Seasons, weather, and device-measured movement behaviors: a scoping review from 2006 to 2020

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Abstract

Background: This scoping review summarized research on (a) seasonal differences in physical activity and sedentary behavior, and (b) specific weather indices associated with those behaviors.

Methods: PubMed, CINAHL, and SPORTDiscus were searched to identify relevant studies. After identifying and screening 1459 articles, data were extracted from 110 articles with 118,189 participants from 30 countries (almost exclusively high-income countries) on five continents.

Results: Both physical activity volume and moderate-to-vigorous physical activity (MVPA) were greater in summer than winter. Sedentary behavior was greater in winter than either spring or summer, and insufficient evidence existed to draw conclusions about seasonal differences in light physical activity. Physical activity volume and MVPA duration were positively associated with both the photoperiod and temperature, and negatively associated with precipitation. Sedentary behavior was negatively associated with photoperiod and positively associated with precipitation. Insufficient evidence existed to draw conclusions about light physical activity and specific weather indices. Many weather indices have been neglected in this literature (e.g., air quality, barometric pressure, cloud coverage, humidity, snow, visibility, windchill).

Conclusions: The natural environment can influence health by facilitating or inhibiting physical activity. Behavioral interventions should be sensitive to potential weather impacts. Extreme weather conditions brought about by climate change may compromise health-enhancing physical activity in the short term and, over longer periods of time, stimulate human migration in search of more suitable environmental niches.

Keywords: Environment, Seasons, Meteorological concepts, Rain, Sunlight, Temperature, Wind, Exercise, Screen time

The global prevalence of insufficient physical activity is approximately 28% but exceeds 40% in some regions [1]. Physical activity promotion efforts have targeted determinants at multiple levels of the socio-ecological model, including the person (e.g., motivation), social environment (e.g., family, peers), and built environment (e.g., access to equipment, neighborhood walkability) [2–4]. The natural environment includes a number of factors that influence physical activity, including seasons and weather. Weather is often cited as a perceived barrier to participation in movement behaviors [5–9]. Although weather conditions are not acutely modifiable, they are important to understand because of their ability to alter opportunities for physical activity and moderate the effectiveness of interventions targeting determinants at other levels.

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Two seminal reviews of research on seasonality, weather, and physical activity across the lifespan were published over a decade ago [10, 11]. Physical activity was typically greatest during spring and summer and lowest during winter, but regions with more extreme weather conditions sometimes yielded different conclusions. For example, a study conducted in Galveston, Texas, where the average temperature during summer months is over 28°C (82 °F), revealed lower levels of physical activity in the summer than in winter [12]. However, the general pattern of seasonal trends demonstrated that people accumulated greater levels of physical activity in warmer and more arid conditions. Weather conditions were also found to have differing impacts on physical activity between sub-groups in the population [10, 13, 14]. For instance, physical activity was not associated with wind gusts for most individuals, but individuals with lower body mass were less active in the presence of stronger wind gusts than individuals with higher body mass [15].

The social context for research on weather and physical activity changed in three significant ways around the time of the seminal Tucker and Gilliland review [10]. First, public interest in weather and health increased following the 2007 Nobel Peace Prize that was awarded jointly to the Intergovernmental Panel on Climate Change and former US Vice President Al Gore [16]. As Earth’s surface temperature rises, extreme weather conditions will increase air pollution and ultraviolet radiation exposure, increasing risk for cardiovascular and lung diseases as well as cancer [17]. Second, the mobile and wearable technology industries experienced major disruptions in 2007 due to the launch of the Apple iPhone and the founding of Fitbit [18, 19]. The widespread adoption of mobile technologies such as smartphones and wearable activity monitors enabled researchers to monitor both physical activity and location-specific weather indices in real-time. Third, sedentary behavior – waking activity conducted in a seated or reclined posture involving low energy expenditure – has emerged as a distinct behavior that has important health consequences independent of physical activity levels [20, 21].

Despite summarizing over 60 studies with over 300,000 participants from approximately 18 countries, these seminal reviews possess several limitations. First, although they both examined seasonal differences in physical activity, most findings at the time focused on a relatively narrow range of specific weather indices with temperature and precipitation being most common. Understanding associations between additional weather indices and physical activity could both explain seasonal differences and facilitate the development of just-in-time interventions that leverage information from short-term weather forecasts. Second, weather and physical activity data were aggregated into person-level summary measures, yet both weather and physical activity are dynamic. Understanding the timing of and changes in weather conditions is essential because current weather conditions are likely to have a more immediate influence on physical activity than average weather conditions. Third, both reviews focused on a general physical activity outcome. Physical activity can be quantified as total volume (to represent energy expended) or the duration of activities completed at specific intensities (to represent time allocated to different effort levels). Sedentary behavior may also be impacted as weather conditions alter people’s activity choices. Additional reviews published since these seminal reviews have been limited by incomplete search strategies and a focus on narrow segments of the population [14, 22]. In light of these limitations and the broader context described earlier (increasing public interest in climate, advances in mobile technology, the emergence of sedentary behavior), an updated review of weather and movement behavior, including both physical activity and sedentary behavior, would be a valuable contribution.

A scoping review was conducted to examine associations between device-based measures of physical activity, sedentary behavior and a broad array of weather-related phenomena at different levels of specificity, ranging from seasons (e.g., spring, summer, fall, winter) to specific weather indices (e.g., humidity, precipitation, temperature). A scoping review was selected over a systematic review or meta-analysis based on the breadth of weather indices available and the need to both analyze the available evidence and identify existing knowledge gaps [23].

**Methods**

**Search strategy**

PubMed, the Cumulative Index of Nursing and Allied Health Literature (CINAHL), and SPORTDiscus electronic databases were searched from January 1, 2006 to October 31, 2020. This date range was chosen to capture all research since the end of the search period used by Tucker and Gilliland [10]. Three databases were selected based on their likelihood of including both environmental and health behavior data. Three main subject categories were included in our searches: movement-related behavior, movement-related behavior measurement (i.e., intensity, volume), and weather. Movement-related behavior search terms related to physical activity or sedentary behavior were combined with “or” statements. These terms mirrored
the search terms used to compile the literature for the 2018 Physical Activity Guidelines Advisory Committee [24]. Measurement search terms related to technologies commonly used to measure physical activity were combined with “or” statements (e.g., accelerometer or pedometer). Weather search terms related to seasonality or specific weather indices were combined with “or” statements (e.g., seasons or temperature or humidity or precipitation). The search strategies for each database used are available in Appendices 1, 2, and 3. The searches were restricted to articles that (a) were written in English, (b) examined human subjects only, and (c) included empirical studies only (i.e., no review papers). This search strategy was constructed in consultation with a trained reference librarian and search specialist at The Pennsylvania State University. The review protocol was not preregistered.

Selection process
Articles were included if (a) physical activity or sedentary behavior was an outcome variable of interest, (b) physical activity data were collected using device-based measurements (e.g., accelerometer, pedometer), and (c) results involved associations or differences between either movement-related behavior and either seasonality or weather indices. Articles were excluded if (a) studies were not published in English, (b) samples included non-human subjects, (c) results were limited to prevalence rates or other descriptive data, or (d) physical activity data were collected using self-report measures exclusively.

Titles and abstracts were independently reviewed in a blinded manner by coders trained by the first author using the eligibility criteria described above. The first author exported citations for each article found in the PubMed, CINAHL, and SPORTDiscus searches, and uploaded these citations into Rayyan. Rayyan is a web application that is used to facilitate collaborative screening of titles and abstracts for reviews [25, 26]. Each coder accessed their assigned articles via the Rayyan web interface, reviewed titles and abstracts, and recorded decisions to include or exclude each article. Figure 1 summarizes study selection [27].

Data extraction
Articles containing studies that met inclusion criteria during full-text review were advanced for data extraction. Prior to data extraction, the first author and four trained coders used a standardized coding guide to code three identical papers that were eligible for data extraction. The coding guide was developed to ensure that sufficient descriptive information was collected to properly characterize associations of interest. The coders then met to compare codes and discuss disagreements to promote consistency for final extraction. After this calibration exercise, each coder independently extracted data from the remaining articles using the standardized coding guide. Prior to analysis, the first author reviewed each article to ensure that the necessary data was extracted in a manner consistent with the coding guide.

A copy of the coding guide is available in supplementary online files. Extracted sample characteristics included age, sex, education, race, and the country where the data were collected. If countries included multiple diverse climate zones, the region of the country was also collected. Physical activity, sedentary behavior, weather indices (temperature, precipitation, wind speed, photo-period, snow, cloud coverage, humidity, visibility, barometric pressure, windchill, and air quality; see Appendix 4 for definitions), and seasonality were all characterized by assessment timeframe and method of measurement. Research designs were classified as cross-sectional or longitudinal. The following statistics were extracted when available: t-scores, F-scores, correlation coefficients, β coefficients, p-values, effect sizes, and odds ratios. Significance thresholds were kept consistent with the author’s prespecified level of significance, and all results were coded having a positive or negative association, or failing to reach significance.

Evidence grading
All of the available evidence from independent samples was observational so all studies were deemed to have a high risk of bias. Instead of rating study-level bias, evidence was graded based on the quantity and consistency of findings when five of more studies were available for a specific comparison or association. A “strong” grade was assigned when a conclusion was based on highly consistent findings related to the direction of a difference or association (or moderately consistent findings when a large number of studies was available). A “moderate” grade was assigned when a conclusion was based on mixed findings but the preponderance of evidence pointed to a consistent direction of a difference or association. A “limited” grade was assigned when a conclusion could not be drawn because of equivocal evidence related to the direction of the difference or association. When fewer than five studies were available, we noted that a grade was not assignable. This grading system was drawn from criteria used by the 2018 Physical Activity Guidelines Advisory Committee and adapted to match the state of this literature [24].

Results
A total of 1459 unique articles were identified during the initial search. Following title and abstract screening,
1208 articles were excluded. Full-text review of the remaining 251 articles led to an additional 141 exclusions. A total of 110 articles reporting 144 studies of independent samples were identified as eligible for inclusion in this review. Among those 110 articles, 26 reported two independent samples, one reported three independent samples, and two reported four independent samples to examine physical activity behaviors between sex, age group, or region, or examined both seasonality and weather [28–44].

Table 1 summarizes participant characteristics and study designs for all included articles. In total, articles included 118,189 participants (62.0% female participants, median $N = 272$, IQR = 85–722) from 30 unique countries on five continents. Figure 2 summarizes the sampling density across the globe. Most data represented western countries such as the United Kingdom, United States, Norway, Australia, Denmark, and Canada. Studies were primarily conducted in countries that the World Bank currently (July 2020) classifies as high income (27/30, 90.0%) and three were upper-middle income (3/30, 10.0%) [45]. None were from low- or middle-income countries.

