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Outdoor temperature, precipitation, and wind speed affect physical activity levels in children: a longitudinal cohort study

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Abstract

Objective—Evaluate effects of local weather conditions on physical activity in early childhood.

Methods—Longitudinal prospective cohort study of 372 children, 3 years old at enrollment, drawn from a major US metropolitan community. Accelerometer-measured (RT3) physical activity was collected every 4 months over 5 years and matched with daily weather measures: day length, heating/cooling degrees (degrees mean temperature < 65°F or ≥ 65°F, respectively), wind, and precipitation. Mixed regression analyses, adjusted for repeated measures, were used to test the relationship between weather and physical activity.

Results—Precipitation and wind speed were negatively associated with total physical activity and moderate-vigorous physical activity ($P<0.0001$). Heating and cooling degrees were negatively associated with total physical activity and moderate-vigorous physical activity and positively associated with inactivity (all $P<0.0001$), independent of age, sex, race, BMI, day length, wind, and precipitation. For every 10 additional heating degrees there was a five-minute daily reduction in moderate-vigorous physical activity. For every additional 10 cooling degrees there was a 17-minute reduction in moderate-vigorous physical activity.

Conclusions—Inclement weather (higher/lower temperature, greater wind speed, more rain/snow) is associated with less physical activity in young children. These deleterious effects should be considered when planning physical activity research, interventions, and policies.

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Keywords

environment; barriers; cooling degree; heating degree; weather

INTRODUCTION

Physical inactivity is the fourth leading cause of death worldwide.[1,2] A better understanding of barriers that limit physical activity in youth is critical to circumvent the negative health consequences associated with low levels of exercise and physical activity.[3,4] Promotion of physical activity is especially critical in children,[5] in part because physical activity behaviors continue from childhood into adulthood.[6,7] In addition, if unique windows of opportunity are missed during childhood, adolescents may become resistant to physical activity intervention.[8]

Outdoor physical activity is an important contributor to overall activity in children.[9,10] Barriers to outdoor activity require consideration in the design of physical activity studies and policies.[11,12] Many studies have reported seasonal variations in physical activity in children.[13–15] Seasonality can be a proxy for other conditions, such as temperature,[16] but may be imprecise due to the substantial variation between different geographic areas.[17] Further, use of seasonality as a proxy for weather is insufficient for comparing environmental conditions between geographic regions.

Heating degrees and cooling degrees are measures used to describe climate-related energy requirements for different cities and regions.[18,19] They are calculated as the difference between the mean temperature and a baseline temperature, typically 65°F.[19] Although temperature and other weather conditions have been associated with physical activity levels in youth,[20–22] to our knowledge heating and cooling degrees have not been used in analyses of environmental barriers to physical activity. More detailed weather information relevant to when and why physical activity is hampered could support patient-centered counseling[23] focused to combat physical inactivity. The purpose of this study was to employ heating and cooling degrees, as well as local precipitation, wind speed, and day length to evaluate the effect of local weather conditions on physical activity in three- to seven-year-old children. The primary hypothesis tested in the current investigation was that greater heating and cooling degrees would be associated with less physical activity in young children.

MATERIALS AND METHODS

Population and Design

In 2001, 372 healthy three-year-old children were recruited from the Cincinnati, OH metropolitan area and enrolled in a longitudinal cohort study of early childhood growth.[9] They were evaluated every four months over a five-year period, yielding up to 13 visits per child.[24] The protocol was approved by the IRB and written informed consent was obtained from the guardian. Age, sex, race/ethnicity, and household income were collected from the parent, and height and weight were measured each visit. BMI was calculated as weight/

height^2 (kg/m^2). BMI z-scores were calculated with use of the Centers for Disease Control & Prevention 2000 growth reference.[25]

Measures

A triaxial accelerometer (RT3, Stayhealthy, Inc., Monrovia, CA) was used to measure physical activity and has been validated in this age group.[26] Children enrolled in the study were instructed to wear the accelerometer at the waist above the right hip with an elastic belt for two weekdays and one weekend day every four months and to take off the device during sleep, bathing, and other activities that might harm the device. The devices recorded activity using a 60 second epoch, and the data were downloaded at each study visit. Accelerometer data were reviewed upon download and excluded if the output appeared invalid (*e.g.*, counts for each minute around 1,000 at all times of day with little to no variation), as previously described.[27]

