Cross-sectional associations between 24-hour activity behaviours and mental health indicators in children and adolescents: a compositional data analysis

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Word count: 5080

Funding

This work was supported by The Waterloo Foundation under Grant #1669-3509.

Abstract

We examined associations between youth 24-hour activity behaviour compositions and mental health. Data were collected from 359 participants (aged 9-13 years). Activity behaviours (sleep, sedentary time (ST), light physical activity (LPA) and moderate-to-vigorous physical activity (MVPA)) were assessed using wrist-worn accelerometers. Questionnaires and a computerised cognitive test battery assessed mental health outcomes. Linear mixed models examined associations between activity behaviour compositions and mental health. Post-hoc analyses modelled the influence of reallocating fixed durations of time between activity behaviours on mental health. ST was associated with worse internalising problems (all participants; $p<0.05$) and poorer prosocial behaviour (primary school participants only; $p<0.05$), relative to the other activity behaviours. LPA was associated with worse cognitive test scores among primary school participants; $p<0.05$). For all participants, reallocating time to ST from sleep and MVPA was associated with higher internalising problems. Among primary school participants, reallocating time to ST from any other behaviour was associated with poorer prosocial behaviour, and reallocating time to LPA from any other behaviour was associated with lower executive function. Children's mental health may be promoted by schools integrating opportunities for MVPA throughout the day. Our results provide further evidence for the influence of daily activity behaviours on youth mental health.

Key words

Physical activity, sedentary behaviour, sleep, mental health, cognition

Introduction

The introduction of 24-hour movement guidelines for children and adolescents (1-3) has heralded a shift in the study of physical activity, sedentary behaviour, and sleep. In youth this has corresponded with a growth in research into the associations between health and 24-hour activity behaviour compositions (4-8). Most studies to date have focused on physical health outcomes such as obesity, cardiometabolic risk, fitness, and musculoskeletal health (4-6, 9). This research demonstrates that generally, higher volumes and intensities of physical activity, less time spent in sedentary behaviours, and longer sleep are beneficial for physical health in youth (4-6, 9). Less is known about the influence of activity behaviours on aspects of youth mental health, such as anxiety, depression, self-esteem, health-related quality of life, and cognitive function (10). In Europe, 12.8% of youth have at least one mental health disorder (11) with anxiety, depression, and low self-esteem particularly prevalent (12). This is mirrored in Australia (13.9%) (13), while among American youth prevalence of a diagnosed mental health disorder ranges from 3.2% (depression) to 9.4% (hyperactivity) with incidence of anxiety and depression increasing temporally (14). Mental health problems during childhood and adolescence increase with age (15), and are likely to impair mental and physical health and limit opportunities to thrive in adulthood (16). Therefore, it is important to identify ways to prevent youth mental health problems, with activity behaviours suggested as viable intervention approaches (17-19).

The relationship between mental health and youth physical activity is complicated by the interplay between different mental health outcomes, personal characteristics, and physical activity type, intensity, and context (10, 20). A recent review of reviews found inconsistent associations between youth physical activity and depression and self-esteem but stronger positive associations with cognitive function (21). No evidence was observed for a physical activity dose-response relationship with depression, self-esteem, or cognitive function, although positive changes in these outcomes as a result of physical activity interventions were reported (21). This concurs with Rodriguez and colleagues' 2019 systematic review and meta-analysis, which observed a small but significant intervention effect for physical activity and youth mental health (22). Moreover, physical activity interventions in school settings have significant moderate to strong beneficial effects on resilience, positive mental health, anxiety, and wellbeing (23). Youth sedentary time (ST) is significantly associated with depression and psychological wellbeing (22, 24), while a recent meta-analyses reported small but significant associations between overall ST and anxiety (25). Time spent using screens (e.g., TV viewing,

video gaming, computer use) has different associations with health than overall ST (25), and among youth there is moderately-strong and moderate evidence for screen time associations with depression and quality of life, respectively (19). Further, unfavourable behavioural conduct, poor self-esteem, and low social support are associated with screen use in youth (26-28). Sleep duration is consistently associated with quality of life and emotional regulation (29), internalising and externalising behavioural problems (30), although associations with cognitive function are inconsistent (29-31). However, other sleep dimensions such as quality, timing, and architecture and their interactions (29) may also be important influences on youth mental health.