Approximately equal numbers of studies examined weather (77/144, 53.5%) and seasonality (67/144, 46.5%). Studies sampled youth (persons under age 18; 73/144, 50.7%), adults (44/144, 30.6%), and older adults (typically defined as over age 65; 27/144, 18.8%). Study designs were longitudinal (97/144, 67.4%) and cross-sectional (47/144, 32.6%). The modal
| Reference | Country | N   | Female (%) | Age Group | Age (M ± SD [years]) | Race | Monitoring Period | Design | Environmental Measure |
|-----------|---------|-----|------------|-----------|----------------------|------|-------------------|--------|------------------------|
| Aadland et al. (2018) | Norway | 465 | 51.6 | Youth | 10.9 ± 0.3 | NA | 7 days | Longitudinal | Season |
| Aebi et al. (2020) | Switzerland | 1314 | 48.7 | Adults | 67.9 ± 7.9 | NA | 8 days | Cross-sectional | Season |
| Aibar Solana et al. (2015) | France, Spain | 646 | 58.8 | Youth | 14.3 ± 0.7 | NA | 7 days | Longitudinal | Weather |
| Akande et al. (2019) | Canada | 272 | 43.8 | Adults | 34.9 ± 12.6 | Inuit: 74.6%; Other: 25.4% | 7 days | Longitudinal |
| Albrecht et al. (2020) | Germany | 577 | 52.0 | Older adults | Range: 65–75 | NA | 7 days | Longitudinal |
| Al-Mohannadi et al. (2016) | Qatar | 2088 | 33.4 | Adults | 41.6 ± 10.7 | Eastern Mediterranean: 52.3%; South East Asian: 30.7%; Western Pacific: 8.0%; African: 3.4%; North/South American: 3.1%; European: 2.5% | 24 months | Longitudinal |
| Arnardottir et al. (2017) | Iceland | 138 | 60.1 | Older adults | 80.3 ± 4.9 | NA | 7 days | Cross-sectional | Season |
| Aspvik et al. (2018) | Norway | 1219 | 51.2 | Older adults | 72.4 ± 2.1 | NA | 7 days | Longitudinal | Weather |
| Atkin et al. (2016) | United Kingdom, Wales, Scotland, Northern Ireland | 704 | 52.6 | Youth | 7.6 ± 0.3 | Caucasian: 92.9%; Other: 7.1% | 7 days | Longitudinal | Weather |
| Badland et al. (2011) | Australia | 1754 | 59.3 | Adults | 39.9 ± 11.8 | NA | 7 days | Longitudinal | Season, Weather |
| Balish et al. (2017) | Canada | 190 | 45.3 | Adults | NA | NA | 7 days | Longitudinal | Season, Weather |
| Barkley and Herrmann (2017) | United States | 16 | NA | Older adults | NA | NA | 7 days | Longitudinal | Season |
| Beighle et al. (2013) | United States | 321 | 52.0 | Youth | 9.1 ± 1.5 | NA | 7 days | Longitudinal | Season |
| Bejarano et al. (2019) | United States | 26 | 42.3 | Youth | 16 ± 1.6 | Caucasian: 69.2%; Native American: 15.4%; Hispanic: 11.5%; Asian: 3.8% | 20 days | Longitudinal | Weather |
| Boutou et al. (2019) | United Kingdom, Belgium, Greece, Netherlands | 157 | 75.8 | Adults | 67.2 ± 7.8 | NA | 7 days | Longitudinal | Weather |
| Brandon et al. (2009) | Canada | 48 | 75.0 | Older adults | 77.4 ± 4.7 | NA | 7 days | Longitudinal | Weather |
| Bremer et al. (2019) | Canada | 110 | 51.8 | Youth | 10.2 ± 1.7 | NA | 7 days | Longitudinal | Weather |
| Bringolf-Isler et al. (2009) | Switzerland | 164 | 52.0 | Youth | Range: 6–14 | NA | 7 days | Longitudinal | Season |
| Brychta et al. (2016) | Iceland | 70 | 64.3 | Older adults | 79.5 ± 4.8 | NA | 7 days | Cross-sectional | Weather |
| Buchowski et al. (2009) | United States | 57 | 100 | Adults | 36.5 ± 9.2 | NA | 7 days | Longitudinal | Season |
| Button et al. (2020) | Canada | 90 | 61.1 | Youth | 10.6 ± 1.4 | White: 56.7%; Indigienous & Visible Minority: 43.3% | 8 days | Longitudinal | Weather |
| Carr et al. (2016) | United States | 132 | 100 | Adults | 41.6 ± 10.1 | Hispanic/Latino: 100% | 12 months | Longitudinal | Season |
Table 1 Sample and design characteristics of eligible articles (Continued)

| Reference | Country                      | N    | Female (%) | Age Group                          | Race                                      | Monitoring Period | Design             | Environmental Measure |
|-----------|-------------------------------|------|------------|------------------------------------|------------------------------------------|-------------------|--------------------|-----------------------|
| Cepeda et al. (2018) | Netherlands  | 1166 | 44.4       | Adults & older adults               | NA                                       | 7 days            | Cross-sectional    | Season                |
| Chang et al. (2020) | China            | 53   | 49.1       | Youth                              | NA                                       | 7 days            | Longitudinal       | Season                |
| Clemes et al. (2011) | United Kingdom | 96   | 53.2       | Adults                             | NA                                       | 4 weeks           | Longitudinal       | Season                |
| Collings et al. (2020) | United Kingdom | 342  | 48.8       | Youth                              | White: 40.9%; South Asian: 59.1%         | 6 days            | Longitudinal       | Season                |
| Colom et al. (2019) | Spain            | 218  | 51.0       | Adults                             | Range: 55–75                            | 9 days            | Cross-sectional    | Weather               |
| Cooper et al. (2010) | United Kingdom | 1010 | 53.3       | Youth                              | NA                                       | 4 days            | Cross-sectional    | Season                |
| Craddock et al. (2009) | United States | 152  | 41.0       | Youth                              | White: 57.0%; Black/African-American: 10.0%; Hispanic: 13.0%; Asian: 12.0%; Other Race/Ethnicity: 9.0% | 4 days            | Cross-sectional    | Weather               |
| Crowley et al. (2016) | United States | 510  | 55.0       | Adults                             | NA                                       | 12 months         | Longitudinal       | Season                |
| Cullen et al. (2017) | United States | 342  | 100        | Youth                              | Range: 8–10                              | 7 days            | Cross-sectional    | Weather               |
| Davis et al. (2011) | United Kingdom | 230  | 49.1       | Older adults                       | African-American: 100%                   | 7 days            | Longitudinal       | Season, Weather       |
| de Vries et al. (2019) | Netherlands | 10   | 50.0       | Youth                              | 12.5                                    | 14 days           | Longitudinal       | Season, Weather       |
| Declós-Álió et al. (2019) | Spain       | 227  | 56.0       | Older adults                       | NA                                       | 7 days            | Longitudinal       | Season                |
| Deng and Fredriksen (2018) | Norway     | 2123 | 49.6       | Youth                              | 9 ± 1.5                                  | 7 days            | Cross-sectional    | Season                |
| Dias et al. (2019) | Switzerland, Belgium, United Kingdom, United States | 1052 | 49.8       | Youth                              | 3.7 ± 0.4                                | 3 days            | Longitudinal       | Season, Weather       |
| Diaz et al. (2016) | United States | 2096 | 54.2       | Adults                             | Range: 45–75                             | 7 days            | Cross-sectional    | Season                |
| Dill et al. (2014) | United States | 353  | NA         | Adults                             | NA                                       | 3 days            | Longitudinal       | Weather               |
| Duncan et al. (2008) | New Zealand   | 1115 | 51.9       | Youth                              | Range: 5–16                              | 5 days            | Cross-sectional    | Season                |
| Edwards et al. (2015) | United States | 372  | 48.0       | Youth                              | 3.4 ± 0.3                                | 3 days            | Longitudinal       | Season                |
| Feinglass et al. (2011) | United States | 241  | 74.7       | Adults                             | < 50 years: (26.1%); 50–65 years: (39.3%); 66–75 years: (22.2%); > 75 years: (12.2%) | 7 days            | Longitudinal       | Weather               |
| Goodman et al. (2012) | United Kingdom | 325  | 52.3       | Youth                              | Range: 8–11                              | 4 days            | Longitudinal       | Weather               |
| Reference                  | Country                                                                 | N     | Female (%) | Age Group | Age (M ± SD [years]) | Race | Monitoring Period | Design | Environmental Measure |
|----------------------------|-------------------------------------------------------------------------|-------|------------|-----------|----------------------|------|-------------------|--------|-----------------------|
| Goodman et al. (2014)      | Australia, Brazil, Denmark, England, Estonia, Spain, Norway, Switzerland, United States | 23188 | 62.0       | Youth     | Range: 5–16          | NA   | 7 days            | Longitudinal | Weather               |
| Gracia-Marco et al. (2013)  | Sweden, Greece, Italy, Spain, Hungary, Belgium, France, Germany, Austria | 2173  | 54.0       | Youth     | 15 ± 1.2            | NA   | 7 days            | Longitudinal | Season                |
| Griew et al. (2010)        | United Kingdom                                                          | 1307  | 51.8       | Youth     | Range: 10–11         | NA   | 5 days            | Longitudinal | Weather               |
| Hagströmer et al. (2014)   | Sweden                                                                  | 1172  | 54.0       | Adults    | 45 ± 15             | NA   | 7 days            | Longitudinal | Season                |
| Hamilton et al. (2009)     | United Kingdom                                                           | 96    | 51.1       | Adults    | 41.0 ± 12.3         | NA   | 4 weeks           | Longitudinal | Weather               |
| Harrison et al. (2011)     | United Kingdom                                                           | 1794  | 55.0       | Youth     | Range: 9–10          | NA   | 7 days            | Longitudinal | Weather               |
| Harrison et al. (2015)     | United Kingdom                                                           | 283   | 55.1       | Youth     | Range: 9–14          | NA   | 7 days            | Longitudinal | Weather               |
| Harrison et al. (2017)     | United Kingdom, Switzerland, Belgium, Australia, Denmark, Estonia, Norway, Madeira, United States | 23451 | 62.0       | Youth     | Range: 3–18          | NA   | 7 days            | Longitudinal | Weather               |
| Hjorth et al. (2013)       | Denmark                                                                  | 730   | 48.5       | Youth     | 10.0 ± 0.6           | NA   | 7 days            | Longitudinal | Weather               |
| Hoaas et al. (2019)        | Norway, Denmark                                                          | 168   | 42.9       | Adults    | Range: 60–73         | NA   | 7 days            | Longitudinal | Season                |
| Hopkins et al. (2011)      | United States                                                            | 145   | 59.3       | Youth     | 10.7 ± 0.3           | NA   | 7 days            | Longitudinal | Season                |
| Hoppmann et al. (2017)     | Canada                                                                   | 126   | 64.0       | Older adults | 71.9 ± 5          | European: 62.0%; Asian: 36.0%; Other: 1.0%; Missing: 1.0% | 10 days | Longitudinal | Weather |
| Hunter et al. (2019)       | Canada                                                                   | 149   | 47.0       | Adults    | 19 ± 1.9            | White: 59.7%; Other: 40.3% | 7 days | Longitudinal | Weather |
| Jehn et al. (2014)         | Germany                                                                  | 15    | 40.0       | Adults    | 66.7 ± 5.2          | NA   | 6 months          | Longitudinal | Season                |
| Jones et al. (2017)        | Canada                                                                   | 42    | 24.0       | Older adults | 77.4 ± 4.7         | NA   | 7 days            | Cross-sectional | Weather |
| Jones et al. (2017)        | Canada                                                                   | 42    | NA         | Older adults | 77.4 ± 4.7         | NA   | 7 days            | Longitudinal | Season, Weather       |
| Katapally et al. (2016)    | Canada                                                                   | 331   | 49.8       | Youth     | 11.6 ± 1.1          | NA   | 7 days            | Longitudinal | Weather               |
| Kharlova et al. (2020)     | Norway                                                                   | 2015  | 50.6       | Youth     | 9.5 ± 1.8           | NA   | 6 days            | Longitudinal | Season                |
| Kimura et al. (2015)       | Japan                                                                    | 39    | 56.0       | Older adults | 70.7 ± 3.2         | NA   | 2 weeks           | Longitudinal | Weather               |
| King et al. (2011)         | United Kingdom                                                           | 480   | 49.1       | Youth     | NA                  | NA   | 7 days            | Longitudinal | Season                |
| Kolle et al. (2021)        | Norway                                                                   | 1824  | 48.5       | Youth     | Range: 9–15         | NA   | 4 days            | Cross-sectional | Weather |

