy) was 0.98 for the 1-profile model and 0.90 for the 2-, 3- and 4-profiles model.

Although there was support for 3- and 4-profiles models, the improvement of the 4-profiles model over the 3-profiles model was negligible and mixed (given the BIC value and LRT p-value). For the 3-profiles model, the percentage of individuals correctly classified were 93.2% for profile 1, 92.5% for profile 2, and 99.9% for profile 3. For the 4-class model, the percentage of individuals correctly classified were 90.7% for profile 1, 85.5% for profile 2, 91.7% for profile 3, and 99.8% for profile 4. These findings indicate greater parsimony for the 3-profiles model than the 4-profiles model. Thus, the 3-profiles model was applied in the current study. Profile 1, 2, and 3 consisted of 31.67% (N = 38), 25.83% (N = 31), and 42.50% (N = 51) of the sample, respectively. Given the mean of PA and SB in each profile (see Fig. 1), profile 1 (SB = 1195.93, LPA = 194.45 and MVPA = 49.62 min) was named as “Low

Activity", profile 2 (SB = 1006.29, LPA = 353.92 and MVPA = 79.79 min) was named as "Average Activity", and profile 3 (SB = 616.40, LPA = 678.29 and MVPA = 145.32 min) was named as "High Activity". The three profiles have a balanced sex composition (male in Profile 1 = 55.26%, Profile 2 = 51.61 %, and Profile 3 = 47.06 %. Chi-square difference test shows that sex is not significantly associated with profile allocation)

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No significant difference was observed among three profiles for reaction time in the three EF tests (all $P > 0.05$). For ST accuracy, students in the Average Activity and High Activity performed better than those in Low Activity ($\chi^2 = 4.81$, $P = 0.03$ for Average Activity; and $\chi^2 = 7.35$, $P < 0.01$ for High activity:). No group difference was observed between the Average Activity and High Activity groups. For FT accuracy, students in Average Activity and High Activity performed better than those in Low Activity ($\chi^2 = 5.2$, $P = 0.02$ for Average Activity; and $\chi^2 = 15.27$, $P < 0.001$ for High Activity). No group difference was observed between Average Activity and High Activity. For SPT accuracy, students belong to Average Activity and High Activity performed better than those in Low Activity ($\chi^2 = 9.59$, $P < 0.01$ for

Average Activity; and $\chi^2 = 11.1$, $P < 0.01$ for High Activity). No group difference was observed between Average Activity and High Activity. The means and standard deviations of EF tests were displayed in Table 2.

---Insert Table 2. ---

No group difference was observed in BMI or predicted VO_{2max} from the multi-stage fitness test (all $P > 0.05$) for the three profiles. The descriptive statistics and comparison are displayed in Table 3.

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Discussion

In the current study, the latent profile approach was first applied to investigate the PA and SB profiles of Hong Kong preadolescents (using accelerometry) and the association with EF. The latent profile analysis supported three profiles: Low Activity (prolonged SB and little PA), Average Activity (moderate SB, LPA, and little MVPA), and High Activity (a balanced SB, LPA, and MVPA). Results indicated that adolescents classified as Low Activity performed worse for accuracy in attention, inhibitory control (i.e., ST and FT) and working memory (i.e., SPT) compared with Average Activity and High Activity; with no significant difference observed between the Average Activity and High Activity groups. Furthermore, there was no difference between the three groups for reaction time in the three EF tests; nor were there significant differences between the activity profiles for BMI and cardiorespiratory fitness (i.e., predicted VO_{2max}).

Whilst evidence to date suggests that PA and SB are essential predictors of preadolescents' EF, the effect of combined PA and SB profiles on EF has not been investigated. Compared with previous studies that adopted survey data and variable-centered analysis (23,48), this study examined the profiles of PA and SB and its relationship with EF. Findings of this study revealed that Average Activity and High Activity performed better for accuracy in EF tasks than Low Activity, which is consistent with a recent survey study suggesting that low SB and high PA (both LPA and MVPA) were positively associated with EF in preadolescents (48). Similar results were also reported by previous review study suggesting that the PA has a beneficial effect on attention, working memory and processing speed (14). The beneficial effect may be explained by the changes in neurophysiological function (28). Specifically, the chronic effects of PA in neurophysiological functioning include improved resting-state attention, greater allocation of attentional resources and altered brain activation in the right anterior prefrontal cortex (28), which may benefit the EF performance.