For the first time, the combined associations between physical activity, sedentary behaviour, and sleep with youth mental health were recently reviewed (32). Meeting public health recommendations for all three behaviours was associated with better mental health when compared to youth who did not meet any of the recommendations, and a dose-response gradient was observed between the number of recommendations achieved and more positive mental health (32). To strengthen the evidence on this topic, recommendations from Sampasa-Kanyinga et al.'s review included the use of robust measures of activity behaviours, validated mental health indicators, and compositional analysis approaches (32). Our study reflects these recommendations and adds to the current knowledge in the area by employing device-based assessment of activity behaviours and examining their association with established measures of mental health and cognitive function within a compositional data analytical framework. The study aims were to (i) examine the cross-sectional associations between device-measured 24-hour activity compositions and validated mental health outcomes in a sample of children and adolescents, and (ii) investigate the predicted differences in mental health outcomes when time was reallocated between the activity behaviours.

Materials and Methods

Participants and settings

This cross-sectional study took place in the XXXX region of northwest England between April 2019 and March 2020. Ten primary schools and two secondary schools from two neighbouring semi-urban towns with similar sociodemographic characteristics were recruited. All children and adolescents aged 9-11 years (Years 5 and 6 of primary school) and 12-13 years (Year 8 of secondary school) in the 12 schools attended project presentations and were invited to take

part. All of the primary schools received curricular and extra-curricular physical activity and school sport provision from the local School Sport Partnership which employs physical education and physical activity specialists to deliver sessions. Physical activity resources and delivery in the two secondary schools was undertaken by the specialist physical education teachers in each school's physical education department. As such, the physical activity opportunities were similar between the participating primary and secondary schools, respectively. To be eligible to participate the students needed to be able to participate in activities of daily living and to provide written parent/carer informed consent and their own written assent. Six hundred and ninety-one students were informed about the project, 382 provided informed consent to participate (55.3% response rate), with 23 of these excluded from the analysis due to absence on the data collection days. As an incentive to take part in the project, each participant received a £10 shopping voucher following data collection. The study received ethical approval from the XXXXXX Research Ethics Committee (# SPA-REC-2018-007) which aligned to the principles of the Declaration of Helsinki.

Demographic measures

Participants' dates of birth, home post codes, and ethnicity were obtained from the schools' information management systems. Decimal age and 2019 Indices of Multiple Deprivation (IMD) scores (33) were calculated using data collection dates and home post codes, respectively. IMD scores provide an area-level relative measure of deprivation based on income, employment, education, health, crime, housing, and living environment (34). Area-level socioeconomic status (SES) was represented by the IMD decile for each participant.

Anthropometric measures

Height was measured to the nearest 0.1 cm using a portable stadiometer (Leicester Height Measure, Seca, Birmingham, UK), and body mass was measured to the nearest 0.1 kg using calibrated scales (813 model, Seca). Body mass index (BMI) was calculated for each participant, BMI z-scores were calculated (35) and IOTF BMI cut-points applied to classify the participants' weight status (36). For all measurements, the participants wore shorts and t-shirt with shoes removed.

Activity behaviours

Participants wore ActiGraph GT9X triaxial accelerometers (ActiGraph, Pensacola, FL, USA) on the non-dominant wrist for 24 $h \cdot day^{-1}$ over 7 days with accelerations recorded at 100 Hz.

Wrist-worn accelerometers have demonstrated excellent validity against energy expenditure (37) and can accurately classify physical activity intensities in youth (38, 39). Data were downloaded using ActiLife version 6.11.9 (ActiGraph, Pensacola, FL, USA), and saved as GT3X files, before being converted to raw csv file format for signal processing. These csv files were processed in R (http://cran.r-project.org) using GGIR v1.9.0 (40) which carried out autocalibration procedures (41), identified non-wear (42), and converted the raw triaxial accelerometer signals into 1 omnidirectional measure of acceleration (Euclidean Norm Minus-One; ENMO) expressed in milligravitational units (m*g*) (42). The ENMO metric has been used extensively (6, 39, 43-46), and ENMO values derived from non-dominant wrist accelerations share 87%-97% of explained variance with alternative raw acceleration metrics (47). ENMO values were reduced to per 5 s epochs and averaged over each of the 7 monitored days to represent average acceleration. Participants were excluded if accelerometer post-calibration error was > 10 m*g* (41) and if less than 3 valid week or weekend days of wear (i.e., at least 16 $h \cdot day^{-1}$ (48)) were recorded (49). Accelerometer non-wear was determined based on the SD and value range of the accelerations at each axis, calculated for 60-minute windows with a 15-minute sliding window (42). If for at least 2 out of the 3 axes the SD was less than 13 m*g* or the value range was less than 50 m*g*, the time window was classified as non-wear (42). By default, GGIR imputed non-wear data by the average at similar time points on other days of the week (5.0 ± 4.0% of data per day were imputed). Youth-specific non-dominant wrist ENMO cutpoints of 50 m*g* (50) and 200 m*g* (39) defined estimated ST/light physical activity (LPA), and moderate-to-vigorous physical activity (MVPA), respectively. Sleep duration was estimated using a polysomnography-validated accelerometer algorithm based on the distribution of change in the z-angle (i.e., corresponding to the axis positioned perpendicular to the skin surface) (51).

