Accelerometer-measured physical activity and sedentary time among children and their parents in the UK before and after COVID-19 lockdowns: a natural experiment

Ruth Salway1, Charlie Foster1, Frank de Vocht2,3, Byron Tibbitts1, Lydia Emm-Collison1, Danielle House1, Joanna G. Williams2,4, Katie Breheny2, Tom Reid1,2, Robert Walker1, Sarah Churchward5, William Hollingworth2,3 and Russell Jago1,2,3*

Abstract

Background: Restrictions due to the coronavirus disease 2019 (COVID-19) pandemic reduced physical activity provision for both children and their parents. Recent studies have reported decreases in physical activity levels during lockdown restrictions, but these were largely reliant on self-report methods, with data collected via unrepresentative self-report surveys. The post-pandemic impacts on children's activity levels remain unknown. A key question is how active children become once lockdown restrictions are lifted.

Methods: Active-6 is a repeated cross-sectional natural experiment. Accelerometer data from 1296 children aged 10–11 and their parents were collected in 50 schools in the Greater Bristol area, UK in March 2017-May 2018 (pre-COVID-19 comparator group), and compared to 393 children aged 10–11 and parents in 23 of the same schools, collected in May-December 2021. Mean minutes of accelerometer-measured moderate-to-vigorous physical activity (MVPA) were derived for weekdays and weekend and compared pre- and post-lockdown via linear multilevel models.

Results: After adjusting for seasonality, accelerometer wear time and child/parent demographics, children's mean weekday and weekend MVPA were 7.7 min (95% CI: 3.5 to 11.9) and 6.9 min (95% CI: 0.9 to 12.9) lower in 2021 than in 2018, respectively, while sedentary time was higher by 25.4 min (95% CI: 15.8 to 35.0) and 14.0 min (95% CI: 1.5 to 26.5). There was no evidence that differences varied by child gender or household education. There was no significant difference in parents' MVPA or sedentary time, either on weekdays or weekends.

Conclusions: Children's MVPA was lower by 7–8 min/day in 2021 once restrictions were lifted than before the pandemic for all groups, on both weekdays and weekends. Previous research has shown that there is an undesirable age-related decline in children's physical activity. The 8-min difference reported here would be broadly comparable to the decline that would have previously been expected to occur over a three-year period. Parents' physical activity was similar to pre-pandemic levels. Our results suggest that despite easing of restrictions, children's activity levels have not returned to pre-pandemic levels. There is an urgent need to understand why these changes have occurred and how long they are maintained.
Introduction

Physical activity is important for health among children and adults. In adulthood, physical activity is associated with reduced risk of heart disease, stroke, type 2 diabetes mellitus and many forms of cancer as well as reduced risk of depression and improved psychological well-being [1–3]. In childhood, physical activity is associated with reduced risk of obesity and improved emotional well-being [4–6]. The World Health Organization and UK Chief Medical Officers (CMO) recommend that children and young people should engage in an average of an hour of moderate-to-vigorous intensity physical activity (MVPA) per day, accumulated across the day, and that all adults should engage in 150 min or more of moderate intensity physical activity per week [3, 7, 8]. However only 41% of children aged 10–11 years in the UK meet this recommendation[9], and evidence shows a decline in physical activity throughout childhood and adolescence [9, 10], with average weekday MVPA declining at a rate of 2.2 min per year between ages 6 and 11.

The coronavirus disease 2019 (COVID-19) pandemic, and resulting restrictions to limit the spread of the virus, has had marked impacts on all aspects of society, including limiting both access and ways in which adults and children are active [11]. In England, an initial lockdown began on 23rd March 2020 with the closure of non-essential businesses, hospitality, leisure facilities and playgrounds, and schools were open only to children of key workers and to vulnerable children, followed by a phased release from 13th May 2020. A second short lockdown, with non-essential business and leisure facilities closed but with schools remaining open to all pupils, was in place between 5th and 24th November 2020, and a third full lockdown with schools closed again to many pupils from 6th January to 3rd March 2021[12]. Thus, the COVID-19 pandemic has resulted in changes to physical activity opportunity via restrictions on physical education, travel to school and work, sport and outdoor play for both children and adults, and potentially changes to screen-viewing habits via home-working and online learning. Moreover, some behaviours continue even when restrictions are lifted, with some adults for example choosing to continue working from home, and many children have been out of school for varying periods of time, including isolation due to COVID-19 infection or contact.

The majority of previous studies examining physical activity during the pandemic have used convenience samples recruited via social media, retrospective measures of pre-COVID-19 activity and subjective self-report measures of physical activity [13, 14]. Most studies report large decreases in the duration and frequency of physical activity across multiple countries in both children and adults [13, 14]. Studies that have used accelerometer assessments of physical activity in healthy primary-aged children are limited with small sample sizes, but have reported decreases of 10–17 min of MVPA during and shortly after school closures, compared to pre-pandemic, in several countries [15–17]. In England, the national Active Lives Children and Young People Survey (ALCYPSS) [18] found a 2.2 percentage point change in the proportion of children meeting the CMO guidelines between the summer term 2019 and 2020, with no further change between 2020 and 2021[18]. Evidence also suggests an increase in screen-viewing of 0.5 h-1.5 h per week [15, 16, 19], although some of this can be attributed to the increase in online schoolwork. Among adults, there were large changes in activity between May 2020 and May 2021, with an estimated 0.8 million fewer adults meeting the CMO guidelines in England since the pandemic began [20, 21].

The main determinants of children’s physical activity during the pandemic were found to be factors associated with the outdoor environment (such as urban area, lack of outdoor space), age, gender and socioeconomic background [14]. In England, boys aged 9–11 experienced the largest decreases in activity [18], although longitudinal changes in meeting CMO guidelines were not found to be associated with ethnicity or sex [22]. While children from the least affluent families did not have reductions in physical activity, the large socioeconomic gap in activity levels remains. Among those aged 35–54, who are more likely to be parents [23], the percentage meeting guidelines fell from 66 to 64%, with larger decreases among men but with women more likely to remain consistently less active, even during periods when restrictions were eased [20, 24]. There is a clear disparity in the impact of COVID-19 restrictions on overall activity levels for different genders and socioeconomic position.

Due to timescales, most of the evidence to date has understandably been on the immediate impact of COVID-19 restrictions on physical activity. However, it is now possible to look at longer-term impacts and a key question is how active children are once lockdown restrictions have been removed. It is crucial that we understand how children’s physical activity has been impacted beyond the immediate lockdown restrictions as early as possible, as well as the factors associated with...
If we are to develop strategies to compensate for or encourage physical activity, this paper compares accelerometer measures in children aged 10–11 from before the pandemic (2018–19) with data on children aged 10–11 in the same schools collected in May-December 2021, to determine whether reductions in physical activity remained after restrictions have eased, to characterise post-pandemic physical activity levels and whether any differences are associated with gender and socioeconomic position (SEP).