Accelerometer periods of at least 60 minutes with either zero counts or no more than 2 consecutive minutes of counts less than 100 were treated as non-wear time.[28] The start of a day was defined as 02:00:00 (hours:minutes:seconds), and the end of the day was 01:59:59. Days with less than eight hours of wear time were excluded from analysis. After processing, a total of 9,264 participant-days of accelerometry were analyzed. Three hundred sixty-five participants (98%) had at least one day of accelerometry measurements. The following summary measures for each day were calculated: total physical activity (counts per day), minutes of moderate-vigorous physical activity (MVPA, number of minutes ≥ 1400 counts), and minutes of inactivity (IA, number of minutes ≤ 175 counts).[26] Each physical activity measure was adjusted for wear time using the residual method as described previously.[27,29] This method involves regressing PA minutes on wear time, and then adding each participant's residual PA to the predicted PA corresponding to the group's average wear time.

Environmental conditions were collected from data available from the United States National Climatic Data Center (ncdc.noaa.gov) and matched with daily accelerometry data. A central location (Cincinnati Municipal Airport, Lunken Field, 84.41889 degrees West, 39.10333 degrees North, elevation 149.4 meters, Station ID KLUK) with frequently observed and recorded weather data was used to represent area conditions. Daily measures (reduced from hourly observations at this station by the NCDC) included minimum temperature (°F), maximum temperature (°F), average wind speed (miles per hour), and precipitation (inches). Precipitation included rainfall and melted snowfall.

Daily mean temperature was calculated as the arithmetic mean of the maximum and minimum temperature. Heating degrees were calculated as 65°F less the mean temperature on days when the mean temperature was less than 65°F. Cooling degrees were calculated as mean temperature less 65°F on days when the mean temperature was greater than or equal to 65°F. Thus, each day could have either a heating degrees measure or a cooling degrees measure, not both. Figure 1 illustrates the relationship between mean temperature and heating/cooling degrees while also displaying monthly totals. Sixty-five degrees F was used as the baseline in order to be consistent with other reports.[30] Day length was calculated as the number of minutes between sunrise and sunset as reported by the United States Naval

Observatory Astronomical Applications Department (http://aa.usno.navy.mil/data/docs/RS_OneYear.php).

Analysis

Statistical analyses were performed with SAS 9.3 (SAS Institute, Carey, NC). Baseline cohort characteristics were calculated based on data obtained at the first visit. Descriptive statistics of weather conditions were calculated and reported for all contiguous days with available data from study start to study end. Mixed model regression analyses using Proc Mixed were conducted to determine the effects of weather conditions on physical activity while accounting for non-independence of the repeated measurements within individual. Weather variables were modeled as fixed effects and subject and intercept were specified as random effects. 'Unadjusted' mixed models (*i.e.*, not adjusted for age, sex, race, etc.) accounting for repeated individual measures were run for each physical activity variable with each weather variable. Fully adjusted models included cooling or heating degrees, age, sex, race, and BMI z-score, wind speed, and precipitation. Several modeling approaches were evaluated as alternatives to separate heating and cooling degree models, including using linear splines, quadratic terms, and logarithmic transformations, and none provided better model fit nor substantially altered the conclusions reached. For purposes of presentation clarity, separate models for heating and cooling degrees are reported herein. Household income was considered as a covariate, but was removed after failing to reach significance ($P < 0.05$) in any adjusted model. By definition, each day could only have heating degrees or cooling degrees, so analyses using either of these measures included only days when the mean temperature was < 65°F or ≥ 65°F, respectively. Models were fitted using restricted maximum likelihood estimation employing a variance components covariance structure.

RESULTS

At baseline, 372 participants were enrolled in the study, of whom 48% were girls and 22% were black. Age at enrollment was 3.4 years ± 0.3 years (mean ± standard deviation). Annual household income was distributed as follows: 10% of families had income < $20,000, 29% $20,000 to $50,000, 31% $50,000 to $75,000, and 30% > $75,000. Average body mass index was 16 kg/m^2 with a corresponding average z-score of 0.27. During the time period the study was conducted, day length ranged from 9.4 to 14.9 h/d (Table 1). Across all person-days of physical activity, median wear time was 13 hours, median MVPA was 76 minutes, and median inactivity was 276 minutes (Table 2).