Mental health outcomes

Three questionnaires assessing mental health outcomes were completed by the children in class following scripted instructions from the second author in the presence of a teacher and two other researchers who were present to assist.

Self-esteem. The Rosenberg Self-Esteem Scale (RSES) (52) assessed self-esteem. The RSES is a 10-item scale which asks about feelings of self-worth in the last 14 days to produce a unidimensional measure of global self-esteem. The scale ranges from 0-30 with scores between

15 and 25 within 'normal range' and those below 15 suggesting low self-esteem (52). The RSES has demonstrated its criterion and construct validity and test-retest reliability (52, 53) and has been previously used with youth (53). Internal consistency of the RSES in our sample was Cronbach's α=0.85.

Depression. Depressive symptoms were assessed using the Mood and Feelings Questionnaire (MFQ) (54), which uses 33 phrases to ask participants how they have been feeling or acting in the last 14 days. Scores range from 0 to 66, with higher scores suggesting more severe depressive symptoms. Scoring 27 or higher may indicate the presence of depression (54).Validity and reliability of the MFQ have been demonstrated in clinical and community samples of children and adolescents (54, 55). Internal consistency of the MFQ in our sample was Cronbach's α=0.95.

Emotional and behavioural problems. Emotional and behavioural aspects of mental health were measured using the Strengths and Difficulties Questionnaire (SDQ) (56). The SDQ comprises five scales of five items each related to perceived emotional problems, behavioural problems, hyperactivity, peer relationship problems, and prosocial behaviour in the last six months. For each scale the scores range from 1 to 10 while overall emotional and behavioural mental health is scored from 0 to 40 (i.e., sum of all scale scores except for prosocial behaviour). Higher scores indicate unfavourable mental health, with the opposite true for prosocial behaviour. The SDQ is widely used and in community samples it is advised to report the broad constructs of internalising problems (emotional problems and peer relationships), externalising problems (behavioural problems and hyperactivity), and prosocial behaviour, as well as overall emotional and behavioural mental health (57). Internal consistency of the SDQ in our sample was Cronbach's α=0.72, 0.76, 0.59, and 0.80 for internalising problems, externalising problems, prosocial behaviour, and overall emotional and behavioural mental health, respectively.

Cognitive function. Executive functions are a subset of higher-order cognitive functions that are involved in goal-directed motor outputs. Three core executive functions are switching between tasks or mental sets, updating and monitoring of spatial working memory, and inhibition of dominant or prepotent responses (58). The CANTAB Connect (Cambridge Cognition Ltd, Cambridge, UK) computerised executive function test battery was used to

assess switching, spatial working memory, and inhibition. Switching was assessed using the Intradimensional/Extradimensional Set-Shifting task, which involves discrimination and reversal learning across nine stages. The number of stages completed can be age-dependent across childhood and adolescence (59). To account for potential variable stage completion, our outcome measure was the total number of errors adjusted for the number of stages completed. The Spatial Working Memory test assesses the ability to maintain and manipulate information in working memory using a self-ordered searching task. The outcome was the total number of errors, which accounted for the different types of errors made during the task. Inhibition was measured using the Multitasking Test, which required participants to manage different sources of conflicting information. The inhibition outcome was the total number of errors calculated across all assessed trials and for all error types. For each of the three executive function tasks, lower error scores indicated better performances. The three tests were completed individually by each participant using an Apple iPad (iPad 6th generation, iOS 13.3.1; Apple Inc., CA, USA) under the direction of a trained researcher.

Data analysis

Twenty-three participants were absent on data collection days and were discounted from the analysis. Of the remaining 359 participants (210 primary, 149 secondary), the number with missing data for the covariates and mental health outcomes ranged from 1 (0.3%) (BMI z-score) to 9 (2.5%) (IMD decile), and 2 (0.6%) (inhibition) to 11 (1%) (switching), respectively. Eighty-eight participants (24.5%) did not meet the accelerometer wear inclusion criteria and their activity behaviour data were coded as missing. A dummy variable was created for the accelerometer data to indicate which participants had observed (0) or missing values (1), and *t*-tests were computed with the continuous covariates and mental health outcomes as the dependent variables. Chi-squared tests examined the association between sex and missing accelerometer data. There were no significant differences in any of the covariates, or the internalising problems and depression scores between participants with observed and missing accelerometer data. Emotional and behavioural mental health (p=.001), externalising problems (p<.001), prosocial behaviour (p<.001), self-esteem (p=.03), and working memory (p=.04*)* were significantly different, with participants with missing accelerometer data scoring more poorly on these outcomes. Further, significantly more boys than girls had missing accelerometer data (p=.004). This suggested that these variables were missing at random (MAR) and multiple imputation was therefore performed for all exposure, outcome, and

covariate variables in IBM SPSS Statistics (version 25, IBM Inc., NY, USA) using the Expectation Maximisation algorithm.