**Methods**

Active-6 [25] is a repeated cross-sectional natural experiment, which compares data in a pre-COVID-19 comparator group to new data collected at two time periods after many restrictions due to the COVID-19 pandemic have lifted. This paper reports cross-sectional data from the pre-COVID-19 comparator group (which we will refer to as Wave 0) and first post-COVID-19 time point (Wave 1). Data collection for the second time point, Wave 2, is currently ongoing (January-July 2022). Pre-COVID-19 data are from Phase 3 of B-Proact1v, a longitudinal study which has been described in detail elsewhere [9]. This study collected questionnaire and accelerometer data from Year 6 children (aged 10–11 years) and at least one of their parents from 50 schools in and around Bristol, UK between March 2017 and May 2018. We invited the same 50 schools to participate in the Active-6 study, with all Year 6 children and one parent per family eligible to take part. As in Wave 0, we collected both questionnaire and accelerometer data from both child and parent. Of the 30 (60%) schools who responded, 25 (83%) agreed to take part in Wave 1, three refused and two agreed to take part only in Wave 2. Two of the consenting schools had to be rescheduled for Wave 2 due to COVID-19 outbreaks. Data collection in the remaining 23 schools took place in two data collection periods; May—July 2021, in which data collection was fully remote, and September—December 2021 when we were able to go into schools. Both the original and current study received ethical approval from the School of Policy Studies Ethics Committee at the University of Bristol, UK, and parental consent was received for all participants at both time points. In Wave 0, children completed paper questionnaires at school, and parents had a choice of paper or online versions. In Wave 1, because of the pandemic and restrictions to in-person data collection, all questionnaire data were collected online. Full details of data collection procedures under different levels of COVID restrictions are provided in the study protocol [25]. A total of 1296 child and parent pairs participated in Wave 0, and 393 in Wave 1 (Fig. 1).

**Accelerometer data**

At each time point, participating children and one of their parents wore a waist-worn ActiGraph wGT3X-BT
accelerometer (Actigraph LLC; Florida, US). Participants were asked to wear accelerometers during waking hours for five consecutive days in Wave 0, including two weekend days, and for seven consecutive days in Wave 1. Accelerometer data from both Waves were processed using a script written in the R software [26], available from the Open Science Framework [27]. Data between midnight and 6am were excluded and a valid day of data was defined as at least 500 min of data, after excluding intervals of ≥60 min of zero counts allowing up to two minutes of any interruptions (consistent with the B-Proact1v study). Analysis of weekday accelerometer data was restricted to participants who provided at least two valid weekdays of data, and weekend accelerometer data to those who provided at least one valid weekend day of data. Activity was recorded in 10 s epochs as sedentary, light intensity or MVPA using Eveson population-specific cut points for children [28], and Troiano cut points for adults [29] (both derived for waist-worn Actigraph accelerometers), and the mean weekday and weekend minutes of MVPA were derived. We also recorded the average number of minutes of accelerometer wear time.

**Covariates**

Parents were asked to report their child’s date of birth, gender and the highest education qualification in the household. Index of Multiple Deprivation [30] (IMD) was determined from home postcode (IMD2015 for Wave 0 and IMD2019 for Wave 1), with higher IMD ranks indicating a greater level of deprivation. At school level, we derived school IMD and Income Deprivation Affecting Children Index (IDACI) score [30] based on school postcode, and used published data on school size and percentage of children receiving free school meals [31].

In Wave 0, child height and weight were measured and recorded to the nearest 0.1 cm and 0.1 kg respectively by trained fieldworkers. During the initial part of Wave 1 we were unable to visit schools in person, and so no height and weight measurements were taken in the first ten schools, but these were collected for subsequent schools after ethical approval was gained on 8\textsuperscript{th} October 2021. We did not collect self-report height and weight data as this would not be comparable with Wave 0 measures and is known to be subject to bias in children [32]. Body mass index (BMI) was calculated where possible and converted to age- and sex-specific standard scores (BMI z-score) based on UK reference curves [33]. Parent BMI was calculated from parent-reported height and weight via questionnaire as weight in kilograms divided by height in metres squared.

Parents and children were asked to complete questionnaires at both time points. Children were asked about the frequency (coded from 0 = ‘Never’ to 3 = ‘5+ days per week’) with which they engaged in different forms of activity outside school hours: sport or exercise club at school, sport or exercise club elsewhere, playing outdoors in their neighbourhood, and playing outdoors at home. These were combined in a total activity participation score from 0 to 12, with a higher value indicating a higher frequency of participation in activities outside school [34]. They were also asked about attendance at active extracurricular clubs. In Wave 0, children were asked how they typically travelled to and from school for each day of the week. As there was very little variation in travel mode across the week [35], we used the modal travel mode to represent typical travel, and in Wave 1 asked children directly for the typical travel across the week. For both waves, we created a binary indicator of whether they typically used active (walk, bike, or scooter) or inactive (car, bus or train) modes of travel in either direction.

Parents were asked about the number of hours they and their child typically spent in screen-viewing activities on weekdays and at weekends. In Wave 0, these questions were asked separately about TV, computers, phones/tablets and games consoles, each coded from 0 = ‘None’ to 5 = ‘4 h or more’, and the midpoints summed to calculate total screen viewing. In Wave 1, parents were asked to report total leisure screen-viewing and TV-viewing on hourly scales for ‘Less than 1 h’ up to ‘ > 3 h’ for TV and up to ‘ > 5 h’ for screen-viewing. We converted both measures to binary indicators of total screen viewing ≥ 2 h and TV viewing ≥ 1 h for weekdays and weekends.

**Statistical analysis**

The detailed statistical analysis plan [36] for the project was agreed prior to the analysis being conducted. The primary outcome was average daily child weekday MVPA and main explanatory variable was the difference between Wave 0 and Wave 1, captured via an indicator variable. We reported school-level characteristics, pupil demographics (gender, household education, IMD, BMI z-score where available) and descriptive summaries of key variables for the 50 schools at Wave 0 and 23 participating schools at Wave 1.

This is a repeated cross-sectional design, matched on schools. To allow for this cluster design, all comparisons of between the Wave 0 and Wave 1 data were estimated via multilevel models with children nested within schools and school-level random intercepts. This allowed us to include data from schools that participated in Wave 0 but not Wave 1 (27 schools); such schools contribute information about the baseline levels of physical activity. All physical activity and sedentary time models were adjusted for accelerometer wear time, and seasonality using second order harmonic sine/cosine functions.
and included the main explanatory variable for differences between waves. Continuous outcomes (MVPA, sedentary time, activity score) were modelled using linear models, and discrete outcomes (meeting UK physical activity guidelines, attending active clubs, using active travel, screen-viewing and TV-viewing) used logistic models. In the first data collection period of Wave 1, some COVID-19 restrictions were still in place and data collection protocols differed. An amendment was made to the statistical analysis plan (approved by the Chair of the Study Steering Committee) after interim data had been analysed but before the full dataset was constructed, to include an indicator variable for this period in all models. For transparency, we report the original unadjusted model as a sensitivity analysis. We reported means and 95% CIs of differences in all key child and parent outcomes firstly from this base model and secondly adjusted for confounders known to be associated with physical activity (child models: gender, household education and parent models: age, gender, household education). To determine whether the impact of COVID-19 on MVPA and sedentary time differed by gender and socio-economic position, we repeated the confounder-adjusted models with interaction terms between wave and gender, and wave and household education, as sample sizes were too small to allow subgroup analyses. Model assumptions of normality and homoskedasticity were checked via visual inspection of the residuals, and multicollinearity was assessed via variance inflation factors.