The daily maximum temperature ranged from 14°F to 100°F, and the daily minimum temperature ranged from −8°F to 76°F. Heating degrees (degrees < 65°F) ranged from 0 to 60°F with a median of 20°F; cooling degrees (degrees ≥ 65°F) ranged from 0 to 21°F with a median of 8°F. Days with heating degrees occurred during every month of the year but were most common in February; days with cooling degrees fell between April and November. Fifty-five percent of days had no precipitation, 37% of days had 0 to 0.5 inches of precipitation, and 9% of days had over 0.5 inches (Table 1). Forty-eight percent of days had an average wind speed of less than 5 mph; 14% of days had an average of over 10 mph.

In unadjusted models, longer day length was associated with more total physical activity, greater MVPA, and fewer minutes of inactivity (all $P < 0.001$; Table 3). Heating and cooling degrees were both associated with less total physical activity, fewer minutes of MVPA, and greater minutes of inactivity (all $P < 0.0001$; Figure 2). Cooling degrees demonstrated the greatest magnitude of association with physical activity measures. Precipitation and wind speed were also associated with less total physical activity ($P < 0.0001$), less MVPA ($P < 0.0001$), and more inactivity ($P = 0.02$ and $P = 0.007$, respectively; Table 3).

Both total physical activity and MVPA were independently associated with both heating degrees and cooling degrees (all $P < 0.001$), after adjustment for age, sex, race, BMI z-score, day length, wind speed, and precipitation (Table 4). In these mixed models, every additional 10 heating degrees were associated with 5 minutes fewer MVPA; every additional 10 cooling degrees were associated with 17 fewer minutes MVPA. Inactivity was also independently and positively associated with heating ($P = 0.011$) and cooling ($P < 0.0001$) degrees after adjustment for age, sex, race, BMI z-score, day length, wind speed, and precipitation. Each additional 10 heating degrees was associated with 3 minutes greater inactivity. Likewise, each additional 10 cooling degrees was associated with 19 minutes greater daily inactivity.

The effect estimate of day length on physical activity in the fully adjusted models differed between the heating degrees model and the cooling degrees model. In the model with heating degrees, day length was significantly associated with all physical activity measures (Table 4; *e.g.*, each additional hour day length was associated with 7 additional minutes MVPA, $P < 0.0001$). In the cooling degrees model, day length was not significantly associated with physical activity (*e.g.*, MVPA parameter estimate = 1, $P = 0.2$).

Greater precipitation was independently associated with fewer minutes of MVPA ($P < 0.001$) in both models and with greater minutes of inactivity in the heating degrees model ($P < 0.0001$) but not the cooling degrees model ($P = 0.4$; Table 4). Greater wind speed was independently associated with less favorable levels of each physical activity measure (all $P < 0.05$) in the heating degrees model but not in the cooling degrees model (Table 4).

DISCUSSION

In this population of healthy children followed over five years, inclement weather (heating degrees, cooling degrees, wind speed, precipitation) was significantly associated with multiple measures of reduced physical activity. The associations of physical activity with heating degrees (degrees < 65°F) and cooling degrees (degrees ≥ 65°) were present even after adjustment for multiple demographic factors, body size, and other weather conditions.

Our findings of an association between temperature and physical activity extend the work that has been done in previous studies into a new, younger age group. Duncan and colleagues employed pedometer-determined physical activity in 1,115 children aged 5–12 years old and found that ambient temperature and rainfall had a substantial effect on step counts.[21] Likewise, in British children aged 8 to 11 both greater temperature and greater rainfall were associated with a reduction in physical activity.[31] Based on the prior evidence and data from this study, inclement weather conditions are a barrier to physical activity in childhood.