Compositional analyses were conducted using R open-source software (v. 3.6.2, www.r-project.org) with the packages, 'compositions' (v. 1.40-5) (60) and 'robCompositions' (v. 2.2.1) (61). Time-use compositions were expressed as four specific sets of three isometric log ratio (ILR) coordinates called pivot coordinates (62, 63). The first coordinate of each set contained one activity behaviour (either sleep, ST, LPA, MVPA) relative to all remaining activity behaviours. The pivot coordinates were created so that each set included a different behaviour relative to all remaining behaviours as the first ILR. The sets of pivot co-ordinates were then used as explanatory variables in subsequent regression analyses. To accommodate the nesting of participants within the 12 schools, a mixed model approach ('school' as the single, random intercept) was used to analyse the association of each mental health outcome with the time-use ILRs. Adjustment was made for age, sex, BMI z-scores, and IMD deciles in each model, which is consistent with similar studies (64). There was no correlation above r=0.25 between any of the explanatory variables so collinearity was not considered to be an issue in the models. In models where sex was significantly associated with the mental health outcome, follow-up sex-stratified analyses were performed to assess the moderating influence of sex. Further analyses were performed by stratifying by type of school, with age removed from these models (primary: n=210; secondary: n=149). All mixed model analyses were performed in R with the 'lme4' package (v. 1.1.3) (65), with statistical significance determined by the 'lmerTest' package (v. 3.1.2) (66).

Models were checked to ensure assumptions were not violated for the use of linear mixed effects ('lmer' function in 'lme4' package). This led to some models being expressed as generalised linear mixed effects ('glmer' function in 'lme4' package). If the ANOVA table of the model fit showed that the set of time-use ILRs were not significantly associated with the selected mental health indicator, no further analysis was carried out. If significance was observed, four models were carried out, each model using a different set of pivot coordinates, so that each model examined associations with one activity behaviour, relative to all remaining behaviours. The regression coefficient and p-value of the first coordinate (ILR_1) representing one behaviour relative to remaining behaviours was examined for each behaviour to determine which behaviour was most dominant in the relationship with the mental health indicator. This behaviour was then the focus of compositional isotemporal substitution analyses to model the

influence of reallocating fixed time durations (5, 10, 15, 20 minutes) between it and the other three behaviours (67). Effect-sizes (*ES*) for predicted differences in mental health indicators were calculated as ratios of the model residual standard deviation (68).

Results

Descriptive results

Of the imputed analytical sample (N=359), 96.9% of the participants were White British, of medium-high SES (IMD decile = 7.3 ± 2.3), 50.7% were girls, and almost 25% were overweight or obese (Table 1). Geometric means of activity behaviours (linearly adjusted to collectively sum to 1440 minutes) and descriptive mental health outcomes are presented in Table 2. Participants spent 44.1% of the 24-hour day in ST and 37% of time sleeping. LPA and MVPA represented 14.6% and 3.5% of daily time, respectively. Primary school participants spent longer sleeping and less time being sedentary than secondary school peers. Less than 25% of the participants averaged at least 60 minutes MVPA per day (69) and almost 75% had less than 9 hours sleep·night^{-1} (70). Participants were highly compliant to wearing the accelerometers, averaging almost 6 days of valid wear for 22.8 ± 1.0 hour·day^{-1}. Emotional and behavioural mental health scores from the SDQ were in the 'close to average' range (71), while MFQ and RSES scores indicated no presence of depressive symptoms (55) and 'normal' range for self-esteem (52), respectively. The secondary school participants performed better on each of the cognitive tests of executive function than their younger peers.