The role of BMI is complex, as it may be acting as a confounder, mediator or both in this analysis. The COVID-19 pandemic has been associated with increases in BMI z-score [38], and increased adiposity has been found to be a causal risk factor for lower physical activity in children [39]. As specified in the statistical analysis plan, since height and weight were not measured in the first ten schools, we imputed missing BMI z-score data under a missing at random assumption, since the data were missing at school level rather than due to individual characteristics. We imputed other missing data at the same time, to include as much information on participants as possible. We used multilevel joint modelling multiple imputation via the package jomo in R [26] that accounted for the clustering within schools, stratified by child gender and using child (age, gender, MVPA and sedentary time), parent (gender, household education and BMI) and school data (average age, gender, MVPA, household education, parent BMI and parent ethnicity for each school) to impute missing data. Fifty imputed datasets were created using a joint multivariate normal model, fitted by Monte Carlo Markov Chains, with a burn-in of 1000 iterations and 1000 iterations between imputation sets (selected via visual inspection of convergence and autocorrelation of the chains). We then used the imputed data in a sensitivity analysis in which MVPA and sedentary time were additionally adjusted for BMI z-score, with results averaged over imputation datasets using Rubin’s rules [40]. Given the level of missing data, we report imputed BMI-adjusted models for PA outcomes only and note that these analyses are considered exploratory.

Several pre-specified sensitivity analyses were conducted. Firstly, to explore any bias due to different underlying populations, we repeated the main analyses restricting data to the subset of schools with data in both waves. We also explored the change in protocol from five days of accelerometer data in Wave 0 to seven in Wave 1 by selecting a random three consecutive weekdays from the Wave 1 data per school (plus the two weekend days) and repeating the main analyses. Finally, as noted above, we compared imputed analyses to complete case analyses, both with and without child BMI z-score. Descriptive summaries were performed in Stata v15 [41] and all multilevel models were run in MLwiN [42] via the Stata command runmlwin.

Results

The subsample of Wave 1 schools was broadly comparable to Wave 0 schools, in terms of socio-economic indicators (IMD, Income Deprivation Affecting Children Index (IDACI) score, free school meals), geographical distribution (local authority, urban/rural) and pupil demographics (age, gender, ethnicity) at baseline (Table 1). Of the 1024 eligible pupils in the Wave 1 schools, the overall response rate was 38% ($n = 393$), lower than in Wave 0 (63%), but when data collection was possible in person this rose to 48%. Parent and child demographics between the two Waves were broadly similar (Tables 1 and 2), with both participating schools and participants in Wave 1 slightly more likely to come from households with higher education qualifications and in less deprived areas. Children in Wave 1 had higher BMI z-scores (0.38 in Wave 1, compared to 0.35 in Wave 0), although due to data collection restrictions, height and weight were collected in only 61% of children in Wave 1. Missing data ranged between 3–18% for parent characteristics and 11–25% for accelerometer data, with more valid parent data in Wave 1 but similar levels of missingness for accelerometer data (Table S1).

Figure 2 shows the raw data for children’s weekday and weekend MVPA before and after the COVID-19 pandemic by gender. Note that these data and the estimates given in Table 3 are unadjusted for seasonality, accelerometer wear time or study design, and thus we make no assumptions about these, in line with the statistical analysis plan [36] as approved by the Study Steering Committee.
Committee. Children’s weekday MVPA was lower in Wave 1 than in 2018, at 55.9 min (95% CI: 52.1 to 59.7) and 60.3 min (95% CI: 57.2 to 63.4) respectively. Weekend MVPA was also lower in Wave 1 (45.7 min (95% CI: 41.8 to 49.6) compared to 53.4 min (95% CI: 49.8 to 57.1) in Wave 0), and we saw a reduction in the percentage of children meeting CMO guidelines from 40% to 36% (Table 3). Sedentary time was higher, at 488.4 min on weekdays and 452.5 min at weekends in Wave 1, compared to 476.8 min and 437.1 min in Wave 0 respectively. These patterns were consistent across gender and highest household education. By contrast, parents’ MVPA was similar between Wave 1 and Wave 0, with 82% to 85% meeting CMO guidelines in Wave 0 and Wave 1 respectively (Table 4).

The estimated difference in children’s weekday MVPA (Table 5) between pre-COVID-19 and Wave 1 was -7.7 min (95% CI: -11.9 to -3.5) after adjusting for gender, age and highest household education. After additionally adjusting for BMI z-score (using multiple imputation for the missing z-BMI) the difference was -6.5 (95% CI: -10.8 to -2.3). There was no evidence of an interaction with gender, household education or BMI z-score. Tables S2 and S3 report estimates of the difference for secondary outcomes for confounder-adjusted models, with estimated differences for physical activity and sedentary time shown in Fig. 3. Children’s weekend MVPA showed a similar difference of -6.9 min (95% CI: -12.9 to -0.9) and increases of 25.4 min (95% CI: 15.8 to 35.0) and 14.0 min (95% CI: 1.5 to 26.5) in sedentary time for weekdays and weekends respectively. After adjusting for BMI z-score, these differences were attenuated slightly by approximately 1 min (Table S4). Parents’ MVPA and sedentary time were similar in Wave 1 compared to pre-COVID-19.

There was negligible difference in participation in active after-school clubs or active travel (Table S3). Children’s overall activity score (which captures a mix of structured clubs and unstructured active play across the week) was lower in Wave 1, equating to roughly 1–1.5 fewer days per week engaged in these types of activities (Table S2). There were differences in screen viewing for both children and parents. The proportion of children and parents who engaged in more than 2 h of leisure screen-viewing was lower in Wave 1 but the proportion

| Table 1 | Comparison of school-level characteristics for participating schools in Wave 0 and Wave 1 |
|---------|------------------------------------------------------------------------------------------|
|         | Wave 0 (Pre-COVID-19)                                                                     | Wave 1 |
|         | n = 50                                                                                   | n = 23 |
| School characteristics in 2021 |                                                                            |        |
| Urban: N (%) | 45 (90%)                                                                                   | 19 (83%) |
| Local Authority N (%) |                                                                            |        |
| Bath & North East Somerset | 4 (8%)                                                                                   | 3 (13%) |
| Bristol | 14 (28%)                                                                                  | 6 (26%) |
| North Somerset | 12 (24%)                                                                                   | 6 (26%) |
| South Gloucester | 20 (40%)                                                                                  | 8 (35%) |
| School size: median (IQR) | 231 (141)                                                                                  | 236 (184) |
| School IMD score in 2015*: mean (SD) | 16.7 (15.3)                                                                               | 13.7 (10.2) |
| School IDACI: mean (SD) | 0.12 (0.11)                                                                                | 0.10 (0.08) |
| Free school meals %: median (IQR) | 11.3% (11.1%)                                                                             | 10.4% (12.2%) |
| Average baseline pupil characteristics per school |                                                                            |        |
| Average child age: mean (SD) | 10.9 (0.2)                                                                                 | 10.9 (0.2) |
| Average % girls: mean (SD) | 53% (11%)                                                                                  | 52% (8%) |
| Average % white British ethnicity: mean (SD) | 85% (13%)                                                                                 | 88% (7%) |
| Average z-BMI: mean (SD) | 0.40 (0.31)                                                                                 | 0.29 (0.26) |
| Average % degree + household education: mean (SD) | 53% (21%)                                                                                 | 60% (16%) |
| Average pupil IMD: mean (SD) | 16.8 (11.5)                                                                                | 14.7 (9.1) |
| Average weekday min of MVPA: mean (SD) | 57.9 (8.9)                                                                                 | 60.0 (6.2) |
| Average weekend min of MVPA: mean (SD) | 52.1 (10.2)                                                                                | 52.7 (9.0) |