However, there is some ambiguity in the evidence for PA and working memory studies in preadolescents. Sjöwall et al. (2017) reported no beneficial development of working memory for the active school (i.e., school with increased PA classes) as compared to the control school (i.e., school with regular PA classes) (37). In contrast, Kamijo et al. (2011) claimed in an RCT study that a nine-month PA program indirectly increased working memory in preadolescents through improved cardiorespiratory fitness (22). de Greeff et al. (2018) reported a small to moderate positive effect for the chronic PA programs on working memory in a meta-review (k = 8) (14). A possible explanation is that PA and working memory were measured by various instruments (e.g., self-report survey and device-measured PA; different cognitive batteries for working memory). The discrepancy in instruments may yield biased PA and working memory value, thus leading to mixed results. Another plausible explanation is that EF improves gradually over the school years (18), and working memory development was not evident before 11 or 12 ages (24). The natural development of working memory may bias the effect of PA on working memory (13,24).

Another key finding of the present study was that Average Activity and High Activity performed similarly on EF. This suggests the importance of replacing SB, by increasing LPA and MVPA. To date, efforts to increase PA have focused mainly on increasing MVPA. For instance, Kamijo et al. (2011) reported that a 9-month MVPA intervention improved accuracy in working memory (assessed on the Sternberg Paradigm) (22). Hillman et al. (2014) adopted the same intervention and reported the improved accuracy measured by the Flanker Task after the program (17). Additionally, van der Niet et al. (2016) found that following a 22-week MVPA program, inhibitory control (measured by the Stroop Test) and working memory (measured by Digit Span test) were improved, compared with the control group (29). However, in addition to MVPA, promoting health by increasing LPA and total PA should not be ignored. MVPA was reported to have no association with inhibition (measured by the Flanker Task) and working memory (measured by the Operation Span Task) (30). Furthermore, due to curriculum design, MVPA may be difficult to increase on school days (16). Thus, the present study provides important evidence for the development of PA guidelines and intervention studies for not only increasing MVPA, but also reducing SB and increasing LPA.

The positive effect of higher PA and lower SB on EF was observed for accuracy, but not reaction time. A possible explanation is that the reaction time was more vulnerable to the acute effect of PA, but not chronic PA. The finding is consistent with the aforementioned intervention studies, where reaction time was enhanced following acute PA, whilst accuracy was unaffected (17,22). Furthermore, a meta-analysis concluded that acute PA had a moderate positive effect on reaction time, but no effect on accuracy (27). Therefore, the acute effect of PA may affect reaction time, whereas chronic PA affects accuracy, on EF tasks. Future studies may further investigate this phenomenon.

Consistent with previous studies (29,35), there were no significant associations between the identified activity profiles and BMI or aerobic fitness (i.e., predicted VO_{2max}). For example, Ruiz et al. (2010) indicated that PA during leisure time positively influenced cognitive performance, but the beneficial effect was independent of cardiorespiratory fitness (i.e., predicted VO_{2max}) and BMI (35). Additionally, in a 22-week MVPA intervention study, no difference was found between the control and intervention groups on any physical fitness variables in preadolescents, including aerobic fitness, speed and agility (29). However, this is not consistent with a previous study indicating that VO_{2max} was positively correlated with time spent in vigorous activity in preadolescents (7). More recently, Jones et al. (2020) suggested that replacing SB or LPA with MVPA was consistently associated with losing weight (in girls only) and improving VO_{2max} in preadolescents (21). The inconsistencies may be attributed to varying study designs or methods by which the association with SB and PA were tested. More efforts are needed to further explore the relationships between the combined SB with PA profiles and physical fitness and BMI.