Table 1. Descriptive characteristics of the participants (M (SD) unless indicated otherwise)

Variables	Primary school	Secondary school	All
N	210	149	359
Age (years)	10.4 (0.7)	13.0 (0.3)	11.5 (1.4)
Girls (%)	49.0	53.0	50.7
Ethnicity			
White British (%)	97.1	96.6	96.9
Socioeconomic status			
IMD score	11.3 (6.5)	15.4 (11.0)	13.0 (8.9)
IMD decile	7.8 (2.0)	6.7 (2.5)	7.3 (2.3)
Height (cm)	143.0 (8.3)	157.8 (9.1)	149.1 (11.3)
Body Mass (kg)	37.9 ± 9.7	50.4 (11.6)	43.1 (12.2)
BMI ($kg \cdot m^{-2}$)	18.3 ± 3.2	20.1 (3.8)	19.1 (3.6)
BMI z-score	0.38 ± 1.23	0.41 (1.17)	0.39 (1.21)
Weight Status			
Underweight (%)	8.2	7.5	7.9
Healthy (%)	66.7	68.9	67.6
Overweight (%)	20.5	18.9	19.8
Obese (%)	4.8	4.7	4.7

Note. IMD=Indices of Multiple Deprivation; BMI=Body Mass Index

Table 2. Descriptive accelerometer and mental health variables (M (SD) unless indicated otherwise)

	Primary school	Secondary school	All schools
Accelerometer [a]			
ST (min·day^{-1})	580.6	693.6	635.8
LPA (min·day^{-1})	211.2	205.6	210.1
MVPA (min·day^{-1})	60.1	41.6	50.9
Meet PA guideline [b] (%)	30.0	13.4	23.1
Sleep (min·day^{-1})	588.1	499.3	543.2
Meet sleep guideline [c] (%)	41.4	8.1	27.6
Valid wear time (hour·day^{-1})	22.4 (0.8)	23.4 (0.9)	22.8 (1.0)
Number of days with valid wear time	6.1 (1.0)	5.6 (2.1)	5.9 (1.6)
Questionnaires			
Self-esteem	20.4 (5.4)	21.1 (5.4)	20.7 (5.4)
Depression	11.7 (11.9)	10.2 (11.5)	11.1 (11.2)
Emotional & behavioural mental health	11.8 (5.6)	10.3 (5.5)	11.2 (5.8)
Internalising problems	5.4 (3.5)	5.1 (3.2)	5.3 (3.4)
Externalising problems	6.4 (3.5)	5.2 (3.5)	5.9 (3.5)
Prosocial behaviour	8.1 (1.6)	8.1 (1.5)	8.1 (1.6)
Cognitive tests			
Switching errors	51.9 (43.3)	42.1 (31.9)	47.8 (39.2)
Spatial working memory errors	18.2 (7.5)	16.3 (8.5)	17.4 (7.9)
Inhibition errors	19.8 (14.3)	14.6 (12.0)	17.6 (13.6)

Note. [a] Each behavioural time-use set was transformed to compositional means (expressed as the geometric mean of each behaviour, linearly adjusted to collectively sum to 1440 minutes); [b] Minimum of 60 min·day^{-1} MVPA averaged over the week (69); [c] Minimum of 9 hours·night^{-1} sleep (70); Questionnaire score ranges were: self-esteem 0-30, depression 0-66, emotional and behavioural mental health 0-40, internalising problems 0-20, externalising problems 0-20, prosocial behaviour 0-10. ST=sedentary time; LPA=light physical activity; MVPA=moderate-to-vigorous physical activity.

Compositional regression analyses

Table 3 summarises the results from the regression models for each mental health indicator using data for primary, secondary, and all schools combined (see Supplementary file 1 for full model outputs). The activity composition ILR coordinates were significantly associated with internalising problems (all schools, p=0.01), prosocial behaviour (p=0.03), and the switching (p=0.02) and inhibition (p<0.001) aspects of executive function among primary school participants. No significant associations were observed between the secondary school participants' activity compositions and mental health outcomes. Sex was a significant predictor in the models for externalising problems (p=0.01) and prosocial behaviour (p<0.001), but sex-stratified analyses revealed non-significant associations between the activity compositions and these mental health outcomes (p=0.60 to 0.75).

Table 3. Associations between activity composition and mental health outcomes

	All schools		Primary schools		Secondary schools	
Mental health outcome	X^2	p	X^2	p	X^2	p
Depression	4.48	0.21	6.15	0.10	2.32	0.51
Self-esteem	4.10	0.25	3.78	0.29	1.50	0.68
Total emotional and behavioural mental health	3.50	0.32	6.55	0.09	0.36	0.95
Internalising problems	**11.29**	**0.01**	4.50	0.21	4.61	0.20
Externalising problems	2.26	0.52	5.24	0.16	3.56	0.31
Prosocial behaviour	2.10	0.55	**8.69**	**0.03**	0.51	0.92
Executive function						
Switching errors	2.90	0.41	**9.26**	**0.02**	2.33	0.84
Spatial working memory errors	3.83	0.28	2.82	0.42	1.51	0.68
Inhibition errors	1.66	0.65	**18.01**	**<0.001**	6.31	0.10

Note. Activity composition expressed as isometric log ratios. Models adjusted for age (All schools analyses only), sex, BMI z-score, and IMD decile. Bolded estimates are significant at $p< 0.05$.