* IMD score: lower scores indicate higher deprivation

Wave 0: Mar 2017-Jul 2018; Wave 1: May 2021-Dec 2021

IMD Index of Multiple Deprivation, IDACI Income Deprivation Affecting Children Index, IQR inter-quartile range, SD standard deviation, z-BMI Body Mass Index standardised z-score, MVPA moderate-to-vigorous physical activity
who engaged in more than 1 h of TV-viewing was higher. (Tables S2 and S3).

Model checking showed no issues with normality assumptions or multicollinearity. Sensitivity analyses showed that restricting analysis to just those schools that took part in both waves had only small impact on the results, increasing the pre/post COVID-19 difference by around 2 min (Table S5). There was a notable difference between the first data collection period, when data collection was undertaken remotely and school-specific COVID-19 measures were in place, and the later data collection period, with the initial period showing an increase in weekday MVPA of 11.0 min (95% CI: 3.3 to 18.7) compared to Wave 0, in contrast to the decrease seen subsequently. The models reported above adjusted for these differences; when no adjustment is included, the overall pre/post COVID-19 difference in weekday MVPA was smaller at -3.8 min (95% CI: -7.1 to -0.5) (Table S5). Differences in physical activity and sedentary time estimates between the B-Proact1v protocol (summaries based on three weekdays) and Active-6 (summaries based on five weekdays) were negligible (Table S6). There

| Table 2 | Comparison of key pupil demographics at Wave 0 and Wave 1 |
|---------|----------------------------------------------------------|
| Wave 0 (Pre-COVID-19) | Wave 1 |
| n = 1296 | n = 397 |
| Child age: mean (SD) | 11.0 (0.4) | 10.8 (0.5) |
| Child gender: N (%) | | |
| Male | 616 (48%) | 193 (50%) |
| Female | 680 (52%) | 189 (49%) |
| Other | 2 (1%) | |
| Child z-BMI: mean (SD) | 0.35 (1.16) | 0.38 (1.24) |
| Parent age: | | |
| < 35 yrs | 106 (10%) | 37 (10%) |
| 35–39 yrs | 142 (13%) | 79 (21%) |
| 40–44 yrs | 414 (39%) | 136 (35%) |
| 45–49 yrs | 273 (26%) | 94 (24%) |
| 50+ yrs | 128 (12%) | 39 (10%) |
| Parent gender: N (%) | | |
| Male | 294 (27%) | 91 (24%) |
| Female | 794 (73%) | 295 (76%) |
| Other | 1 (< 1%) | |
| Parent ethnicity: N (%) | | |
| White British | 944 (87%) | 305 (86%) |
| White other | 57 (5%) | 23 (7%) |
| Black/African/Caribbean/Black British | 16 (1%) | 4 (1%) |
| Asian/Asian British | 40 (4%) | 16 (5%) |
| Mixed | 9 (1%) | 4 (1%) |
| Other | 17 (2%) | 4 (1%) |
| Household education: N (%) | | |
| Up to GCSE/equivalent | 243 (20%) | 43 (11%) |
| A level/equivalent | 312 (26%) | 93 (24%) |
| Degree/HND/equivalent | 435 (37%) | 165 (43%) |
| Higher degree | 201 (17%) | 86 (22%) |
| IMD rankb: median (IQR) | 22,914 (15,839) | 25,523 (11,342) |

---

* z-BMI only collected on a subset of 241 children in Wave 1

* IMD rank uses 2015 index for Wave 0 and 2019 index for Wave 1, with lower ranks indicating higher deprivation. IMD measures relative deprivation and so ranks can be compared

* GCSE = qualification at age 16; A level = qualification at age 18

Wave 0: Mar 2017-Jul 2018; Wave 1: May 2021-Dec 2021

IMD Index of Multiple Deprivation, IQR inter-quartile range, SD standard deviation, z-BMI Body Mass Index standardised z-score, GCSE General Certificate of Education (qualification at age 16), HND Higher National Diploma
were negligible differences between complete case and imputed models that exclude BMI z-score (7.7 min/day and 7.2 min/day lower children's weekday MVPA post COVID-19 respectively; Table S7).

Discussion

The data presented in this paper suggest that children's MVPA was lower post-COVID-19 by around 7–8 min per day on both weekdays and weekends when compared to data collected in the same schools, in the same way, prior to the COVID-19 pandemic. The data have also shown that average daily sedentary time was higher for children by nearly half an hour during the week and quarter of an hour at weekends. There was no evidence, however, that these differences were associated with gender or SEP. The reason for this reduction is unclear. Although the two waves were conducted 3 years apart, we are not aware of any study that has reported population change previously over such a short period, so we believe that the COVID-19 pandemic, associated restrictions and/or behaviour change in response are at least in part responsible. More detailed exploration of possible reasons is beyond the scope of the current paper, but we hope to explore this in more depth in qualitative analysis of the Active-6 project. The decrease in MVPA reported in this study is slightly lower than the decreases of 10–17 min found in the only other studies [15–17] we identified using device-measured MVPA, all outside the UK. It is important to note, however, that these studies had much smaller sample sizes and the data were collected during the first lockdown period in 2020, during school closures. Our data collection was predominantly in Autumn 2021 when lockdown restrictions had mostly been removed. The key message from this study is therefore that the initial detrimental impact of the pandemic on children's physical activity appears to continue beyond the period of actual restrictions. This is supported by the findings of the ALCYPS survey, which found a decrease in the number of active children in the initial lockdown May–July 2020 compared to the previous year, but no subsequent recovery [18]. This is concerning as children's MVPA declines with age at a rate of on average 2.2 min
Table 3  Estimates of child physical activity for Wave 0 and Wave 1, by gender and household education