To the best of our knowledge, the present study is the first to adopt latent profile analysis to classify patterns of PA and SB, and examine the relationships between these profiles and EF, predicted VO_{2max} and BMI in preadolescents. Latent profile analysis used in this study allowed the exploration of the relation between physical activity profiles and EF in preadolescents, contributed to the variable-centered studies that only examined the relations between separate variables. This study also benefits from the device-measured PA and SB. Given that self-report measures of PA and SB are particularly prone to yield biased results, this study used device-measured PA and SB, which increased the reliability of the results. However, there were several limitations with our study. First, the accelerometer protocol excluded use during water-based activities, and it was possible that some activities (such as swimming) were not accounted for when developing the PA variables. Second, approximately 34.78% of participants were excluded from the analysis because of missing or invalid accelerometry data, potentially leading to sample bias. Third, owing to the cross-sectional nature of the study, the causality of the observed association cannot be determined. More longitudinal studies are needed to further understand the associations of combined SB and PA profiles with EF and clarify the mechanisms of these associations.

Conclusion

In conclusion, the present study suggested that the combined profiles of PA and SB are associated with EF in preadolescents. Preadolescents with higher PA and lower SB displayed enhanced accuracy across EF tasks. Findings of this study may aid in the development of evidence-based public health guidelines targeting the reduction of SB, and the subsequent improvement of EF, for preadolescents (i.e., keeping the overall time spent in SB low and replacing the SB with both LPA and MVPA).

Availability of data and materials

The data are available from the corresponding author, upon reasonable request.

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Figure 1. Time Spent on Physical Activity and Sedentary Behavior for Each Profile. SB: Sedentary behavior; PA: Physical activity; LPA: Light physical activity; MVPA: Moderate to vigorous physical activity. Low Activity N = 38; Average Activity N = 31; High Activity N = 51

Table 1. Fit Statistics of the Latent Profile Analysis Models

Model	BIC	Adjusted BIC	LRT P value	Adjusted LRT P value	Entropy
1-class	4694.39	4675.42	-	-	-
2-class	4404.08	4372.46	0.00	0.00	0.98
3-class	4374.06	4329.80	0.16	0.00	0.90
4-class	4369.14	4312.24	0.57	0.00	0.90
5-class	4372.26	4302.70	0.74	1.00	0.90

Note. BIC = Bayesian information criterion; LRT = Lo-Mendel Rubin likelihood ratio test

Table 2. Executive Function Performance across Three Latent Profiles (N = 120)

	Low Activity N=38	Average Activity N=31	High Activity N=51	Overall Wald χ^2
Stroop task				
Reaction time [ms]	1148.91(35.4)	1273.57(54.61)	1232.88(36.89)	χ^2= 4.14, P = 0.13
Accuracy [%]	88.55(2.74)	95.36(0.85)*	96.1(0.52)**	χ^2= 8.74, P = 0.01
Flanker task				
Reaction time [ms]	682.16(31.03)	699.52(29.62)	688.07(16.76)	χ^2= 0.16, P = 0.93
Accuracy [%]	88.64(2.48)	96.16 (1.8)*	98.4(0.29)***	χ^2=18.54, P < 0.001
Sternberg task				

Reaction time [ms]	914.13(32.44)	1004.08(61.35)	857.64(26.26)	χ^2=18.54, P = 0.051
Accuracy [%]	88.4(2.28)	96.47(0.77)**	96.25(0.59) **	χ^2= 11.1, P < 0.01

Note. Data are presented as mean (standard error)

* P < 0.05; ** P < 0.01; *** P < 0.001; all compared with Low Activity

Table 3. Physical Fitness across Three Latent Profiles (N = 120)

	Low Activity N=38	Average Activity N=31	High Activity N=51	Overall Wald χ^2
BMI [$kg{\cdot}m^{-2}$]	17.02(0.52)	16.96(0.62)	17.6(0.44)	χ^2= 1.1, P = 0.58
VO_{2max} [$ml{\cdot}kg^{-1}.min^{-1}$]	37.98(1.39)	35.28(1.55)	37.82(1.01)	χ^2= 2.05, P = 0.36

Note. Data are presented as mean (standard error)