Beta coefficients for the first pivot coordinate of the models showing significant associations between activity composition and outcomes are presented in Table 4. For all participants, ST, relative to the other activity behaviours was associated with worse internalising problems (β_1= 0.32, p=0.03). Among primary school participants, ST, relative to the other behaviours, was associated with poorer prosocial behaviour (β_1 = -2.25, p=0.007), and LPA, relative to the other behaviours, was associated with more switching and inhibition test errors (β_1= 51.89 p=0.004; β_1 =23.56, p<0.001).

Table 4. Relationship between significant mental health outcomes and the activity behaviour isometric log-ratio regression coefficients

Mental health outcome	β_1 *ilr* Sleep	β_1 *ilr* ST	β_1 *ilr* LPA	β_1 *ilr* MVPA
All schools				
Internalising problems	-0.26	**0.32**	0.15	-0.21
Primary schools				
Prosocial behaviour	1.92	**-2.25**	-0.01	0.33
Executive function				
Switching errors	-33.61	-3.85	**51.89**	-14.62
Inhibition errors	-4.10	-14.0	**23.56**	-5.44

Note. β_1 *ilr* first isometric log-ratio regression coefficients from regression models represents one activity behaviour relative to all remaining behaviours. Bolded coefficients indicate those significantly associated with the outcomes at p<0.05. ST=sedentary time; LPA=light physical activity; MVPA=moderate-to-vigorous physical activity.

Compositional isotemporal substitution analyses: one-for-one reallocations

Using the average composition (Table 2) as the starting durations for each activity, Figures 1-4 and Supplementary file 2 show predicted differences in mental health outcomes when incremental durations of time (5, 10, 15, 20 minutes) were added/subtracted from the most influential activity behaviour in Table 4, and redistributed from/to one other activity, keeping

all remaining activities constant. The 95% CIs did not cross zero for any estimated differences in the outcomes (Supplementary file 2; CIs not shown on Figures to avoid overcrowding). For all participants, time reallocations to ST from either sleep or MVPA were associated with more internalising problems (*ES* = 0.27 (5 min) to 1.33 (20 min when MVPA replaced ST). Among primary school participants there were positive predicted differences in prosocial behaviour when ST was replaced with any of the other three behaviours (*ES* = 0.03 (5 min) to 0.10 (20 min) when MVPA replaced ST). In relation to executive function, when LPA replaced sleep, ST, and MVPA unfavourable predicted differences in primary school participants' performances on the switching (*ES* = 2.74 (5 min) to 11.77 (20 min) when LPA replaced MVPA) and inhibition tasks (*ES* = 1.47 (5 min) to 6.26 (20 min) when LPA replaced MVPA) were observed. In all of these compositional isotemporal substitution analyses, predicted differences in the outcomes were greatest when MVPA was replaced with either ST or LPA, rather than when time was reallocated to MVPA.

FIGURES 1 AND 2 HERE

FIGURES 3 AND 4 HERE

Discussion

This study investigated associations between 24-hour activity behaviours and a range of mental health outcomes in youth, which extend beyond those previously examined in compositional analysis studies (i.e., overall mental wellbeing (4) and health-related quality of life (68)). Overall, we found that activity compositions were significantly associated with internalising problems, while among primary school participants they were associated with prosocial behaviours, and the switching and inhibition aspects of executive function. Relative to other activity behaviours, the time spent in ST was significantly associated with increased risk of internalising problems, and inversely associated with prosocial behaviour (primary school participants only). Further, more time engaged in LPA by the primary school participants was significantly associated (relative to other behaviours) with poorer performances on the switching and inhibition tasks.

Internalising problems encompass emotional and peer relationship difficulties and there is limited literature reporting associations between ST and these aspects of mental health. There is though, systematic review evidence supporting a direct positive relationship between sedentary screen time and increased risk of internalising problems in school-aged youth (27). Further, longitudinal findings from the UK show that children who watched TV and/or played video games for more than 3 hour/day were more likely to report emotional and peer-relationship difficulties 2 years later (72). Similarly, US children and adolescents with more than 1 hour/day of daily screen time had lower emotional stability and increased difficulty making friends, with associations typically stronger among adolescents (73). Our findings of higher internalising problems associated with higher ST (relative to other behaviours) may reflect the unfavourable influence of more sedentary screen time. It is possible that in analyses stratified by primary and secondary school, these relationships were only observed among primary school participants because there was more observed variance in the activity exposure and mental health outcome variables (see variation matrix in Supplementary file 3), and a lack of statistical power for the smaller secondary school sample.