|                          | Wave 0 (Pre-COVID-19) | 95% CI          | Wave 1                  | 95% CI          |
|--------------------------|-----------------------|-----------------|-------------------------|-----------------|
| All children             |                       |                 |                         |                 |
| Mean weekday MVPA (min/day) | 60.3 (57.2, 63.4)     |                 | 55.9 (52.1, 59.7)       |                 |
| Mean weekday light physical activity (min/day) | 209.4 (204.8, 213.9) |                 | 198.1 (190.9, 205.3)    |                 |
| Mean weekday sedentary (min/day) | 476.8 (470.1, 483.6) |                 | 488.4 (477.7, 499.0)    |                 |
| Mean weekend MVPA (min/day) | 53.4 (49.8, 57.1)     |                 | 45.7 (41.8, 49.6)       |                 |
| Mean weekend light physical activity (min/day) | 195.2 (190.0, 200.5) |                 | 185.4 (179.8, 190.9)    |                 |
| Mean weekend sedentary (min/day) | 437.1 (429.3, 444.9) |                 | 452.5 (442.6, 462.4)    |                 |
| % meeting UK PA guidelines | 40% (34%, 46%)        |                 | 36% (29%, 44%)          |                 |
| Child gender             |                       |                 |                         |                 |
| Boys                     |                       |                 |                         |                 |
| Mean weekday MVPA (min/day) | 68.4 (64.6, 72.2)     |                 | 64.3 (60.6, 67.9)       |                 |
| Mean weekday light physical activity (min/day) | 212.0 (206.7, 217.2) |                 | 206.4 (198.1, 214.7)    |                 |
| Mean weekday sedentary (min/day) | 466.1 (456.6, 475.7) |                 | 478.7 (466.1, 491.4)    |                 |
| Mean weekend MVPA (min/day) | 61.1 (56.0, 66.2)     |                 | 52.6 (48.3, 56.8)       |                 |
| Mean weekend light physical activity (min/day) | 193.1 (187.1, 199.1) |                 | 190.2 (180.7, 199.7)    |                 |
| Mean weekend sedentary (min/day) | 444.3 (432.8, 455.8) |                 | 449.6 (434.6, 464.5)    |                 |
| % meeting UK PA guidelines | 55% (48%, 61%)        |                 | 52% (44%, 60%)          |                 |
| Girls                    |                       |                 |                         |                 |
| Mean weekday MVPA (min/day) | 53.4 (50.3, 56.4)     |                 | 47.3 (43.1, 51.5)       |                 |
| Mean weekday light physical activity (min/day) | 207.1 (201.7, 212.5) |                 | 189.7 (182.2, 197.2)    |                 |
| Mean weekday sedentary (min/day) | 485.9 (479.2, 492.6) |                 | 498.1 (485.9, 510.3)    |                 |
| Mean weekend MVPA (min/day) | 46.7 (43.4, 50.1)     |                 | 38.2 (33.2, 43.2)       |                 |
| Mean weekend light physical activity (min/day) | 197.1 (190.5, 203.6) |                 | 190.0 (175.1, 186.9)    |                 |
| Mean weekend sedentary (min/day) | 430.9 (422.3, 439.5) |                 | 455.0 (445.9, 466.1)    |                 |
| % meeting UK PA guidelines | 28% (22%, 34%)        |                 | 20% (12%, 27%)          |                 |
| Household education      |                       |                 |                         |                 |
| Up to A level or equivalent^{a} |  |                 |                         |                 |
| Mean weekday MVPA (min/day) | 59.8 (56.3, 63.3)     |                 | 55.0 (50.3, 59.7)       |                 |
| Mean weekday light physical activity (min/day) | 211.8 (207.0, 216.7) |                 | 200.3 (190.1, 210.5)    |                 |
| Mean weekday sedentary (min/day) | 478.3 (469.9, 486.7) |                 | 474.5 (460.8, 488.2)    |                 |
| Mean weekend MVPA (min/day) | 52.5 (47.8, 57.2)     |                 | 42.3 (36.0, 48.7)       |                 |
| Mean weekend light physical activity (min/day) | 198.5 (191.6, 205.4) |                 | 184.7 (176.3, 193.0)    |                 |
| Mean weekend sedentary (min/day) | 434.6 (424.1, 445.0) |                 | 441.8 (426.6, 457.0)    |                 |
| % meeting UK PA guidelines | 39% (33%, 46%)        |                 | 39% (30%, 49%)          |                 |
| Degree equivalent or higher |  |                 |                         |                 |
| Mean weekday MVPA (min/day) | 60.5 (57.0, 64.1)     |                 | 56.4 (52.2, 60.5)       |                 |
| Mean weekday light physical activity (min/day) | 206.4 (200.9, 212.0) |                 | 196.4 (188.5, 204.2)    |                 |
| Mean weekday sedentary (min/day) | 477.4 (469.4, 485.3) |                 | 496.6 (485.4, 507.8)    |                 |
| Mean weekend MVPA (min/day) | 54.4 (50.2, 58.6)     |                 | 46.8 (42.7, 50.9)       |                 |
| Mean weekend light physical activity (min/day) | 191.5 (185.6, 197.3) |                 | 184.1 (177.8, 190.5)    |                 |
| Mean weekend sedentary (min/day) | 439.7 (430.1, 449.3) |                 | 458.1 (447.5, 468.7)    |                 |
| % meeting UK PA guidelines | 41% (33%, 48%)        |                 | 35% (26%, 43%)          |                 |

Standard errors are adjusted for clustering, but estimates are not adjusted for wear time or seasonality

^{a} A level = qualification at age 18

Wave 0: Mar 2017–Jul 2018; Wave 1: May 2021–Dec 2021
CI confidence interval, MVPA moderate-to-vigorous physical activity, PA physical activity
per year [9], so a reduction of 8 min due to the pandemic is potentially accelerating children three years along that age-related decline. Evidence around longer-term trajectories is limited, and so it is difficult to quantify the potential impact of a reduction in MVPA of this size. However, previous studies [43, 44] have reported inverse associations between physical activity and cardiometabolic risk factors, such as insulin, glucose, triglycerides and HDL-cholesterol, which would potentially suggest that some children may be at increased cardiometabolic risk after the pandemic.

Previous studies have reported large decreases in adult physical activity during initial lockdowns, with limited evidence suggesting that while activity levels increase as restrictions are eased, for many they do not return to pre-COVID-19 levels [45–47]. However, the parents in our study had similar levels of MVPA and sedentary time post-COVID-19 when compared to parents recruited from the same schools three years earlier. It should be noted, however, that these are parents of Year 6 children who were mainly female, aged 35–49 and with higher education levels than the general population, and so these findings may not be applicable to all adults. As the impact of lockdowns on physical activity has differed by age, gender and SEP, it may be that recovery will differ as well. More research using device-based measures of physical activity is needed to explore whether these results hold more widely, and in particular to identify groups who may need additional support.