**Table 1** Sample and design characteristics of eligible articles (Continued)
Table 1 Sample and design characteristics of eligible articles (Continued)

| Reference                     | Country                        | N     | Female (%) | Age Group | Age (M ± SD [years]) | Race                  | Monitoring Period | Design          | Environmental Measure |
|-------------------------------|--------------------------------|-------|------------|-----------|----------------------|-----------------------|-------------------|-------------------|----------------------|
| (2009)                        | South Korea                    | 555   | 43.8       | Adults    | 61.1 ± 8.9           | NA                    | 7 days            | Cross-sectional   | Weather              |
| Kong et al. (2020)            | Netherlands                    | 1200  | 52.3       | Older adults | 77.5 ± 5.0         | NA                    | 7 days            | Cross-sectional   | Season               |
| Koolhaas et al. (2017)        | Canada                         | 1699  | 55.0       | Youth     | 10.2 ± 1.0           | NA                    | 8 days            | Cross-sectional   | Season               |
| Larouche et al. (2019)        | Australia and Canada           | 953   | 57.0       | Youth     | 10.6 ± 0.4           | NA                    | 7 days            | Cross-sectional   | Season               |
| Lewis et al. (2016)           | Hong Kong                      | 210   | 33.8       | Adults    | 26.1 ± 8.7           | NA                    | 35 days           | Longitudinal      | Season               |
| Ma et al. (2018)              | Brazil                         | 16    | 50.0       | Adults    | Range: 18–35         | NA                    | 6 days            | Longitudinal      | Weather              |
| Martins et al. (2015)         | Scotland                       | 33    | 54.5       | Youth     | 12.2 ± 0.3           | NA                    | 8 days            | Cross-sectional   | Weather              |
| McCrorie et al. (2015)        | Northern Ireland               | 85    | 38.8       | Youth     | Range: 4–5           | NA                    | 6 days            | Longitudinal      | Weather              |
| McMurdie et al. (2012)        | United Kingdom                 | 547   | 54.0       | Older adults | 79 ± 8               | NA                    | 7 days            | Cross-sectional   | Weather              |
| Mitchell et al. (2018)        | United States                  | 575   | 34.3       | Adults    | 38.6 ± 0.1           | Hispanic: 100.0%      | 1 day             | Cross-sectional   | Weather              |
| Mitsui et al. (2010)          | Japan                          | 50    | 0.0        | Adults    | 43.6 ± 10.8          | NA                    | 7 days            | Longitudinal      | Weather              |
| Nagy et al. (2019)            | United Kingdom                 | 108   | 51.0       | Youth     | 7.5 ± 0.5            | Caucasian: 59.0%; South Asian: 41.0% | 7 days           | Cross-sectional   | Season               |
| Nakashima et al. (2019)       | Japan                          | 22    | 86.4       | Older adults | 75.1 ± 7.3          | NA                    | 7 days            | Longitudinal      | Season               |
| Newman et al. (2009)          | United States                  | 500   | 100.0      | Adults    | 57 ± 2.9             | African-American: 13.2% | 7 days           | Cross-sectional   | Season               |
| Nilisen et al. (2019)         | Norway                         | 1154  | 49.0       | Youth     | 4.7 ± 0.9            | NA                    | 14 days           | Longitudinal      | Season               |
| O’Connell et al. (2013)       | United Kingdom                 | 46    | 72.0       | Adults    | 41.7 ± 14.4          | NA                    | 7 days            | Longitudinal      | Season               |
| Ogawa et al. (2018)           | Japan                          | 35    | 65.7       | Adults    | 69.3 ± 5.3           | NA                    | 1 month           | Longitudinal      | Season               |
| Oliver et al. (2011)          | New Zealand                    | 135   | 60.0       | Youth     | Range: 5–6           | NA                    | 8 days            | Cross-sectional   | Season               |
| Pagels et al. (2016)          | Sweden                         | 179   | 48.6       | Youth     | 11.1 ± 2.1           | NA                    | 5 days            | Longitudinal      | Season               |
| Patnode et al. (2010)         | United States                  | 294   | 49.3       | Youth     | 15.4 ± 1.7           | Caucasian: 93.5%; Other: 6.5% | 7 days           | Cross-sectional   | Season, weather     |
| Pearce et al. (2012)          | United Kingdom                 | 482   | 52.0       | Youth     | Range: 8–10          | NA                    | 7 days            | Longitudinal      | Season               |
| Pechova et al. (2019)         | Czech Republic, Slovakia & Poland | 83   | 89.7       | Adults    | 65 ± 6              | NA                    | 8 days            | Longitudinal      | Season, Weather      |
| Pelclova et al. (2010)        | Czech Republic                 | 13    | 84.6       | Youth     | 15.6 ± 0.5           | NA                    | 10 months         | Longitudinal      | Weather              |
| Prins and van Lenthe (2015)   | Netherlands                    | 43    | 52.5       | Adults    | NA                  | NA                    | 7 days            | Longitudinal      | Weather              |
| Rahman et al. (2019)          | Canada                         | 972   | 58.0       | Youth     | 10.9 ± 0.4           | NA                    | 7 days            | Cross-sectional   | Season, weather     |
Table 1 Sample and design characteristics of eligible articles (Continued)

| Reference       | Country                      | N   | Female (%) | Age Group | Age (M ± SD [years]) | Race | Monitoring Period | Design               | Environmental Measure     |
|------------------|------------------------------|-----|------------|-----------|----------------------|------|-------------------|------------------------|---------------------------|
| Remmers et al. (2017) | Australia                  | 307 | 52.0       | Youth     | 11.1 ± 0.7           | NA   | 7 days            | Longitudinal          | Season, Weather           |
| Ridgers et al. (2015)  | Australia                  | 326 | 50.3       | Youth     | 10 ± 0.7             | NA   | 7 days            | Cross-sectional        | Season                   |
| Ridgers et al. (2018)  | Australia                  | 326 | 50.3       | Youth     | Range: 8–11          | NA   | 7 days            | Longitudinal          | Season                   |
| Robbins et al. (2013)   | Canada                     | 38  | 26.3       | Adults    | 54 ± 7.0             | NA   | 7 days            | Cross-sectional        | Weather                  |
| Rosenthal et al. (2020) | United States             | 266 | 58.4       | Adults    | 52.1 ± 14            | NA   | NA                | Cross-sectional      | Weather                  |
| Rowlands et al. (2009)   | United Kingdom            | 64  | 50.0       | Youth     | 9.9 ± 0.3            | NA   | 6 days            | Longitudinal          | Season                   |
| Sartini et al. (2017)   | United Kingdom            | 1361| 0.0        | Older adults | 78.5 ± 4.6        | NA   | 7 days            | Longitudinal          | Weather                  |
| Schepps et al. (2018)   | United States             | 16,741| 100.0 | Older adults | 72.0 ± 5.7         | NA   | 7 days            | Cross-sectional        | Weather                  |
| Sewell et al. (2010)    | United Kingdom            | 95  | 41.0       | Adults    | 65.5 ± 8.5           | NA   | 2 days            | Cross-sectional        | Season                   |
| Shen et al. (2013)      | United States             | 46  | 56.5       | Youth     | 4.2 ± 0.2            | Caucasian: 68.0%; Other: 32.0% | 5 days | Cross-sectional | Weather                  |
| Silva et al. (2011)     | Portugal                   | 24  | 50.0       | Youth     | 11.0 ± 1.5           | NA   | 7 days            | Longitudinal          | Season                   |
| Sit et al. (2019)       | Hong Kong                  | 270 | 40.0       | Youth     | NA                   | NA   | 3 days            | Longitudinal          | Season                   |
| Stabell et al. (2020)   | United States             | 38  | 10.5       | Adults    | Range: 50–75         | Caucasian: 81.6%; Other: 18.4% | 24 weeks | Longitudinal | Weather                  |
| Sugino et al. (2012)    | Japan                      | 9   | 0.0        | Adults    | 71.7 ± 8.3           | NA   | 2 weeks           | Cross-sectional        | Season                   |
| Sumukadas et al. (2008) | Scotland                   | 127 | 71.0       | Older adults | 78.6 ± 6.5        | NA   | 7 days            | Longitudinal          | Season                   |
| Van Kann et al. (2016)  | Netherlands                | 520 | 55.6       | Youth     | 10.1 ± 0.7           | NA   | 7 days            | Longitudinal          | Weather                  |
| Wang et al. (2017)      | China                      | 34  | 38.2       | Adults    | 31 ± 10              | NA   | 7 days            | Longitudinal          | Weather                  |
| Witham et al. (2014)    | United Kingdom            | 547 | 54.3       | Older adults | 78.5 ± 7.7        | NA   | 7 days            | Longitudinal          | Weather                  |
| Wong et al. (2020)      | Mexico                     | 559 | 49.0       | Youth     | 4.8 ± 0.5            | NA   | 7 days            | Longitudinal          | Weather                  |
| Wu et al. (2017)        | United Kingdom            | 4051| 55.7       | Adults    | 67.4 ± 9.5           | NA   | 7 days            | Cross-sectional        | Weather                  |
| Yildirim et al. (2012)  | Belgium, Greece, Hungary, Netherlands, Switzerland | 722 | 53.0       | Youth     | 11.6 ± 0.9           | NA   | 6 days            | Cross-sectional        | Weather                  |
| Zheng et al. (2019)     | Hong Kong                  | 740 | 40.9       | Youth     | 14.7 ± 1.6           | Chinese: 100.0% | 7 days | Longitudinal     | Weather                  |
duration of activity monitoring for movement behavior was 7 days (82/144, 56.9%) but ranged from 1 day to 2 years.