ST was also inversely associated with prosocial behaviour but only in primary school participants. This is consistent with the associations between TV viewing/gaming and prosocial behaviours reported in Carson et al.'s 2016 systematic review (26) and longitudinal data from the UK Millennium Cohort Study (72). While these studies provide some support for our findings it is important to recognise that total ST as reported in our compositional analysis is a different measure than screen time; screen time can occur in non-sedentary postures (74), and high ST is largely independent of screen time (75). It is unclear whether total ST (25) or specific types of ST are more strongly related to mental health outcomes (76). To address this, future studies should employ methodologies such as ecological momentary assessment or device-based pattern recognition approaches to identify specific types of sedentary behaviours (76), which may provide a more precise picture of the compositional relationships between activity behaviours and mental health.

The daily activity compositions were not associated with overall emotional and behavioural mental health, externalising problems, depression, or self-esteem. Contrastingly, non-compositional studies have reported associations between these outcomes and sleep, ST, and physical activity (21, 24, 26, 29), but none accounted for the mutually exclusive and compensatory nature of these behaviours, which are relative to one another over a 24-hour day.

Recently, this has been examined with studies showing that youth who met multiple guidelines for sleep, ST, and MVPA were likely to have better mental health than peers meeting fewer recommendations (20, 32, 64). However, as our sample had low prevalence of meeting physical activity and sleep guidelines, it is unlikely that this explanation would hold true with our data. Another possible explanation for the lack of observed associations is the relatively similar and favourable mental health questionnaire scores, which indicated that our sample was at low risk for poor mental health. Further, their SES was moderate to high, which is consistent with previous research reporting positive SES and youth mental health relationships (64, 77). The relatively high SES of our participants may have predisposed them to have favourable mental health status, which could have limited the precision and ability to detect associations between activity behaviours and the mental health outcomes (i.e., a ceiling effect) (64). We recognise though that the IMD was not sensitive to individual family level SES, hence, we exercise some caution with this supposition.

Among the primary school participants, the switching and inhibition aspects of executive function were positively associated with LPA relative to sleep, ST, and MVPA. Moreover, when time was reallocated between behaviours, the effect sizes were large and more substantial than for internalising problems and prosocial behaviour. For example, a modelled reallocation of 10 minutes of LPA to MVPA estimated a -4.20 difference in switching error score with an ES of 5.24. In contrast, a 10 minutes reallocation of ST to MVPA with prosocial behaviour as the outcome, estimated a 0.08 unit difference, with a substantially smaller ES of 0.05. Hence, in our sample the effect of reallocating more time to MVPA from ST or LPA appears to have been be more beneficial for executive function than for indictors of mental ill health.

Evidence exists for a relationship between physical activity and cognition and brain structures that support complex processes in controlled laboratory environments (78). Translating such findings to practice is important, particularly in school settings where there is great interest in how replacing sedentary class time with physical activity can promote learning through improved cognitive performance. Currently though, there is inconsistent evidence of the beneficial effects of such interventions (79, 80). Similarly, evidence for associations between sleep duration and cognitive function is equivocal (29) with the most recent meta-analysis of objectively assessed sleep and cognition reporting small, non-significant effects (31). It has been proposed that because most youth sleep for less than the recommended duration (70) the cognitive performance of those with adequate sleep has been underrepresented in studies to