The role of BMI is complex, and further complicated in our study by COVID-19-related data collection issues. A UK longitudinal study found an increase in child BMI over the period of the pandemic [38], but as there is some evidence that children with higher BMI are less active

### Table 4 Estimates of parent physical activity for Wave 0 and Wave 1

|                      | Wave 0 (Pre-COVID-19) | Wave 1                            |
|----------------------|-----------------------|-----------------------------------|
|                      | Estimate  | 95% CI  | Estimate | 95% CI  |
| All parents          |           |         |          |         |
| Mean weekday MVPA (min/day) | 54.6     | (52.2, 57.0) | 55.6 | (51.7, 59.5) |
| Mean weekday light physical activity (min/day) | 198.5 | (193.9, 203.1) | 190.8 | (184.7, 196.8) |
| Mean weekday sedentary (min/day) | 542.3 | (535.4, 549.2) | 521.6 | (512.0, 531.3) |
| Mean weekend MVPA (min/day) | 46.4     | (43.2, 49.6) | 49.0 | (44.0, 54.0) |
| Mean weekend light physical activity (min/day) | 191.6 | (186.8, 196.5) | 190.6 | (183.5, 197.8) |
| Mean weekend sedentary (min/day) | 486.5 | (480.4, 492.6) | 486.8 | (475.0, 498.6) |
| % achieving 150+min/wk | 82%           | 85% |

Standard errors are adjusted for clustering, but estimates are not adjusted for wear time or seasonality

Wave 0: Mar 2017-Jul 2018; Wave 1: May 2021-Dec 2021

CI confidence interval, MVPA moderate-to-vigorous physical activity

### Table 5 Modelled difference in child weekday MVPA between Wave 0 and Wave 1

|                      | Difference between Wave 0 and Wave 1 | Interaction effect (interaction with Wave) |
|----------------------|-------------------------------------|------------------------------------------|
|                      | Estimate  | 95% CI  | p-value a | Estimate | 95% CI  | p-value b |
| Model 1: unadjusted  | -6.7      | (-11.0, -2.3) | 0.003    |          |         |         |
| Model 2: adjusted    | -7.7      | (-11.9, -3.5) | <0.001   |          |         |         |
| Model 3: adjusted + z-BMI c | -6.5 | (-10.8, -2.3) | 0.002    |          |         |         |
| Model 4: gender interaction | -7.9 | (-12.7, -3.2) | 0.001    | 0.6      | (-4.2, 5.3) | 0.818   |
| Model 5: education interaction | -7.5 | (-12.2, -2.8) | 0.002    | -0.4    | (-5.4, 4.6) | 0.876   |
| Model 6: z-BMI interaction c | -6.2 | (-10.5, -1.9) | 0.005    | -0.6    | (-2.9, 1.6) | 0.579   |

All models are adjusted for accelerometer wear time, seasonality and remote data collection

Models 2 & 3 also control for gender, age and household education

a p-value for a test for a difference between Wave 0 and Wave 1

b p-value for a test for an interaction effect

c z-BMI models use multiple-imputed data: see text for details

Wave 0: Mar 2017-Jul 2018; Wave 1: May 2021-Dec 2021

CI confidence interval, MVPA moderate-to-vigorous physical activity, CMO Chief Medical Officer, PA physical activity, z-BMI Body Mass Index standardised z-score
(although the direction of association is not clear) [9, 39], it is difficult to separate the effect of COVID-19 restrictions on physical activity from indirect effects on BMI. When adjusting for BMI z-score, the difference in MVPA pre and post COVID-19 was slightly smaller but still evident, suggesting that the pandemic has impacted both BMI and physical activity. As noted above it is important to highlight that we had a large amount of missing BMI data and had to impute data, so extra caution is required when interpreting the results of analyses that included z-BMI.

We found no evidence of a difference in participation in extra-curricular clubs taking place at the school, but there was a reduction in the activity score, which includes community clubs and unstructured play, amounting to approximately one day fewer per week. Participation in these activities differs by gender and socioeconomic position [34, 35], and so further investigation is warranted.

---

**Fig. 3** Model estimates and 95% confidence intervals for the difference in physical activity summaries for children and parents between Wave 0 (pre-COVID-19: Mar 2017-Jul 2018) and Wave 1 (May 2021-Dec 2021). Note ‘Weekend’ refers to a weekend day.
into whether the type of activities engaged in and where they take place has changed since the pandemic, especially for key groups who are typically less active. Leisure screen-viewing was lower for both children and parents on both weekdays and weekends, although care should be taken in making these comparisons as the measures were somewhat different across the two waves. While this contrasts with patterns seen elsewhere during lockdowns [15, 16], other studies typically did not separate leisure and school screen viewing. In our study a third of parents reported post-COVID-19 restrictions that their child spent more than an hour per day engaged in screen viewing for schoolwork. TV viewing (including on-demand TV) was substantially higher in Wave 1 for both adults and children than during Wave 0, with the odds of children watching more than one hour of TV two to three times higher. This may reflect a change in screen-viewing patterns, with an increase in family TV time and screen-viewing for schoolwork but reduced use of phones and games consoles. Ongoing qualitative work as part of the Active-6 project will explore changes in screen-viewing in more depth.

In this paper we have focused on differences in physical activity and sedentary time between pre-COVID-19 and Autumn 2021, adjusted for contextual differences in the initial data collection period (May–July 2021). However, the data suggest that children's PA levels were higher than pre-COVID-19 by around 10 min during that period, compared to the reduction seen subsequently. Some of this may be due to differential recruitment with both participating schools and pupils in that time likely to be more active, with lower BMI z-score and from higher educated and less deprived households. However, it is also likely that the post-lockdown impact of the COVID-19 pandemic is not constant but changing over time, in response to local risk assessment and disruptions as well as changing behaviour. Understanding and monitoring the longer-term impacts is crucial, in particular how these change over time, and is the focus of continued data collection in the Active-6 project.

Strengths and limitations
It is important to recognise several limitations. We experienced poorer response rates due to COVID-19 (including fewer participating schools), changes in data collection protocols, differing school risk assessments and disruption due to COVID-19 within schools, all of which affect the amount of data that we were able to collect. This was expected given the challenges of conducting school-based research during a pandemic. This is a repeated cross-sectional study, which is appropriate to investigate physical activity and sedentary time of children and their parents before and after the COVID-19 restrictions, but lack of longitudinal data means we do not know how active children were before, or if this affected participation. While the participating schools were demographically similar to the original Wave 0 cohort, schools with pupils who were previously more active were more likely to take part. We are therefore unable to determine if the pandemic has differentially affected the most or the least active children. To facilitate comparison with Wave 0 data and the wider field, we processed the accelerometer data using widely used cut-points that were developed for earlier versions of the Actigraph accelerometer. It is possible that alternative data processing approaches, including compositional data analysis, may have yielded different results. Finally, as for any analysis covering the period of the COVID-19 pandemic, we cannot rule out that differences are due to changes in physical activity and sedentary levels over time driven by factors other than COVID-19, although the scale of the observed differences and other evidence support our interpretation. However, our study also has several strengths. Despite the difficulty in collecting data on children in schools over the pandemic, we were able to build on our excellent existing relationships with local schools to collect much-needed data on physical activity and sedentary time. Both pre-COVID-19 comparator data and data for the current study were measured contemporaneously by accelerometers, rather than relying on retrospective self-report measures of activity, and collected as far as possible under the same circumstances. Moreover, the data were collected in the same schools, which in the case of this study increased the statistical power of the study and reduced potential for school-level imbalance between pre- and post-COVID-19 measures. We have also concentrated on understanding the longer-term impacts of the pandemic once restrictions are lifted, an area where there is little current evidence, but potentially of great policy relevance.