In this article, temperature was represented by heating degrees and cooling degrees, the degrees by which the mean outdoor temperature deviated from a baseline temperature of 65°F. Heating and cooling degrees have been used to quantify energy needs for communities, but to our knowledge this is the first time this concept has been used to relate weather conditions to health-related behaviors. We found that cooling degrees (degrees ≥ 65°F) had a relatively greater association with MVPA than heating degrees, which indicates that in this population, "hot" weather was the strongest deterrent to physical activity. Other studies have analyzed the effect of temperature in a linear fashion,[21] or broken temperature up into high or low "extreme" categories.[22] In 1,115 children from New Zealand a 10 degree rise in mean ambient temperature was associated with an increase in pedometer-measured steps, more so in boys than girls.[21] In adult populations mean daily temperature being < 20°F or ≥ 75°F was also associated with less physical activity,[22] as was maximum temperature.[32] Our findings that hotter weather was a stronger barrier to physical activity than colder weather may be due to several factors. Adding layers of clothing and staying active may be easier on a cold day than shedding layers on a hot day; there is a limit to how many layers can be shed. Also, recommendations regarding avoiding UV exposure may make it more difficult to be active outside on warm sunny days. Third, it is possible other factors (e.g., smog, local preference for cooler temperatures) may have a deleterious effect on physical activity that is more pronounced on hot summer days.[33]

The method outlined herein of using heating and cooling degrees to describe temperature effects is advantageous because it avoids the potential loss of fidelity that occurs in categorization and allows for comparing relative effects of high vs. low temperature conditions. It also offers advantages over using seasonality as a proxy for environmental variation,[34] since seasonal conditions vary so greatly from region to region.[35] The increased fidelity in measurement supports the more robust multivariate prediction models utilized in the current project. Specifically, the data indicated that for every additional 10 heating degrees children were involved in 5 minutes less in MVPA and 3 minutes more being inactive. Similarly, for every 10 additional cooling degrees (degrees ≥ 65°F) children were involved with 17 minutes fewer MVPA and 19 minutes greater inactivity.

Precipitation and wind speed were also independently predictive of multiple measures of physical activity in our analyses. Greater precipitation was associated with less total physical activity and MVPA on hot and cold days, and greater inactivity on cold days. These findings show that the effects of precipitation on physical activity differ by temperature, implying that all precipitation is not equal. Snow on a cold day may be a bigger driver of inactivity than rain on a hot day. Higher wind speeds were associated with less favorable physical activity measures on cold days only. This finding is consistent with human temperature regulation – at higher ambient temperatures, the primary method of heat transfer in humans is evaporation through via perspiration,[36] making windier hot days potentially more favorable for physical activity than windy cold days. Wind on cold days has long been recognized as unfavorable and has even prompted new methods for expressing the perceived effect on humans.[37,38] Other investigators have reported effects of rain but not wind speed on physical activity in elderly persons.[39,40] and children.[21]

Our findings of a general association between day length and physical activity is consistent in with a recent study of 8 to 11 year old British children.[31] We also found that in the cooling degrees model (hotter days), day length was not associated with physical activity when adjusting for other covariates, but was significantly associated with all physical activity measures (longer days with greater total physical activity, greater MVPA, and less inactivity) in the fully adjusted heating degrees model (colder days). Since most ‘heating degree’ days are in the winter, this may indicate that every hour of extra light has an impact on whether children and their families go outside and are active. It is possible that in the summer, the days are long enough and may reach past bedtime in many young children, thereby not affecting activity choices.

There are several strengths of this investigation that advance the current literature. First, the use of triaxial accelerometers for measurement of physical activity improves on previous studies that used questionnaires[41] or pedometers.[21,40,42] Second, the information quality of the weather data is high; it is from an airport and has a high frequency of weather data reporting and weather data quality. Lastly, since this study was performed over five years, a change in activity influenced by accelerometer usage is much less susceptible to bias commonly associated with shorter term or cross sectional studies.

This study has a few limitations. First, the accelerometer was worn during inside and outside activities, thus capturing physical activities in multiple settings. We assume that weather conditions adversely affect physical activity as they spend more time indoors during inclement weather, and indoor time is associated with decreased physical activity. This assumption may not be appropriate for all people. Second, the weather conditions used in this study were measured at a central location. These centrally measured conditions may have differed to some degree from where each individual was on the days measured. Additionally, the particular findings in our study may be related to the use one geographic area for this study, limiting the external validity. For instance, people in warmer climates may acclimate[43] and be more tolerant of warmer weather than those in colder climates. Third, since the data collected for some measures, such as rainfall, mostly fell within a relatively narrow range (~92% of days had less than 0.5 inches precipitation), the applicability of the findings outside of that range may be limited. Fourth, although our analyses are novel in the use of heating and cooling degrees to model high and low temperatures differently, the relationship between temperature and physical activity is likely more complex than two linear models can represent, and error in the estimates may be greater at temperature extremes.