**Activity monitoring methods**

Almost all studies measured physical activity (138/144, 95.2%) and fewer measured sedentary behavior (50/144, 34.7%). Table 2 summarizes characteristics of the devices used to measure physical activity and sedentary behavior. Physical activity was measured with research-grade accelerometers (121/144, 84.0%), pedometers (22/144, 15.3%), or global positioning system logger (1/144, 0.7%). Although most studies with accelerometer-based measurements used wearable devices, one study measured physical activity using the accelerometer contained within a smartphone [46].

Physical activity measures included volume (i.e., step counts, total accelerometer counts) and intensity-specific durations. Volume measures represent the total amount of energy expended in physical activity whereas intensity-specific durations represent how individuals allocate their time to more and less effortful forms of physical activity. Figure 3 summarizes the frequency of studies using volume and intensity-specific duration measures in samples of youth, adults, and older adults. Seasonal differences in physical activity were more frequently estimated in youth than adults or older adults. Weather indices associated with physical activity were studied most frequently in youth, and approximately equally in adults and older adults.

Sedentary behavior was typically classified using accelerometer cut-points that included < 50, < 100, ≤ 100, < 150, < 175, and < 200 counts per minute [33, 38, 39, 47–70]. Other sedentary behavior classifications were based on accumulating less than 122 counts per minute, less than or equal to 328 counts per minute [71], less than 800 vector magnitude counts per minute [72], less than 820 vector magnitude counts per minute [73, 74], less than 1110 vector magnitude counts per minute [75, 76], falling below activity registering at 1.0 [77] or 1.5 [78–80] metabolic equivalents to task (METs). Four studies in three papers did not report how sedentary behavior was defined [30, 34, 81].

**Seasonal differences in physical activity and movement-related behaviors**

Table 3 summarizes seasonal differences in a variety of movement-related behaviors. Studies either compared two seasons (29/67, 43.3%), three seasons (9/67, 13.4%), or four seasons (25/67, 37.3%). Four studies did not report their definition of season (4/67, 6.0%) [86, 87, 103]. Winter (64/67, 95.5%) and summer (51/67, 76.1%) were studied most frequently, with spring (40/67, 59.7%) and autumn (36/67, 53.7%) receiving less attention. Studies comparing physical activity and sedentary behavior between seasons sampled youth (40/67, 59.7%), adults (17/67, 25.4%) and older adults (10/67, 14.9%). Studies of seasonal differences measured volume (47/67, 70.1%), moderate-to-vigorous intensity physical activity (MVPA) duration (37/67, 55.2%), light-intensity physical activity (LPA) duration (19/67, 28.4%), and sedentary behavior (25/67, 37.3%).

**Physical activity volume**

Studies comparing volume between seasons sampled youth (29/47, 61.7%), adults (13/47, 27.7%) and older adults (5/47, 10.6%). The most common seasonal comparisons of volume involved winter vs. summer (30/47, 63.8%), winter vs. spring (22/47, 46.8%), spring vs. autumn (12/47, 25.5%), and winter vs. autumn (12/47, 25.5%).
| Reference                                      | Type of Device | Specific Device                  | Wear Location | Measure(s) of Activity |
|------------------------------------------------|----------------|---------------------------------|---------------|------------------------|
| Aadland et al. (2018)                          | Accelerometer  | ActiGraph GT3X+                 | NA            | SB, LPA, MVPA, V       |
| Aebi et al. (2020)                             | Accelerometer  | ActiGraph wGT3X-BT              | Hip           | SB, LPA, MVPA          |
| Albar Solana et al. (2015)                      | Accelerometer  | ActiGraph GT3X                  | NA            | SB                     |
| Alande et al. (2019)                            | Pedometer      | Kaden G-Sport Pocket Pedometer 793 | Waist        | V                      |
| Albrecht et al. (2020)                          | Accelerometer  | ActiGraph wGT3X-BT              | Wrist         | V                      |
| Al-Mohannadi et al. (2016)                      | Pedometer      | Omron HJ-720 ITC                | NA            | V                      |
| Arnardottir et al. (2017)                       | Accelerometer  | ActiGraph GT3X+                 | Hip           | SB, LPA, MVPA, V       |
| Aspvik et al. (2018)                            | Accelerometer  | ActiGraph GT3X+                 | Waist         | V                      |
| Atkin et al. (2016)                             | Accelerometer  | ActiGraph GT1M                  | Waist         | SB, MVPA               |
| Badland et al. (2011)                           | Pedometer      | Yamax Digiwalker SW-200         | Hip           | V                      |
| Badlish et al. (2017)                           | Pedometer      | Yamax Digiwalker SW-200         | Hip           | V                      |
| Barkley and Herrmann (2017)                     | Accelerometer  | ActiGraph GT3X                  | Waist         | LPA, MVPA              |
| Beighle et al. (2013)                           | Pedometer      | MLS 205                         | Waist         | V                      |
| Bejarano et al. (2019)                          | Accelerometer  | ActiGraph wActi Sleep-BT        | Wrist         | SB, MVPA               |
| Boutou et al. (2019)                            | Accelerometer  | ActiGraph GT3X                  | Hip           | MVPA, V                |
| Brandon et al. (2009)                           | Accelerometer  | ActiGraph GT1M                  | Torso         | V                      |
| Bremer et al. (2019)                            | Pedometer      | PiezoRX                         | Hip           | V                      |
| Bringolf-Isler et al. (2009)                    | Accelerometer  | ActiGraph AM7164                | Waist         | V                      |
| Brychta et al. (2016)                           | Accelerometer  | ActiGraph GT3X                  | Hip           | V                      |
| Buchowski et al. (2009)                         | Accelerometer  | Tritrac-R3D                     | NA            | SB, V                  |
| Button et al. (2020)                            | Accelerometer  | Actical Z                       | Hip           | LPA, MVPA              |
| Carr et al. (2016)                              | Pedometer      | Omron HJ-720 ITC                | NA            | V                      |
| Cepeda et al. (2018)                            | Accelerometer  | GENActiv                       | Wrist         | SB, LPA, MVPA          |
| Chang et al. (2020)                             | Accelerometer  | ActiGraph GT3X                  | Hip           | SB, LPA, MVPA, V       |
| Clemes et al. (2011)                            | Pedometer      | Yamax Digiwalker SW-200         | Waist         | V                      |
| Collings et al. (2020)                          | Accelerometer  | ActiGraph GT3X+                 | Hip           | SB, LPA, MVPA, V       |
| Colom et al. (2019)                             | Accelerometer  | GENActiv                       | Wrist         | MVPA                   |
| Cooper et al. (2010)                            | Accelerometer  | ActiGraph GT1M                  | Wrist         | V                      |
| Craddock et al. (2009)                          | Accelerometer  | TriTac-R3D                      | Hip           | MVPA                   |
| Crowley et al. (2016)                           | Pedometer      | Jawbone UP                      | Wrist         | V                      |
| Cullen et al. (2017)                            | Accelerometer  | ActiGraph GT3X+                 | NA            | V                      |
| Davis et al. (2011)                             | Accelerometer  | ActiGraph GT1M                  | Waist         | LPA                    |
| de Vries et al. (2019)                          | Accelerometer  | 1. ActiWatch 2; 2. GENActiv Original; 3. Sensewear Mini | 1. Wrist; 2. Wrist; 3. Arm | SB, LPA, MVPA, V       |
| Declos-Alò et al. (2019)                        | Accelerometer  | ActiGraph GT3X                  | NA            | V                      |
| Deng and Fredriksen (2018)                      | Accelerometer  | ActiGraph wGT3X-BT              | Hip           | MVPA                   |
| Dias et al. (2019)                              | Accelerometer  | 1. ActiGraph 7164; 2. ActiGraph GT1M; 3. ActiGraph 71256 | Waist         | SB, V, MVPA             |
| Diaz et al. (2016)                              | Accelerometer  | Actical                         | Waist         | SB                     |
| Dill et al. (2014)                              | Accelerometer  | ActiGraph GT3X                  | Hip           | V, MVPA                |
| Duncan et al. (2008)                            | Pedometer      | New Lifestyles 2000             | Waist         | V                      |
| Edwards et al. (2015)                           | Accelerometer  | RT3                             | Hip           | SB, MVPA, V             |
| Feinglass et al. (2011)                         | Accelerometer  | ActiGraph GT1M                  | Hip           | V                      |
| Goodman et al. (2012)                           | Accelerometer  | RT3                             | Waist         | MVPA                   |
Table 2 Characteristics of devices used to measure physical activity and sedentary behavior (Continued)