Conclusion
Children's MVPA was lower by 7–8 min per day in 2021 once restrictions were lifted than before the COVID-19 pandemic across gender and SEP, on both weekdays and weekends, equating to a three-year acceleration in otherwise expected age-related decline. Parents' physical activity and sedentary time were similar to pre-pandemic levels. Previous evidence has shown substantial decreases in children's physical activity during lockdowns associated with the COVID-19 pandemic, and our results suggest that despite easing of restrictions, children's activity levels have not returned to pre-pandemic levels. There is an urgent need to understand why these changes have occurred and whether they are maintained during the recovery from the COVID-19 pandemic.
Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12966-022-01290-4.

Acknowledgements
We would like to thank all the families and schools that have taken part in both the B-Proact1v and Active-6 projects.

Authors’ contributions
The study was conceived by RJ, RS, CF, FDv, JW, and WH. BT, LEC and DH were the project managers. KB, TR, SC and RW assisted with study design and study methodologies. All analyses were conceived by RS, RJ and FDv and performed by RS. The first draft of the paper was written by RJ and RS. All authors reviewed the paper and made key intellectual contributions to content and reporting and approved the final manuscript.

Funding
This project is funded by the National Institute for Health Research [Public Health Research Programme – project 131847]. The views and opinions expressed herein are those of the authors and do not necessarily reflect those of the NIHR PHR Programme or the Department of Health and Social Care. Funders had no involvement in data analysis, data interpretation or writing of the paper. Public Health Research Programme, 131847, Russell Jago, British Heart Foundation, 3P 14/4/31123. FDv, WH and RJ are partly funded by the British Heart Foundation. The data for the comparator study (Wave 0) was funded by the British Heart Foundation. The data for the current study was partly funded by the British Heart Foundation.

Availability of data and materials
As the Active-6 project is still ongoing, data are not currently available. At the end of the project data will be made available in the University of Bristol’s data repository (https://data.bris.ac.uk/data/).

Declarations
Ethics approval and consent to participate
Both the original B-Proact1v study and the current Active-6 study received ethical approval from the School of Policy Studies Ethics Committee at the University of Bristol, UK (Ref SPSREC/20–21/150). Schools participating in B-Proact1v consented to being contacted again. Written and online parental consent were received for all participants in B-Proact1v and Active-6 respectively.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
1Centre for Exercise, Nutrition & Health Sciences, School for Policy Studies, University of Bristol, Bristol BS8, ITZ, UK. 2Bristol Medical School, Population Health Sciences, University of Bristol, Bristol BS8, 2PS, UK. 3Applied Research Collaboration West (NIHR ARC West), The National Institute for Health Research, University Hospitals Bristol and Weston NHS Foundation Trust, Bristol BS1 2NT, UK. 4Communities and Public Health, Bristol City Council, Bristol BS1 9NE, UK. 5Independent Public Member of the Project Team, Bristol, UK.

Received: 21 February 2022 Accepted: 31 March 2022
Published online: 16 May 2022

References
1. Department of Health (UK): Start Active, Stay Active: A report on physical activity from the four home countries. London: Chief Medical Officers; 2011.
2. Barreto S, Stubbs B: The Role of Exercise in Preventing and Treating Depression. Current Sports Med Reports 2019, 18(8).
3. UK Chief Medical Officers: UK Chief Medical Officers’ Physical Activity Guidelines. London: Department of Health and Social Care; 2019.
4. Strong WB, Robert M, Malina RM, Blimkie CJR, Daniels SR, Dishman RK, Gutin B, Hergenroeder AC, Must A, Nixon PA, Pivarnik JM, et al. Evidence Based Physical Activity for School-age Youth. Journal of Pediatrics. 2005;146(6):732–7.
5. Skrede T, Steene-Johannessen J, Anderssen SA, Resaland GK, Ekelund U: The prospective association between objectively measured sedentary time, moderate-to-vigorous physical activity and cardiometabolic risk factors in youth: a systematic review and meta-analysis. Obes Rev 2018.
6. Ekelund U, Luan J, Sherar LB, Esliger DW, Gniwuch C, Cooper A. International Children’s Accelerometry Database C: Moderate to vigorous physical activity and sedentary time and cardiometabolic risk factors in children and adolescents. JAMA. 2012;307(7):704–12.
7. Bull FC, Al-Ansari SS, Biddle S, Boordulin K, Buman MP, Cardon G, Carty C, Chaput JP, Chastin S, Chou R, et al. World Health Organization 2020 guidelines on physical activity and sedentary behaviour. Br J Sports Med. 2020;54(24):1451–62.
8. Chaput JP, Willumsen J, Bull F, Chou R, Ekelund U, Firth J, Jago R, Ortega FB, Katzmarzyk PT. 2020 WHO guidelines on physical activity and sedentary behaviour for children and adolescents aged 5–17 years: summary of the evidence. Int J Behav Nutr Phys Act. 2020, 17(1):141.
9. Jago R, Salway R, Emm-Collison L, Sebire SJ, Thompson JL, Lawlor DA. Association of BMI category with change in children’s physical activity between ages 6 and 11 years: a longitudinal study. Int J Obes (Lond). 2020;44(1):104–13.
10. Farooq MA, Parkinson KN, Adamson AJ, Pearce MS, Reilly JK, Hughes AR, Janssen X, Basterfield L, Reilly JJ. Timing of the decline in physical activity in childhood and adolescence. Gateshead Millennium Cohort Study. Br J Sports Med. 2018;52(15):1002–6.
11. Hale T, Anania J, Angrisani N, Baby T, Cameron-Blake E, Di Folco M, Ellen L, Goldszmid R, Hallas L, Kira B, et al. Variation in Government Responses to COVID-19 Version 12.0. Blavatnik School of Government Working Paper; 2021.
12. Timeline of UK government coronavirus lockdowns [https://www.instituteforgovernment.org.uk/charts/uk-government-coronavirus-lockdowns]
13. Stockwell S, Trott M, Tully M, Shin J, Barnett Y, Butler L, McDermott D, Schuch F, Smith L. Changes in physical activity and sedentary behaviours from before to during the COVID-19 pandemic lockdown: a systematic review. BMJ Open Sport Exerc Med 2021, 7(1).
14. Rossi L, Behme N, Breuer C. Physical Activity of Children and Adolescents during the COVID-19 Pandemic: A Scoping Review. Int J Environ Res Public Health 2021, 18(2).
15. Burkan S, Parker H, Weaver RG, Beets MW, Jones A, Adams EL, Chaput JP, Armstrong B. Impact of the COVID-19 pandemic on elementary school-ers’ physical activity, sleep, screen time and diet: A quasi-experimental interrupted time series study. Pediatric Obes. 2022;17(1):e12846.
16. Ten Velde G, Lubrecht J, Arayess L, van Loo C, Hesselink M, Reijniers D, Vreugdenhil A. Physical activity behaviour and screen time in Dutch children during the COVID-19 pandemic Pre-, during- and post-school closures. Pediatr Obes 2021:e12779.
17. Dallolli L, Marinis A, Masini A, Toselli S, Stagni R, Bisi MC, Gori D, Tessari A, Sansavini A, Lanari M, et al. The impact of COVID-19 on physical activity behaviour in Italian primary school children: a comparison before and during pandemic considering gender differences. BMC Public Health. 2022;22(1):52.