These findings may have practical implications for parents making decisions about activities for their children and for public health practitioners promoting physical activity in their communities. Although past studies have linked outdoor activity with overall physical activity,[9,10] alternative indoor venues should be sought, such as community centers, school recreation areas, workout facilities, and sports complexes. If not available or not in existence, these alternative indoor venues should be built or expanded to promote physical activity. Further, inclement weather should be considered as a potential limiting factor on the effects of built environment changes (*e.g.*, installing outdoor playgrounds, trails) on physical activity. Finding alternative ways to keep children active should be prioritized at daycare facilities as well.[11]

In conclusion, physical activity is hampered in inclement weather conditions; public health practitioners should take this into account when developing strategies to promote and maintain healthy physical activity levels in youth. The impact of inclement weather conditions should be considered by investigators planning outdoor physical activity studies[44] and policy-makers contemplating decisions about the built environment. Testing the utility of climate-controlled facilities in promoting physical activity despite inclement weather should be prioritized.

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Abbreviations

MVPA	moderate-vigorous physical activity
IA	Inactivity

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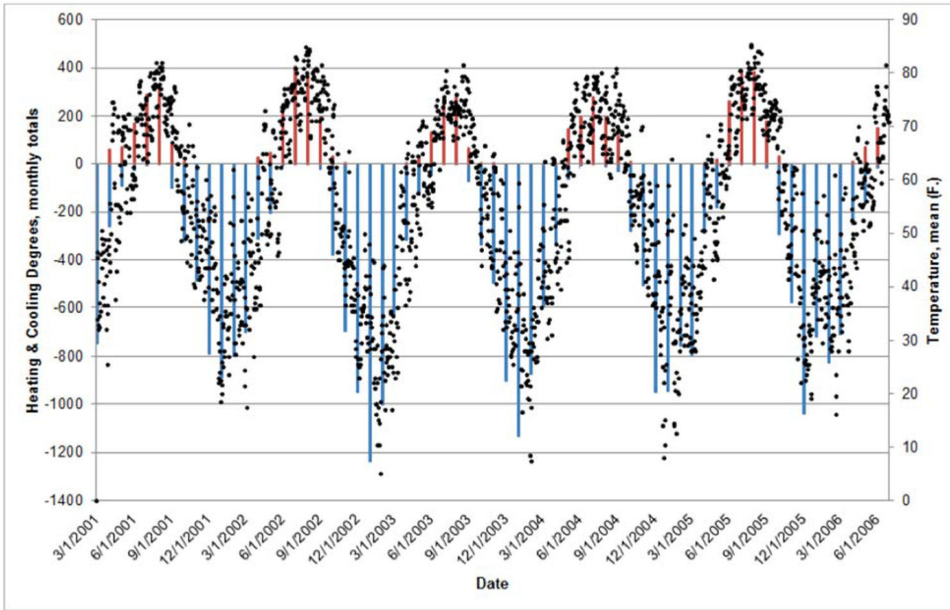

Figure 1.

Cincinnati area mean temperature and monthly degree days, 2001–2006. The solid dots represent the mean temperature for each day. The bars represent the cooling degrees (where mean temperature ≥ 65°F) and heating degrees (where mean temperature < 65°F) totaled by month. Weather conditions plotted are for all contiguous days with available data from study start to study end.