| Reference          | Type of Device | Specific Device | Wear Location | Measure(s) of Activity |
|--------------------|----------------|-----------------|---------------|------------------------|
| Goodman et al. (2014) | Accelerometer | 1. ActiGraph 7164; 2. ActiGraph GT1M; 3. ActiGraph 71256 | Waist | V |
| Gracia-Marco et al. (2013) | Accelerometer | ActiGraph GT1M | Back | SB, MVPA, V |
| Griew et al. (2010) | Accelerometer | ActiGraph GT1M | Hip | V |
| Hagströmer et al. (2014) | Accelerometer | ActiGraph 7164 | Hip | SB, MVPA, V |
| Hamilton et al. (2009) | Pedometer | New Lifestyles Digi-Walker SW-200 | NA | V |
| Harrison et al. (2011) | Accelerometer | ActiGraph GT1M | Hip | SB, V, MVPA |
| Harrison et al. (2015) | Accelerometer | ActiGraph GT1M | Hip | SB, MVPA, V |
| Harrison et al. (2017) | Accelerometer | 1. ActiGraph 7164; 2. ActiGraph GT1M | NA | V |
| Hjorth et al. (2013) | Accelerometer | ActiGraph GT3X+ | Hip | SB, MVPA, V |
| HoaaS et al. (2019) | Accelerometer | SenseWear Pro | Arm | SB, LPA, MVPA, V |
| Hopkins et al. (2011) | Accelerometer | ActiGraph GT1M | Hip | V |
| Hoppmann et al. (2017) | Accelerometer | ActiGraph GT3X | Hip | MVPA, V |
| Hunter et al. (2019) | Accelerometer | ActiGraph wGT3X-BT | Waist | SB, LPA, MVPA, V |
| Jehn et al. (2014) | Accelerometer | AiperMotion | Hip | V |
| Jones et al. (2017) | Accelerometer | ActiGraph GT1M | Waist | V |
| Jones et al. (2017) | Accelerometer | ActiGraph GT1M | Waist | V |
| Katapally et al. (2016) | Accelerometer | Actical | Waist | SB |
| Kharlova et al. (2020) | Accelerometer | ActiGraph wGT3X-BT | Hip | SB, MVPA |
| Kimura et al. (2015) | Pedometer | Kenz Lifecorder EX | Waist | V |
| King et al. (2011) | Accelerometer | 1. ActiGraph 7164; 2. ActiGraph GT1M | Hip | SB, V |
| Kolle et al. (2009) | Accelerometer | ActiGraph MTI 7164 | Waist | V |
| Kong et al. (2020) | Accelerometer | Fitbit Flex | Wrist | MVPA, V |
| Koolhaas et al. (2017) | Accelerometer | GENEActiv | Wrist | SB, LPA, MVPA |
| Larouche et al. (2019) | Pedometer | SC-Step Rx | NA | MVPA, V |
| Lewis et al. (2016) | Accelerometer | ActiGraph GT3X+ | Hip | SB, MVPA |
| Ma et al. (2018) | Accelerometer | 1. iPhones 5S; 2. iPhone 6 | NA | V |
| Martins et al. (2015) | Accelerometer | ActiGraph GT3X+ | Hip | MVPA |
| McCrorie et al. (2015) | Accelerometer | activPAL | Thigh | V |
| McKee et al. (2012) | Pedometer | DigiWalker DW-2000 | NA | V |
| McMurdo et al. (2012) | Accelerometer | RT3 | Hip | V |
| Mitchell et al. (2018) | Accelerometer | Actical | NA | V |
| Mitsui et al. (2010) | Pedometer | Yama EM-180 | NA | V |
| Nagy et al. (2019) | Accelerometer | ActiGraph GT3X+ | Hip | SB, MVPA, V |
| Nakashima et al. (2019) | Accelerometer | LifeLyzer05 Coach | Back | LPA, MVPA, V |
| Newman et al. (2009) | Pedometer | Accusplit AE120 | Hip | V |
| Nilsen et al. (2019) | Accelerometer | ActiGraph GT1M | Hip | SB, LPA, MVPA, V |
| O’Connell et al. (2013) | Accelerometer | ActiGraph GT1M | Hip | SB, LPA, MVPA |
| Ogawa et al. (2018) | Accelerometer | Kenz Lifecorder GS | Waist | MVPA, V |
| Oliver et al. (2011) | Accelerometer | Mini-mitter | NA | MVPA |
| Pagels et al. (2016) | Accelerometer | ActiGraph GT3X+ | NA | MVPA |
| Patnode et al. (2010) | Accelerometer | ActiGraph 7164 | Hip | MVPA |
| Pearce et al. (2012) | Accelerometer | ActiGraph GT1M | Hip | V |
| Pechova et al. (2019) | Accelerometer | ActiGraph GT1M | Hip | SB |
Table 2 Characteristics of devices used to measure physical activity and sedentary behavior (Continued)

| Reference                  | Type of Device | Specific Device                | Wear Location | Measure(s) of Activity |
|----------------------------|----------------|--------------------------------|---------------|------------------------|
| Pelclova et al. (2010)     | Pedometer      | Omron HJ-105                   | Hip           | V                      |
| Prins and van Lenthe (2015)| GPS Logger     | QStarz BT-Q1000XT              | Hip           | V                      |
| Rahmen et al. (2019)       | Pedometer      | Omron HU-720 ITC               | Hip           | V                      |
| Remmers et al. (2017)      | Accelerometer  | ActiGraph GT3X+                | Hip           | SB, LPA, MVPA          |
| Ridgers et al. (2015)      | Accelerometer  | ActiGraph GT3X+                | Hip           | MVPA                   |
| Ridgers et al. (2018)      | Accelerometer  | ActiGraph GT3X+                | Hip           | LPA, MVPA              |
| Robbins et al. (2013)      | Accelerometer  | ActiGraph GT1M                 | Hip           | MVPA, V                |
| Rosenthal et al. (2020)    | Accelerometer  | NA                             | NA            | V                      |
| Rowlands et al. (2009)     | Accelerometer  | ActiGraph GT1M                 | Hip           | MVPA, V                |
| Sartini et al. (2017)      | Accelerometer  | ActiGraph GT3X                 | Hip           | SB, LPA, MVPA, V       |
| Schepps et al. (2018)      | Accelerometer  | ActiGraph GT3X+                | Hip           | SB, LPA, MVPA, V       |
| Sewell et al. (2010)       | Accelerometer  | Gaehwiler Electronic Z80-32 k V1 | Waist      | V                      |
| Shen et al. (2013)         | Accelerometer  | ActiGraph GT1M                 | Hip           | LPA, MVPA              |
| Silva et al. (2011)        | Accelerometer  | ActiGraph MTV/CSD 7164         | Hip           | SB, MVPA               |
| Sit et al. (2019)          | Accelerometer  | ActiGraph GT3X                 | Hip           | SB, MVPA               |
| Stabell et al. (2020)      | Pedometer      | Omron HU-324 U                 | Waist         | V                      |
| Sugino et al. (2012)       | Accelerometer  | 1. Actimarker; 2. Dynaport Activity Monitor (DAM) | Waist      | V                      |
| Sumukadas et al. (2008)    | Accelerometer  | RT3                            | Hip           | V                      |
| Van Kann et al. (2016)     | Accelerometer  | Actiheart                      | Chest         | LPA, MVPA              |
| Wang et al. (2017)         | Accelerometer  | ActiGraph GT3X                 | Waist         | MVPA, V                |
| Witham et al. (2014)       | Accelerometer  | RT3                            | Waist         | V                      |
| Wong et al. (2020)         | Accelerometer  | ActiGraph GT3X+                | Hip           | SB                     |
| Wu et al. (2017)           | Accelerometer  | ActiGraph GT1M                 | Wrist         | SB, V                  |
| Yildirim et al. (2012)     | Accelerometer  | 1. ActiGraph ActiTrainer; 2. ActiGraph GT1M; 3. ActiGraph GT3X | Waist      | SB, LPA, MVPA, V       |
| Zheng et al. (2019)        | Accelerometer  | activPAL                       | Thigh         | SB, MVPA               |

Note. V Physical activity volume, LPA light-intensity physical activity duration, MVPA moderate-to-vigorous intensity physical activity duration, SB sedentary behavior duration

Fig. 3 Movement behavior measures in studies examining seasonality and weather indices across the lifespan
Strong evidence indicated that physical activity volume was greater in summer than winter (23/30, 76.7%), although one study found it was greater in winter than summer (1/30, 3.3%). Six studies (20.0%) comparing volume in winter and summer yielded null results. Strong evidence also indicated that physical activity volume was consistently greater in spring than winter (15/22, 68.2%), but seven studies indicated no difference (7/22, 31.8%). No studies found evidence of greater volume in winter than spring.

Moderate evidence indicated mixed findings for physical activity volume between spring and autumn with most studies revealing either greater volume in spring than autumn (5/12, 41.7%) or no differences in volume (6/12, 50.0%). One study reported greater volume in autumn than spring (1/12, 8.3%). Moderate evidence indicated mixed findings for physical activity volume between autumn and winter with some studies indicating no difference (7/12, 58.3%) and others indicating great volume in autumn than winter (5/12, 41.7%). No
studies found evidence of greater physical activity volume in winter than autumn.

Limited evidence compared physical activity volume in spring and summer were equivocal: six studies indicated no difference in volume between summer and spring (6/10, 60%) but the remaining studies were evenly split between greater volume in summer (2/10, 20.0%) and spring (2/10, 20.0%). Limited evidence compared physical activity volume between autumn and summer. Findings generally indicated no difference (5/7, 71.4%) with the exception of one study indicating greater volume in autumn than summer (1/7, 14.3%) and another study indicating greater volume in summer than autumn (5/7, 14.3%).

Intensity-specific physical activity duration
Seasonal comparisons more frequently involved the duration of MVPA (37/37, 100.0%) than LPA (20/37, 54.1%). Studies comparing MVPA duration between seasons sampled youth (25/37, 67.6%), adults (6/37, 16.2%), and older adults (6/67 16.7%). Seasonal comparisons of LPA duration sampled youth (11/20, 55.0%), older adults (6/20, 30.0%), and adults (3/20, 15.0%).

As shown in Table 3, the most common seasonal comparisons of intensity-specific behavior durations involved winter vs. spring (overall: 22/37 [59.5%]; MVPA: 22/22 [100%]; LPA: 14/22 [63.6%]; winter vs. summer (overall: 19/37 [51.4%]; MVPA: 19/19 [%]; LPA: 12/19 [63.2%]), winter vs. autumn (overall: 17/37 [45.9%]; MVPA: 17/17 [100%]; LPA: 11/17 [64.7%]), spring vs. summer (overall: 13/37 [35.1%]; MVPA: 13/13 [100%]; LPA: 8/13 [61.5%]), and spring vs. autumn (overall: 12/37 [32.4%]; MVPA: 12/12 [100%]; LPA: 7/12 [58.3%]).

Strong evidence indicated either greater MVPA in spring than winter (12/22, 54.5%) or no difference between these seasons (10/22, 44.5%). No studies found greater MVPA duration in winter than spring. Based on moderate evidence, findings about LPA were mixed: half of the studies reported greater LPA in spring than winter (7/14, 50.0%) and half reported no difference in LPA between spring and winter (7/14, 50.0%). Strong evidence indicated that MVPA duration was generally greater in summer than winter (11/19, 57.9%). Six studies found no difference between these seasons (6/19, 20%) and one study found winter activity greater than summer (1/30, 3.3%). Based on moderate evidence, studies indicated either greater LPA in summer than winter (6/12, 50.0%) or no difference (6/12, 50.0%). Strong evidence found mixed findings for seasonal differences in MVPA between autumn and winter, either indicating no difference (12/17, 70.6%) or greater MVPA in autumn than winter (4/17, 23.5%). One study demonstrated greater MVPA duration in autumn compared to winter (1/17, 5.9%). Based on limited evidence, LPA was either greater in autumn than winter (5/11, 45.5%), not different between these seasons (4/11, 36.6%), or greater in winter than autumn (2/11, 18.2%). Strong evidence indicated that MVPA duration typically did not differ between summer and spring (10/13, 76.9%), but two studies revealed greater MVPA durations in summer (2/13, 15.3%) and another revealed greater MVPA duration in spring (1/13, 7.7%). Moderate evidence indicated that LPA generally did not differ between summer than spring (7/8, 87.5%) but one study indicated greater LPA in spring than summer (1/8, 12.5%).