18. Sport England: Active Lives Children and Young People Survey, Academic Year 2020–21. UK: Sport England; 2021.

19. Chambonniere C, Lambert C, Fearnbach N, Tardieu M, Fillon A, Genin P, Laraas B, Melmers P, Bois J, Pereira B, et al. Effect of the COVID-19 lockdown on physical activity and sedentary behaviours in French children and adolescents: New results from the ONAPS national survey. Eur J Integr Med. 2021;43:101308.

20. Sport England: Active Lives Adult Survey May 2020/21 Report. UK: Sport England; 2021.

21. Strain T, Sharp SJ, Spiers A, Price H, Williams C, Fraser C, Brage S, Wijnlaede K, Kelly P. Population level physical activity before and during the first national COVID-19 lockdown. A nationally representative repeat cross-sectional study of 5 years of Active Lives data in England. Lancet Reg Health Eur. 2022;12:100265.

22. Bingham DD, Daly-Smith A, Hall J, Seims A, Dogra SA, Fairclough SJ, Ajeton M, Kelly B, Hou B, Shire KA, et al. Covid-19 lockdown: Ethnic differences in children’s self-reported physical activity and the importance of leaving the home environment; a longitudinal and cross-sectional study from the Born in Bradford birth cohort study. Int J Behav Nutr Phys Act. 2021;18(1):117.

23. Estimated number of parents in families with dependent children by ethnic group of the parent, UK [https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/adhoc/00759.

24. Public Health England: National Diet and Nutrition Survey. Diet, nutrition and physical activity in 2020: a follow up study during COVID-19. London: Public Health England, 2021.

25. Protocol for Assessing the impact of COVID-19 on the physical activity of Year 6 children and their parents: Identifying scalable actions to mitigate adverse impacts & provide rapid evidence to policy makers (ACTIVE-6) [https://fundingawards.nihr.ac.uk/award/NHRI13184/7].

26. R Core Team: R: A Language and Environment for Statistical Computing. Vienna: R Foundation for Statistical Computing, 2020.

27. Accelerometer Processing Code [osf.io/y8mwu].

28. Evenson KR, Catellier DJ, Gill K, Ondrak KS, McMurray RG. Calibration of two objective measures of physical activity for children. J Sports Sci. 2008;26(14):1557–65.

29. Troiano RP, Berrigan D, Dodd KW, Masse LC, Tilert T, McDowell M. Physical activity in the United States measured by accelerometer. Med Sci Sports Exerc. 2008;40(1):181–8.

30. English indices of deprivation [https://www.gov.uk/government/collections/english-indices-of-deprivation].

31. Get information about Schools [https://get-information-schools.service.gov.uk/].

32. Whincup PH. Physical activity, obesity and cardiometabolic risk factors in 9- to 10-year-old UK children of white European, South Asian and black African-Caribbean origin: the Child Heart And Health Study in England (CHASE). Diabetologia. 2010;53(8):1620–30.

33. Parent-reported height and weight as sources of bias in survey estimates from the Born in Bradford birth cohort study. Int J Behav Nutr Phys Act. 2018;15(1):1–10.

34. Salway R, Hunt ET, Armstrong B, Beets MW, Brazendale K, Turner-McGrew G, Pate RR, Youngstedt SD, Dugger R, Parker H, et al. COVID-19 Leads to Accelerated Increases in Children’s BMI z-Score Gain: An Interrupted Time-Series Study. Am J Prev Med. 2021;61(4):e161–9.

35. Richmond RC, Davey Smith G, Ness AR, den Hoed M, McMahon G, Timpson NJ. Assessing causality in the association between child adiposity and physical activity levels: a Mendelian randomization analysis. PLoS Med. 2014;11(3):e1001618.

36. Bhaskaran K, Gasparini A, Hajat S, Smeeth L, Armstrong B. Time series regression studies in environmental epidemiology. Int J Epidemiol. 2013;42(4):1187–95.

37. Weaver RG, Hunt ET, Armstrong B, Beets MW, Brazendale K, Turner-McGrew G, Pate RR, Youngstedt SD, Dugger R, Parker H, et al. COVID-19 Leads to Accelerated Increases in Children’s BMI z-Score Gain: An Interrupted Time-Series Study. Am J Prev Med. 2021;61(4):e161–9.

38. Weaver RG, Hunt ET, Armstrong B, Beets MW, Brazendale K, Turner-McGrew G, Pate RR, Youngstedt SD, Dugger R, Parker H, et al. COVID-19 Leads to Accelerated Increases in Children’s BMI z-Score Gain: An Interrupted Time-Series Study. Am J Prev Med. 2021;61(4):e161–9.

39. Salway R, Emm-Collison L, Sebire S, Thompson J, Lawlor D, Jago R. The association of school-related active travel and active after-school clubs with children’s physical activity: a cross-sectional study in 11-year-old UK children. Int J Behav Nutr Phys Act. 2019;16(1):1–10.

40. Rubin D. Multiple Imputation after 18 years. J Am Stat Assoc. 1996;91(437):473–89.

41. StataCorp.: Stata Statistical Software: Release 15. College Station: StataCorp LLC, 2017.

42. Charlton C, Ratbush J, Browne WJ, Healy M, Cameron B. MLwiN Version 3.05. Centre for Multilevel Modelling, University of Bristol, 2020.

43. Owen CG, Nightingale CM, Rudnicka AR, Sattar N, Cook DG, Ekelund U, Whincup PH. Physical activity, obesity and cardiometabolic risk factors in 9- to 10-year-old UK children of white European, South Asian and black African-Caribbean origin: the Child Heart And Health Study in England (CHASE). Diabetologia. 2010;53(8):1620–30.

44. Tarp J, Child A, White T, Westgate K, Bugge A, Grontved A, Wedderkopp N, Andersen LB, Cardon G, Davey R, et al. Physical activity intensity, bout-duration, and cardiometabolic risk markers in children and adolescents. Int J Obes (Lond). 2018;42(9):1639–50.

45. Salway R, Su TT, Ismail R, Glynis Armstrong ME, Foster C, Johnson L. The impact of COVID-19 movement restrictions on physical activity in a low-income semi-rural population in Malaysia: A longitudinal study. J Glob Health. 2021;11:05029.

46. Bu F, Bone JK, Mitchell JJ, Steptoe A, Fancourt D. Longitudinal changes in physical activity during and after the first national lockdown due to the COVID-19 pandemic in England. Sci Rep. 2021;11(1):17723.

47. Massar SAA, Ng ASC, Soon CS, Ong JL, Chua XY, Chee N, Lee TS, Chee MWL. Reopening after lockdown: the influence of working-from-home and digital device use on sleep, physical activity, and wellbeing following COVID-19 lockdown and reopening. Sleep 2022, 45(1).

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.