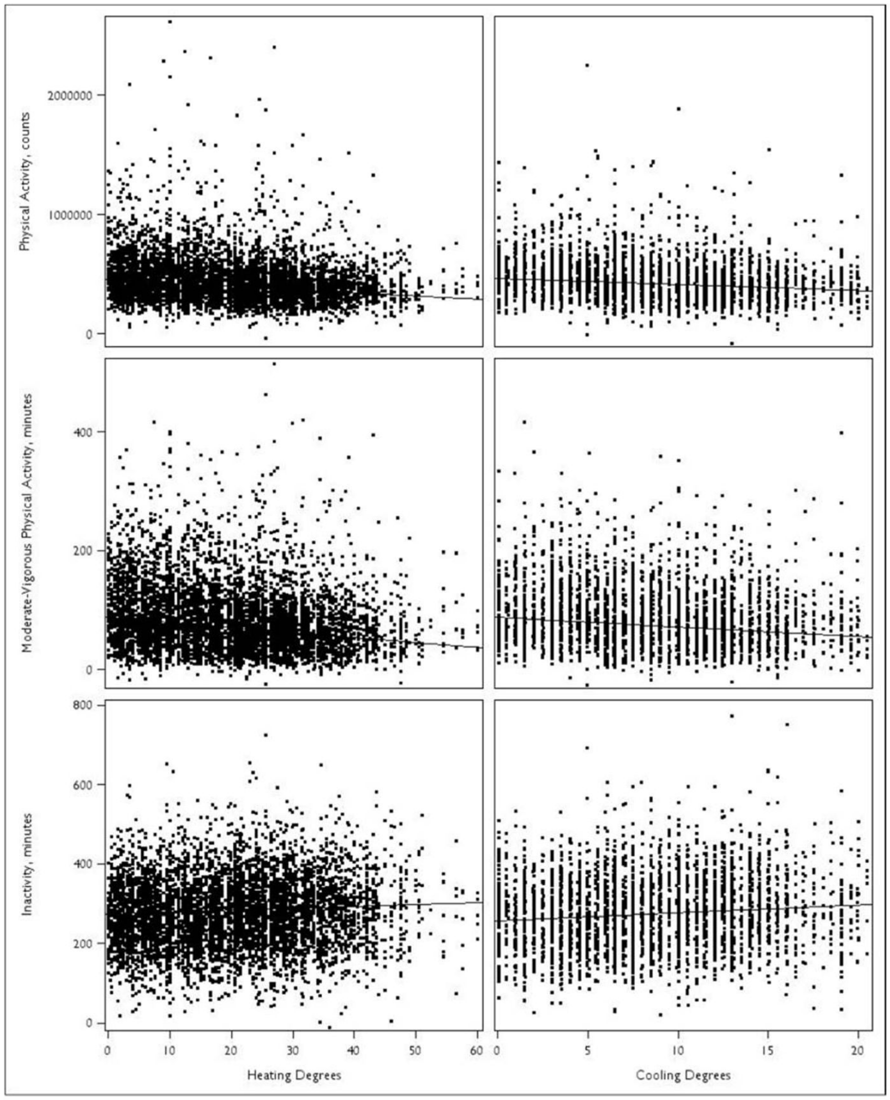

Figure 2.

Plots of heating and cooling degrees and physical activity. The line represents a regression based on mixed models of physical activity and heating or cooling degrees, adjusted for multiple measurements for each individual.

Table 1

Area Weather Conditions, March 2001 – June 2006

N = 1,948 days*	**Proportion of days (%)**	**Median (IQR)**	**Range**
Day length, hours		12.4 (10.5–14.1)	9.4–14.9
< 12 hours, %	45		
≥ 12 hours, %	55		
Temperature, maximum, °F		68 (51–81)	14–100
Temperature, mean daily, °F		57 (42–70)	5–86
Temperature, minimum, °F		45 (31–59)	−8–76
Heating degrees, °F	65	20 (9–29)	0–60
Cooling degrees, °F	35	8 (5–12)	0–21
Precipitation, inches		0 (0–0.08)	0–4
None, %	55		
0–0.5 inch, %	37		
0.5–1 inch, %	6		
> 1 inch, %	3		
Wind speed, mph		5 (3–8)	0–20
< 1 mph, %	2		
1–5 mph	46		
5–10 mph	39		
> 10 mph	14		

*Weather conditions reported for all contiguous days with available weather data from study start to study end.

Table 2

Physical Activity Measures*

N = 9,264 person-days	Median (IQR)
Wear time, hours	13 (11–14)
Total physical activity, counts per day	420,000 (330,000–530,000)
Moderate-vigorous physical activity (MVPA), minutes	76 (49–115)
Inactivity, minutes	276 (169–335)

*All variables except wear time were adjusted using the residual method.