Moderate evidence indicated mixed findings from comparisons of MVPA between spring and autumn, either indicating no differences (7/12, 58.3%) or greater MVPA in spring than autumn (5/12, 41.7%). No study demonstrated greater MVPA duration in autumn compared to spring. Based on limited evidence, LPA generally did not differ between spring and autumn (5/7, 71.4%); however, one study indicated greater LPA in spring than autumn (1/7, 14.3%) and another study indicated greater LPA in autumn than spring (1/7, 14.3%). Moderate evidence indicated that MVPA duration did not differ between summer and autumn in five studies (5/5, 100%). A grade was not assignable for LPA comparisons between summer and autumn.

Sedentary behavior
Studies comparing sedentary behavior between seasons sampled youth (14/23, 60.9%), adults (7/23, 30.4%) and older adults (2/23, 8.7%). The most common seasonal comparisons of volume involved winter vs. spring (16/23, 69.6%), winter vs. summer (13/23, 56.5%), winter vs. autumn (11/23, 47.8%), spring vs. summer (10/23, 43.5%), spring vs. autumn (9/23, 39.1%), and summer vs. autumn (6/23, 26.1%).

Strong evidence indicated that sedentary behavior was generally greater in winter than spring (11/16, 68.8%) although some studies indicated no difference (5/16, 31.3%). Strong evidence indicated that sedentary behavior was generally greater in winter than summer (10/13, 76.9%) with a few studies indicating no difference (3/13, 23.1%). Moderate evidence indicated that sedentary behavior did not vary between autumn and winter (8/11, 72.7%) but a few studies indicated greater sedentary behavior in winter than autumn (3/11, 27.3%). Moderate evidence indicated that sedentary behavior generally did not differ between spring and summer (8/10, 80%) but two studies indicated greater sedentary behavior during summer (2/10, 20%). Limited evidence also indicated that sedentary behavior either did not differ between spring and autumn (5/9, 55.6%) or was greater in autumn than spring (4/9, 44.4%). Limited evidence indicated that sedentary behavior either did not differ
| Weather Index | Finding       | Physical Activity Volume | Light-Intensity Physical Activity | Moderate-to-Vigorous Intensity Physical Activity | Sedentary Behavior |
|---------------|--------------|--------------------------|---------------------------------|-----------------------------------------------|---------------------|
| Temperature   | Positive     | 19 [35–38, 40, 43, 47, 70, 88, 107–114] | 4 [47, 64, 70, 115] | 11 [35, 39, 42, 47, 57, 73, 79, 81, 110, 116] | 2 [38, 81] |
|               | Null         | 13 [28, 35–37, 61, 117–122] | 4 [34, 56, 116] | 14 [34, 35, 40, 42, 56, 61, 70, 120, 121, 123, 124] | 7 [34, 63, 70, 73, 81, 115] |
|               | Negative     | 6 [38, 46, 125–128] | 0 | 3 [81, 122, 124] | 9 [38, 39, 47, 60–63, 71, 109] |
|               | Evidence Grade | Strong | Limited | Strong | Moderate |
| Precipitation | Positive     | 1 [28] | 0 | 2 [79, 123] | 12 [38, 39, 48, 60, 61, 63, 71, 73, 81, 109, 129] |
|               | Null         | 5 [37, 70, 114, 118] | 3 [34, 56, 70] | 15 [35, 39, 42, 56, 70, 81, 121, 122, 124, 130, 131] | 7 [34, 39, 62, 63, 70, 81] |
|               | Negative     | 25 [28, 36–38, 40, 43, 46, 48, 57, 61, 88, 109, 111–113, 119, 121, 122, 125, 127, 131, 132] | 3 [34, 57, 116] | 15 [34, 40, 48, 57, 61, 73, 81, 109, 116, 124, 129, 133, 134] | 0 |
|               | Evidence Grade | Strong | Limited | Strong | Strong |
| Wind Speed    | Positive     | 0 | 0 | 1 [39] | 2 [48, 60] |
|               | Null         | 6 [28, 36, 40, 43] | 2 [34] | 3 [34, 40] | 4 [34, 39] |
|               | Negative     | 6 [36, 46, 48, 109, 113, 127] | 0 | 3 [39, 48, 135] | 0 |
|               | Evidence Grade | Moderate | Not Assignable | Limited | Limited |
| Photoperiod   | Positive     | 15 [38, 46–48, 50, 72, 78, 88, 109, 114, 125, 127, 134, 136, 137] | 4 [34, 47, 64, 78] | 9 [34, 48, 50, 72, 73, 78, 133, 135] | 1 [63] |
|               | Null         | 6 [43, 113, 118, 121, 122] | 1 [34] | 6 [47, 79, 81, 121, 122] | 3 [34, 81] |
|               | Negative     | 0 | 0 | 0 | 10 [38, 47, 48, 50, 63, 71–73, 78, 81] |
|               | Evidence Grade | Strong | Limited | Strong | Strong |
| Snow          | Positive     | 0 | 0 | 0 | 0 |
|               | Null         | 3 [111, 114, 125] | 1 [116] | 4 [39, 42, 116] | 0 |
|               | Negative     | 4 [38, 88, 93] | 1 [64] | 1 [40] | 0 |
|               | Evidence Grade | Limited | Not Assignable | Limited | Not Assignable |
| Cloud Coverage| Positive     | 1 [127] | 0 | 0 | 0 |
|               | Null         | 2 [36, 37] | 0 | 0 | 0 |
|               | Negative     | 2 [36, 37] | 0 | 2 [41, 135] | 0 |
|               | Evidence Grade | Limited | Not Assignable | Not Assignable | Not Assignable |
| Humidity      | Positive     | 0 | 0 | 2 [78, 81] | 0 |
|               | Null         | 0 | 1 [34] | 6 [39, 81, 124] | 5 [34, 39, 81] |
|               | Negative     | 5 [78, 107, 126, 127] | 2 [34, 78] | 6 [34, 78, 79, 81, 124] | 0 |
between summer and autumn (4/6, 66.7%) or was greater in autumn than summer (2/6, 33.3%).

Specific weather indices associated with movement-related behaviors
Weather indices were typically collected from regional weather stations or national institutes (73/77, 94.8%); few studies used self-reported weather indices (3/77, 3.9%) or did not specify where weather indices were collected (1/77, 1.3%). Associations between specific indices and behavior examined in five or more studies are discussed below; all available results are summarized in Table 4. The weather indices are defined in Appendix 2.

The most frequently-reported weather indices included temperature (60/77, 77.9%), precipitation (58/77, 75.3%), photoperiod (33/77, 42.9%), wind speed (20/77, 26.0%), humidity (16/77, 20.8%), snow (12/77, 15.6%), and cloud coverage (7/77, 9.1%). No grade was assigned to research on barometric pressure, visibility, wind chill, or air quality due to insufficient evidence.

| Weather Index | Finding | Physical Activity Volume | Light-Intensity Physical Activity | Moderate-to-Vigorous Intensity Physical Activity | Sedentary Behavior |
|---------------|---------|--------------------------|-----------------------------------|-----------------------------------------------|-------------------|
| Visibility    | Positive Associations | 1 [73]                  | 0                                 | 0                                             | 0                 |
| Null Associations | 0                             | 1 [34]                  | 0                                 | 2 [34]                                        |                   |
| Negative Associations | 1 [127]                     | 1 [34]                  | 1 [34]                            | 0                                             |                   |
| Evidence Grade | Not Assignable                       | Not Assignable           | Not Assignable                     | Not Assignable                                   |                   |
| Barometric Pressure | Positive Associations | 1 [127]                  | 0                                 | 0                                             | 0                 |
| Null Associations | 0                             | 0                       | 0                                 | 0                                             |                   |
| Negative Associations | 0                             | 0                       | 0                                 | 0                                             |                   |
| Evidence Grade | Not Assignable                       | Not Assignable           | Not Assignable                     | Not Assignable                                   |                   |
| Wind Chill    | Positive Associations | 1 [73]                  | 0                                 | 0                                             | 0                 |
| Null Associations | 0                             | 0                       | 0                                 | 0                                             |                   |
| Negative Associations | 0                             | 0                       | 0                                 | 0                                             |                   |
| Evidence Grade | Not Assignable                       | Not Assignable           | Not Assignable                     | Not Assignable                                   |                   |
| Air Quality   | Positive Associations | 0                             | 0                                 | 0                                             | 0                 |
| Null Associations | 1 [120]                     | 0                       | 1 [120]                           | 0                                             |                   |
| Negative Associations | 1 [138]                     | 0                       | 0                                 | 0                                             |                   |
| Evidence Grade | Not Assignable                       | Not Assignable           | Not Assignable                     | Not Assignable                                   |                   |

between summer and autumn (4/6, 66.7%) or was greater in autumn than summer (2/6, 33.3%).
Associations between temperature and physical activity volume were more often positive (19/38, 50.0%) than null (13/38, 34.2%) or negative (6/38, 15.8%). No studies explicitly tested for curvilinear relations, but four studies noted an inverted-U pattern in which volume was lower during normatively warmer or colder days [38, 78, 117, 125]. Additional negative associations with volume were found when extreme temperatures were present [126, 127]. This evidence was graded as strong in favor of an inverted-U relation between temperature and physical activity volume.

Moderate evidence indicated that associations between temperature and MVPA duration were more often null (14/28, 50.0%) or positive (11/28, 39.3%) than negative (3/28, 10.7%). Limited evidence suggested that LPA exhibited a similar pattern with studies showing either a null (4/8, 50.0%) or positive (4/8, 50.0%) association with temperature. Moderate evidence indicated that sedentary behavior exhibited more negative associations with temperature (9/18, 50.0%) than null (7/18, 38.9%) or positive associations (2/18, 11.1%).

Precipitation
Associations between precipitation and movement-related behaviors were estimated in youth (28/58, 48.3%), adults (21/58, 36.2%) and older adults (9/58, 15.5%). Precipitation was most frequently studied in relation with physical activity volume (31/58, 53.4%) followed by intensity-specific physical activity durations (overall: 32/58 [55.2%]; MVPA: 32/32 [100%]; LPA: 6/32 [18.8%]) and sedentary behavior (19/32, 32.8%).