498 date. Therefore reported associations between 'typical' sleep and cognition were attenuated
499 because of the restricted range of sleep durations observed (31). As less than 25% of our
500 participants achieved the recommended sleep duration this attenuation of a sleep-cognition
501 relationship may have also occurred in our sample.
502
503 In the compositional isotemporal substitution analyses, reallocations between MVPA and
504 ST/LPA had the greatest predicted associations with internalising problems, prosocial
505 behaviours, switching, and inhibition (relative to the other behaviours), and estimated
506 differences increased incrementally with the duration of time reallocated. MVPA is
507 characterised by much higher energy expenditure than sleep, ST, and LPA; it may therefore
508 provide a more powerful physiological stimulus for structural and hormonal changes that are
509 favourable for cognition (81). Moreover, MVPA for youth (e.g., sport, structured activities)
510 often involves participation with peers, parental encouragement, and enhancement of
511 emotional status (20, 82), which are consistent with better internalising mental health and
512 prosocial behaviours. While these are possible explanations for the influence of MVPA on the
513 outcomes in this study, it is acknowledged that the mechanistic evidence for this is currently
514 limited (81). Interestingly, associations with the outcomes were greatest when MVPA was
515 replaced by ST or LPA, rather than when MVPA replaced these behaviours. These
516 asymmetrical associated differences in health outcomes involving MVPA have previously
517 been observed in youth studies considering adiposity, fitness, cardiometabolic risk, mental
518 health, and health-related quality of life (4, 6, 68). This was likely due to MVPA constituting
519 a relatively small proportion (50.9 minutes or 3.5%) of the activity composition. Therefore, a
520 20 minute reallocation in MVPA represents a change of 39%, whereby the equivalent absolute
521 change in SB reflected only 3% of the geometric mean proportion of ST of 635 $min \cdot day^{-1}$ (67).
522
523 Strengths of this study included device-based assessment of 24-hour activity behaviours and
524 use of compositional data analysis to examine how the full activity composition related to
525 mental health. Moreover, ours is the first compositional analysis study to investigate multiple
526 mental health indicators, measured using validated instruments and including objectively
527 assessed cognitive function. We also used multiple imputation methods which when the data
528 are MAR and covariates are available, can provide unbiased results compared to complete case
529 analysis, and maintain statistical power because the sample size is not reduced (83). There were
530 also limitations which warrant consideration. The cross-sectional design precludes any claims

of causal inferences and directionality between the activity composition and mental health indicators. We had a 55% participation rate and an imbalanced sample of primary and secondary school participants, who were relatively homogenous in respect of area-level SES, which may have been reflected in their relatively high mental health status and the limited associations with the activity compositions. Most of the mental health outcomes were measured using questionnaires which although validated, have potential for social desirability bias. Lastly, the activity behaviours were defined using validated wrist acceleration cutpoints which for LPA and MVPA, reflect absolute intensity rather than relative intensity for each participant. This is likely to result in some misclassification of activity behaviours among the sample. Use of machine learning to label activity behaviours and intensities would contribute to addressing this issue in future studies.

Conclusions

Relative to other activity behaviours, ST and LPA had the greatest influence on some mental health outcomes. In stratified analyses, associations were only observed among primary school participants. Our results provide some support for the influence of daily activity behaviours on youth mental health. When time was incrementally reallocated between the activity behaviours, the largest predicted changes in the outcomes occurred when MVPA was replaced by ST or LPA. The results provide further support for schools to promote children's mental health by integrating opportunities for MVPA throughout the school day, particularly during periods such as classroom lessons that would traditionally be spent with children engaged in ST or LPA. From a practical perspective approaches such as active classroom breaks and walking/running initiatives (e.g., The Daily Mile) have great potential to displace ST or LPA with MVPA and confer mental health benefits (84). Our findings highlight the value of compositional data analysis for understanding the collective influence of activity behaviours on mental health outcomes, and guiding the focus of behaviour change interventions. Promoting these behaviours using conceptually developed family- (85) and school-based frameworks (86) is advocated. Future studies should study associations between activity behaviours and mental health longitudinally in samples that are representative of key demographic characteristics of the target population.

<u>Supplementary files</u>

- Supplementary file 1 ILR regression models.docx: Compositional isometric log ratio multiple regression models

- Supplementary file 2.docx: Predicted differences in significant mental health outcome from time reallocations
- Supplementary file 3 variation matrices.docx: Compositional variation matrices of time spent in sleep, ST, LPA, and MVPA

Disclosure of interest

The authors report no conflict of interest.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Figure legends

Figure 1. Estimated difference in mental health associated with time reallocation between pairs of behaviours: difference in all participants' internalising problems associated with the difference in ST to each of the remaining behaviours. For example, adding 20 minutes to ST at the expense of MVPA (green line) while keeping sleep and LPA constant was associated with a predicted increase in internalising problems of 0.69 units.

Figure 2. Estimated difference in mental health associated with time reallocation between pairs of behaviours: difference in primary school participants' prosocial behaviour associated with the difference in ST to each of the remaining activities.

Figure 3. Estimated difference in executive function associated with time reallocation between pairs of movement behaviours: difference in primary school participants' inhibition errors associated with LPA to each of the remaining activities. For example, adding 20 minutes to LPA at the expense of MVPA (red line) while keeping sleep and ST constant was associated with a predicted increase of 9.5 errors on the inhibition task.

Figure 4. Estimated difference in executive function associated with time reallocation between pairs of movement behaviours: difference in primary school participants' switching errors associated with LPA to each of the remaining activities.

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