Table 3

Association between individual weather conditions and physical activity measures, unadjusted models*

	Total Physical Activity†, counts			MVPA†, minutes			Inactivity†, minutes		
	Estimate	**SE**	***P***	**Estimate**	**SE**	***P***	**Estimate**	**SE**	***P***
Intercept	301,383	12,844	< 0.0001	37	3.7	< 0.0001	300	5.8	< 0.0001
Day length, hours	12,167	989	< 0.0001	4	0.28	< 0.0001	−1.5	0.44	0.0007
Intercept	504,936	6,129	< 0.0001	103	1.9	< 0.0001	270	2.9	< 0.0001
Heating Degrees, °F	−2,844	195	< 0.0001	−0.9	0.055	< 0.0001	0.5	0.083	< 0.0001
Intercept	499,231	7412	< 0.0001	103	2.2	< 0.0001	266	3.8	< 0.0001
Cooling Degrees, °F	−5,325	626	< 0.0001	−1.6	0.18	< 0.0001	1.9	0.31	< 0.0001
Intercept	455,277	4391	< 0.0001	89	1.4	< 0.0001	281	2.3	< 0.0001
Precipitation, inches	−44,807	5935	< 0.0001	−14	1.7	< 0.0001	6	2.6	0.02
Intercept	470,445	5441	< 0.0001	94	1.7	< 0.0001	278	2.7	< 0.0001
Wind, miles per hour	−3,496	562	< 0.0001	−1.1	0.16	< 0.0001	0.7	0.25	0.007

*Estimated using mixed effects regression models. Weather variables were modeled as fixed effects and subject and intercept were specified as random effects.

†Physical activity measures represent daily values, recorded while accelerometer was worn, on valid days, *i.e.*, days with ≥ 8 hours wear time.

Table 4

Mixed multivariate models of heating or cooling degrees and physical activity measures*

	Total Physical Activity†, counts			MVPA†, minutes			Inactivity†, minutes		
	Estimate	SE	*P*	Estimate	SE	*P*	Estimate	SE	*P*
Heating Degrees Model, N = 6,024 participant-days									
Intercept	203,384	28,792	< 0.0001	12	8.3	0.2	323	13	< 0.0001
Heating degrees, °F	−1,472	233	< 0.0001	−0.5	0.066	< 0.0001	0.3	0.10	0.011
Age, years	−3,999	2,026	0.048	−1	0.57	0.08	3	0.88	0.004
Sex‡	47,227	8,964	< 0.0001	19	2.8	< 0.0001	−11	4.8	0.019
Race§	49,867	11,634	< 0.0001	13	3.7	0.0004	−15	6.1	0.017
BMI z-score	10,961	4,057	0.007	3	1.2	0.009	−6	2.0	0.0014
Day length, hours	22,405	1,858	< 0.0001	7	0.52	< 0.0001	−4	0.81	< 0.0001
Wind, mph	−2,962	668	< 0.0001	−0.9	0.19	< 0.0001	0.7	0.29	0.016
Precipitation, inches	−76,252	8,390	< 0.0001	−24	2.4	< 0.0001	15	3.6	< 0.0001
Cooling Degrees Model, N = 3,230 participant-days									
Intercept	452,786	48,220	< 0.0001	70	14	< 0.0001	265	24	< 0.0001
Cooling degrees, °F	−5,276	648	< 0.0001	−1.7	0.19	< 0.0001	1.9	0.32	< 0.0001
Age, years	−3,723	2,301	0.1	−0.4	0.67	0.6	2	1.1	0.1
Sex‡	43,196	10,323	< 0.0001	18	3.1	< 0.0001	−10	5.5	0.1
Race§	33,821	13,265	0.01	9	4.0	0.03	−0.6	7.0	0.9
BMI z-score	5,857	4,748	0.2	2	1.4	0.2	−0.3	2.5	0.9
Day length, hours	751	3,433	0.8	1	1.0	0.2	−0.2	1.7	0.9
Wind, mph	1,365	1,116	0.2	0.5	0.32	0.1	−0.2	0.56	0.7
Precipitation, inches	−26,284	8,045	0.001	−9	2.3	0.0001	−4	4.0	0.4

[*] Estimated using mixed effects regression models. Weather variables were modeled as fixed effects and subject and intercept were specified as random effects.

[†] Physical activity measures represent daily values, recorded while accelerometer was worn, on valid days, *i.e.*, days with ≥ 8 hours wear time.

[‡] Sex was represented in the model as follows: Male = 1, Female = 2.

[§] Race was represented in the model as follows: White = 1, Black = 2.