Strong evidence indicated that associations between precipitation and physical activity volume were largely negative (25/31, 80.6%) with a few null (5/31, 16.1%) and one positive (1/31, 3.2%) association. Strong evidence indicated that the association between precipitation and MVPA durations were mixed with negative (15/32, 46.9%) and null (15/32, 46.9%) results. Two studies reported a positive association between precipitation and MVPA duration (2/32, 6.3%). Limited evidence indicated that precipitation and LPA had either a negative (3/6, 50.0%) or null (3/6, 50.0%) association. Moderate evidence indicated a mix of positive (12/19, 63.2%) and null associations (7/19, 36.8%) between precipitation and sedentary behavior. No studies reported a negative association between precipitation and sedentary behavior.

Photoperiod
Associations between the photoperiod and movement-related behaviors were estimated in youth (14/33, 42.4%), adults (10/33, 30.3%) and older adults (9/33, 27.3%). These studies reported associations between the photoperiod and measures of physical activity volume (21/33, 63.6%), intensity-specific physical activity duration (overall: 19/33 [57.6%]; MVPA: 15/19 [78.9%], LPA: 5/19 [26.3%]) and sedentary behavior (14/33, 42.4%).

Strong evidence indicated that associations between photoperiod and physical activity volume were mostly positive (15/21, 71.4%) with a few null associations (6/21, 28.6%). No studies reported a negative association between photoperiod and physical activity volume. Strong evidence indicated that associations between the photoperiod and MVPA duration were mostly positive (9/15, 60.0%) or null (6/15, 40.0%). No studies reported a negative association between photoperiod and MVPA duration. Limited evidence suggested a positive association between photoperiod and LPA duration (4/5, 80.0%) with a single study indicating a null association (1/5, 20.0%). Strong evidence indicated that the photoperiod and sedentary behavior had a negative association (10/14, 71.4%), with a few studies indicating either null (3/14, 21.4%) or positive associations (1/14, 7.1%).

Wind speed
Associations between wind speed and movement-related behaviors were estimated in youth (8/20, 40.0%), older adults (7/20, 35.0%), and adults (5/20, 25.0%). These studies reported associations between wind speed and total physical activity volume (12/20, 60.0%) intensity-specific physical activity durations (overall: 7/20 [35.0%]; MVPA: 7/7 [100%]; LPA: 3/7 [42.9%]), and sedentary behavior (6/20, 35.0%).

Moderate evidence indicated that associations between wind speed and physical activity volume were a mix of null (6/12, 50.0%), and negative associations (6/12, 50.0%). No study reported a positive association between wind speed and volume.

Limited evidence indicated that wind speed and MVPA durations demonstrated mostly null (3/7, 42.9%) or negative associations (3/7, 42.9%), although one study found a positive association (1/7, 14.3%). A grade was not assignable for evidence on wind speed and LPA. Limited evidence indicated that wind speed and sedentary behavior primarily displayed null (4/6, 66.7%) or positive associations (2/6, 33.3%); no studies reported a negative association.

Humidity
Associations between humidity and movement-related behaviors were estimated in adults (7/16, 43.8%), youth (5/16, 31.3%), and older adults (4/16, 25.0%). Studies including humidity frequently examined measures of physical activity volume (5/16, 31.3%), followed in frequency by intensity-specific physical
activity duration (overall: 12/16 [75.0%]; MVPA: 12/12 [100%]; LPA: 3/12 [25.0%], sedentary behavior: 7/16 [43.8%]).

Moderate evidence indicated a consistently negative association between humidity and physical activity volume (5/5, 100.0%). Moderate evidence indicated a mix of negative (6/12, 50.0%) and null (6/12, 50.0%) associations between humidity and MVPA. A grade was not assignable to evidence linking humidity and LPA. Limited evidence suggested a null association between humidity and sedentary behavior (5/7, 71.4%) although some studies found a positive association (2/7, 28.6%).

**Cloud coverage**

Associations between cloud coverage and movement-related behaviors were estimated in youth (5/12, 41.7%), adults (3/12, 25.0%), and older adults (4/12, 33.3%). Studies including snow frequently examined measures of physical activity volume (7/12, 58.3%), followed in frequency by intensity-specific physical activity duration (overall: 6/12 [50.0%]; MVPA: 5/6 [83.3%], LPA: 2/6 [33.3%]).

Limited evidence on snow and physical activity volume was split between negative (4/7, 57.1%) and null (3/7, 42.9%) associations. No study examining snow and volume demonstrated a positive association. Limited evidence on snow and MVPA duration was split between null (4/5, 80.0%) and negative (1/5, 20.0%) associations. A grade was not assignable to evidence linking snow with either LPA or sedentary behavior.

**Discussion**

The present review summarized 144 studies from 110 articles with 118,189 participants from 30 countries. It updates conclusions from two seminal reviews based on a total of over 60 studies on over 300,000 participants from approximately 18 countries [10, 11]. In those reviews, studies on seasonal differences in physical activity greatly outnumbered studies on weather correlates. Over the past decade, attention has been divided more equally between seasonal differences in and weather correlates of movement behaviors. This review also extended the prior reviews by capturing the spectrum of movement behaviors ranging from physical activity volume to intensity-specific durations to sedentary behavior. Collectively, these reviews establish how key features of the natural environment are linked with a variety of movement behaviors.

Physical activity volume and MVPA duration were the most frequent measures of movement behavior. Consistent with prior work, winter and summer were marked by the lowest and greatest movement behavior, respectively [10, 11]. The present review extended those conclusions by documenting a trend in favor of greater physical activity volume and MVPA in spring than autumn. Comparisons of spring vs summer and summer vs autumn largely revealed no differences. Overall, the pattern of seasonal differences in physical activity volume and MVPA duration resembled a sinusoidal pattern and corresponded with both fluctuations in temperature and the waxing and waning photoperiod across the calendar year.

One contribution of the present review was that it examined a broad spectrum of movement behaviors that contribute to physical activity volume. MVPA duration has enjoyed a privileged status in the scientific literature because it has the strongest connections with health benefits [24]. MVPA also exhibited the clearest pattern of relations with seasonality and specific weather indices, including temperature, precipitation, and photoperiod. Thus, MVPA may provide one pathway by which the natural environment gets “under the skin” to affect health [139, 140].

Moving the needle on population-level MVPA has proven to be difficult [141, 142]. Far more time is spent in LPA than MVPA and LPA is a greater contributor to physical activity volume for most people [143]. Recent work has established unique health benefits from LPA after adjusting for MVPA [144]. As a consequence, LPA is a desirable substitute for prolonged sedentary behavior when MVPA is not feasible. Although a trend for increased LPA in summer and spring compared to winter was observed in the literature, LPA in the spring did not differ from LPA in the summer or autumn. In the interest of understanding how the natural environment facilitates or inhibits movement, this common form of physical activity should be a priority measure in future research examining seasonal differences and weather correlates.
Sedentary behavior was consistently greater in winter than spring or summer. Weather has been cited as a barrier to physical activity that facilitates sedentary behavior [8, 9]. This study extended previous work by reviewing how specific weather indices, as opposed to perceptions of the weather, are associated with sedentary behavior. People engage in more sedentary behavior on shorter days (photoperiod), when precipitation is greater, and when temperatures are lower. These findings revealed that weather is likely to be a third variable influencing the entire spectrum of movement-related behaviors.

These findings have two major implications. First, although the studies reviewed here were necessarily observational, they can inform behavioral interventions. Weather conditions that may serve as actual, as well as perceived, barriers to physical activity (e.g., too hot, cold, rainy or snowy, windy, or shorter days). Current or forecasted weather conditions may be useful for providing contextual information about opportunities for activity that could inform just-in-time interventions for movement behaviors. For example, users could be prompted to develop coping plans for exercise in adverse weather conditions and then reminded of those plans when adverse weather conditions were expected. Digital tools could also extend work on person-specific physical activity interventions by learning how to identify user-specific preferred weather patterns for movement behaviors and prompt users to ensure they capitalize on their preferred conditions to be active [145].

At a more general level, the impact of seasonal differences in movement behaviors on the implementation and evaluation of physical activity promotion programs should be considered when interpreting ambulatory behavior changes. Lifestyle physical activity intervention evaluations often last 1–6 months, and few last 12 months, so baseline and follow-up assessments are often conducted during different seasons. Seasonal influences on activity levels are typically allocated to the error term of statistical models but may be informative to include as a covariate or moderator of intervention effects. For example, including season as a moderator could reveal if interventions work better when days are lengthening (winter to summer) or when days are shortening (summer to winter).

Second, climate change is increasing the frequency of extreme weather conditions. Climatic zones that are currently favorable for movement behaviors may become inhospitable, inhibit physical activity, and contribute to health disparities. Some have speculated that climate change will increase migration as people seek to preserve an adaptive environmental niche [146]. Population-level data on movement behaviors could be investigated as a leading indicator of future health or migration due to climate change.

This review had limitations as well. The search was conducted using three databases and limited to English language publications. It is possible that studies were missed if they were published in journals not indexed by PubMed, CINAHL, or SPORTDiscus, or were written in languages other than English. All data were observational so strong causal inferences are not possible. Results were obtained from 30 countries on five continents but western and high-income countries were overrepresented in the data. Low- and middle-income countries are home to over 80% of the world’s population and four times as many deaths are attributed to physical inactivity in those countries than in high-income countries [147, 148]. Conclusions may not generalize equally well to all regions, climatic zones, or economic strata. Most studies did not report on race or ethnicity so it is unclear how physical, social or cultural differences influence seasonal differences or relations between weather and movement behaviors. Devices were used to obtain measures of physical activity volume and intensity-specific duration – primarily MVPA - but some activity types do not lend themselves to accurate measurement with devices (e.g., cycling, swimming) or are sub-optimal with devices attached at the waist (e.g., sedentary behavior). Devices also provide no insights into the specific domains of physical activity (e.g., occupational, transport-related, occupational, domestic) or sedentary behavior (e.g., reading, screen time, socializing, eating). The available literature has focused almost exclusively on aggregated weather summaries during monitoring periods. Yet weather is dynamic so those summaries may not generalize to within-person change processes [149]. Additionally, physiological or psychological differences in environmental tolerances likely exist. Some people, for example, will be more heat tolerant or may simply enjoy running in the rain. Person-specific models of physical activity under different weather conditions could shed light on these dynamics [145]. Finally, the review focused on 11 common weather indices but other indices may also be relevant.

Conclusions
In sum, this review established consistent patterns of seasonal and weather-specific differences in physical activity and sedentary behavior. People tend to be most active in summer and least active in winter. This pattern coincides with temperature and photoperiod cycles. Weather may also influence comfort with physical activity as indicated by associations with precipitation and wind speed. These findings can inform physical activity promotion initiatives in the short-term and may have long-term implications for environmental influences on human health during the climate crisis.
Appendix A

Table 5 Search Methods | PubMed

Search terms: (["Exercise"[MeSH] OR "Exercises"[tiab] OR "Exercising"[MeSH] OR "Exercising"[tiab] OR "Physical activities"[MeSH] OR "Physical activities"[tiab] OR "Physical activity"[MeSH] OR "Physical activity"[tiab] OR "Physical fitness"[MeSH] OR "Physical fitness"[tiab] OR "Recreation"[MeSH] OR "Recreation"[tiab] OR "Run"[MeSH] OR "Run"[tiab] OR "Running"[MeSH] OR "Running"[tiab] OR "Walk"[MeSH] OR "Walking"[MeSH] OR "Walking"[tiab] OR "Computer game"[MeSH] OR "Computer game"[tiab] OR "Computer gamers"[MeSH] OR "Computer gamers"[tiab] OR "Computer usage"[MeSH] OR "Computer usage"[tiab] OR "Computer use"[MeSH] OR "Computer use"[tiab] OR "Physically inactive"[MeSH] OR "Physically inactive"[tiab] OR "Screen time"[MeSH] OR "Screen time"[tiab] OR "Sedentarism"[MeSH] OR "Sedentarism"[tiab] OR "Sedentary behavior"[MeSH] OR "Sedentary behavior"[tiab] OR "TV viewing"[MeSH] OR "TV viewing"[tiab] OR "TV watching"[MeSH] OR "TV watching"[tiab] OR "Video game"[MeSH] OR "Video game"[tiab] OR "Video games"[MeSH] OR "Video games"[tiab] OR "Video gaming"[MeSH] OR "Video gaming"[tiab]]) AND ("Accelerometer"[MeSH] OR "Accelerometer"[tiab] OR "Accelerometry"[MeSH] OR "Accelerometry"[tiab] OR "Pedometer"[MeSH] OR "Pedometer"[tiab] OR "Steps"[MeSH] OR "Steps"[tiab]) AND ("Season"[MeSH] OR "Season"[tiab] OR "Seasonal"[MeSH] OR "Seasonal"[tiab] OR "Seasons"[MeSH] OR "Seasons"[tiab] OR "Atmospheric Pressure"[MeSH] OR "Atmospheric Pressure"[tiab] OR "Cloud"[MeSH] OR "Cloud"[tiab] OR "Cloud Cover"[MeSH] OR "Cloud Cover"[tiab] OR "Clouds"[MeSH] OR "Clouds"[tiab] OR "Climate"[MeSH] OR "Climate"[tiab] OR "Fog"[MeSH] OR "Fog"[tiab] OR "Heat index"[MeSH] OR "Heat index"[tiab] OR "Humid"[MeSH] OR "Humid"[tiab] OR "Humidity"[MeSH] OR "Humidity"[tiab] OR "Ice"[MeSH] OR "Ice"[tiab] OR "Lightning"[MeSH] OR "Lightning"[tiab] OR "Overcast"[MeSH] OR "Overcast"[tiab] OR "Precipitation"[MeSH] OR "Precipitation"[tiab] OR "Rain"[MeSH] OR "Rain"[tiab] OR "Saturation"[MeSH] OR "Saturation"[tiab] OR "Severe weather"[MeSH] OR "Severe weather"[tiab] OR "Snow"[MeSH] OR "Snow"[tiab] OR "Sunlight"[MeSH] OR "Sunlight"[tiab] OR "Temperature"[MeSH] OR "Temperature"[tiab] OR "Temperatures"[MeSH] OR "Temperatures"[tiab] OR "Ultraviolet rays"[MeSH] OR "Ultraviolet rays"[tiab] OR "UV index"[MeSH] OR "UV index"[tiab] OR "UV rays"[MeSH] OR "UV rays"[tiab] OR "Visibility"[MeSH] OR "Visibility"[tiab] OR "Weather"[MeSH] OR "Weather"[tiab] OR "Wind"[MeSH] OR "Wind"[tiab] OR "Wind chill"[MeSH] OR "Wind chill"[tiab] OR "Windy"[MeSH] OR "Windy"[tiab]])

Limiters: ("2006/01/01"[Date - Publication] OR "2010/10/31"[Date - Publication]) AND (English[Language])

Filters: Humans

Appendix B

Table 6 Search Methods | CINAHL

Search terms: (MH "Exercise") OR (MH "Physical Fitness") OR (MH "Cardiorespiratory Fitness") OR (MH "Physical Activity") OR (MH "Recreation") OR (MH "Running, Distance") OR (MH "Running") OR (MH "Walking") OR (MH "Life Style, Sedentary") OR (MH "Television") OR (MH "Video Games") OR (MH "Computers, Portable") OR (MH "Computers, Hand-Held") OR (MH "Screen Time") OR TI "Exercise" OR "Physical Fitness" OR "Cardiorespiratory Fitness" OR "Physical Activity" OR "Recreation" OR "Running, Distance" OR "Running" OR "Walking" OR "Life Style, Sedentary" OR "Television" OR "Video Games" OR "Computers, Portable" OR "Computers, Hand-Held" OR "Screen Time" OR AB "Exercise" OR "Physical Fitness" OR "Cardiorespiratory Fitness" OR "Physical Activity" OR "Recreation" OR "Running, Distance" OR "Running" OR "Walking" OR "Life Style, Sedentary" OR "Television" OR "Video Games" OR "Computers, Portable" OR "Computers, Hand-Held" OR "Screen Time"

AND (MH "Accelerometers") OR (MH "Pedometers") OR (MH "Step") OR (MH "Fitness Trackers") OR TI "Accelerometers" OR "Pedometers" OR "Step" OR "Fitness Trackers" OR "Wearable Electronic Devices" OR AB "Accelerometers" OR "Pedometers" OR "Step" OR "Fitness Trackers" OR "Wearable Electronic Devices"

AND (MH "Weather") OR (MH "Extreme Weather") OR (MH "Seasons") OR (MH "Temperature") OR (MH "Humidity") OR (MH "Heat") OR (MH "Ice") OR (MH "Ultraviolet Rays") OR (MH "Sunlight") OR (MH "Smog") OR (MH "Light") OR (MH "Lightning") OR (MH "Atmospheric Pressure") OR (MH "Rain") OR (MH "Snow") OR (MH "Atmosphere") OR (MH "Meteorological Factors") OR (MH "Climate") OR TI "Weather" OR "Extreme Weather" OR "Seasons" OR "Temperature" OR "Humidity" OR "Heat" OR "Ice" OR "Ultraviolet Rays" OR "Sunlight" OR "Smog" OR "Light" OR "Lightning" OR "Atmospheric Pressure" OR "Rain" OR "Snow" OR "Atmosphere" OR "Meteorological Factors" OR "Climate" OR AB "Weather" OR "Extreme Weather" OR "Seasons" OR "Temperature" OR "Humidity" OR "Heat" OR "Ice" OR "Ultraviolet Rays" OR "Sunlight" OR "Smog" OR "Light" OR "Lightning" OR "Atmospheric Pressure" OR "Rain" OR "Snow" OR "Atmosphere" OR "Meteorological Factors" OR "Climate"

Limiters: ("2006/01/01"[Date - Publication] OR "2010/10/31"[Date - Publication]) AND (English[Language])

Filters: Humans
Appendix C

Table 7 Search Methods | SPORTDiscus

Search terms: (DE “EXERCISE”) OR (DE “PHYSICAL fitness”) OR (DE “PHYSICAL activity”) OR (DE “RECREATION”) OR (DE “RUNNING”) OR (DE “WALKING”) OR (DE “SEDENTARY behavior”) OR (DE “SUBSCRIPTION television”) OR (DE “VIDEO games”) OR (DE “COMPUTER games”) OR (DE “SEDENTARY people”) OR (DE “EXERCISE”) OR (DE “PHYSICAL fitness”) OR (DE “PHYSICAL activity”) OR (DE “RECREATION”) OR (DE “RUNNING”) OR (DE “WALKING”) OR (DE “SEDENTARY behavior”) OR (DE “SUBSCRIPTION television”) OR (DE “VIDEO games”) OR (DE “COMPUTER games”) OR (DE “SEDENTARY people”)

AND

(DE “Pedometers”) OR (DE “AcceLerometers”) OR (DE “Pedometers”) OR (DE “AcceLerometers”) OR (DE “Step”) OR (DE “Fitness Trackers”) OR (DE “Wearable electronic devices”)

AND

(DE “WEATHER”) OR (DE “TEMPERATURE”) OR (DE “HUMIDITY”) OR (DE “ICE”) OR (DE “ULTRAVIOLET radiation”) OR (DE “SUNSHINE”) OR (DE “ATMOSPHERIC pressure”) OR (DE “SNOW”) OR (DE “COLD (Temperature)”) OR (DE “WEATHER”) OR (DE “TEMPERATURE”) OR (DE “HUMIDITY”) OR (DE “ICE”) OR (DE “ULTRAVIOLET radiation”) OR (DE “SUNSHINE”) OR (DE “ATMOSPHERIC pressure”) OR (DE “SNOW”) OR (DE “COLD (Temperature)”) OR (DE “ATMOSPHERE”) OR (DE “METEOROLOGICAL FACTORS”) OR (DE “EXTREME WEATHER”) OR (DE “CLIMATE”) OR (DE “WEATHER”) OR (DE “TEMPERATURE”) OR (DE “HUMIDITY”) OR (DE “ICE”) OR (DE “ULTRAVIOLET radiation”) OR (DE “SUNSHINE”) OR (DE “ATMOSPHERIC pressure”) OR (DE “SNOW”) OR (DE “COLD (Temperature)”) OR (DE “ATMOSPHERE”) OR (DE “METEOROLOGICAL FACTORS”) OR (DE “EXTREME WEATHER”) OR (DE “CLIMATE”)

Limiters: (*2006/01/01* [Date - Publication]) AND (*2020/10/31* [Date - Publication]) AND (English [Language])

Filters: Humans

Appendix D

Table 8 Glossary of Weather Indices

| Index            | Definition                                                                 |
|------------------|---------------------------------------------------------------------------|
| Temperature      | Degree or intensity of heat in the environment                             |
| Precipitation    | Product of condensation from atmospheric water vapor                       |
| Wind Speed       | Atmospheric quantity resulting from air traveling from high to low pressure|
| Photoperiod      | Day length, or the period of daily illumination                            |
| Snow             | Small, frozen white crystals generated from atmospheric water vapor        |
| Cloud Coverage   | The fraction of the sky obscured by clouds in a particular location        |
| Humidity         | Concentration of atmospheric water vapor present in the environment        |
| Visibility       | Distance that can be seen due to light and weather conditions              |
| Barometric Pressure | Pressure within the atmosphere                                      |
| Wind Chill       | Quantity of air temperature that is effectively lowered due to wind        |
| Air Quality      | A measure of how clean or polluted the air is                             |

Note: Definitions obtained from the National Weather Service and the Oxford English Dictionary [150, 151]

Supplementary Information

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Additional file 1.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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