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Does surrounding greenness moderate the relationship between apparent temperature and physical activity? Findings from the PHENOTYPE project

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Abstract

Background: Physical activity can be affected by both meteorological conditions and surrounding greenness, but few studies have evaluated the effects of these environmental factors on physical activity simultaneously. This multi-city comparative study aimed to assess the synergetic effects of apparent temperature and surrounding greenness on physical activity in four European cities. Specifically, we aimed to identify an interaction between surrounding greenness and apparent temperature in the effects on physical activity.

Methods: Data were collected from 352 adult residents of Barcelona (Spain), Stoke-on-Trent (United Kingdom), Doetinchem (The Netherlands), and Kaunas (Lithuania) as part of the PHENOTYPE study. Participants wore a smartphone for seven consecutive days between May-December 2013 and provided additional sociodemographic survey data. Hourly average physical activity (Metabolic Equivalent of Task (MET)) and surrounding greenness (NDVI) were derived from the Calfit mobile application collecting accelerometer and location data. Hourly apparent temperature was calculated from temperature and relative humidity, which were obtained from local meteorological stations along with other meteorological covariates (rainfall, windspeed, and sky darkness). We assessed the interaction effects of apparent temperature and surrounding greenness on hourly physical activity for each city using linear mixed models, while adjusting for meteorological, demographic, and time-related variables.

Results: We found significant interactions between apparent temperature and surrounding greenness on hourly physical activity in all four cities. Significant quadratic effects of apparent temperature were found in the highest level of surrounding greenness for Stoke-on-Trent and Doetinchem, with 4% decrease in median MET observed for a 10°C departure from optimal temperature (15.2°C and 14.6°C, respectively). On the other hand, significant linear effects were found for higher levels of surrounding greenness in Barcelona and Kaunas, whereby an increase of 10°C was associated with ~4% increase in median MET.

Conclusion: Apparent temperature and surrounding greenness interacted in the effect on hourly physical activity across the four European cities, with varying effect between cities. While quadratic effects of temperature suggest diminishing levels of physical activity in the highest greenness levels in cities of temperate climates, the variation in surrounding greenness between cities could be further explored, particularly by looking at indoor-outdoor locations. The study findings support the need for evidence-based physical activity promotion and urban design.

Keywords: Temperature, apparent temperature, greenness, NDVI, physical activity

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Introduction

Physical activity is an important protective factor for premature mortality, chronic disease prevention, and well-being (I. M. Lee et al., 2012). However, physical activity levels are generally low globally (Hallal et al., 2012) and are affected by external environmental factors such as weather and the built environment (Bauman et al., 2012). With climate change, cities will generally shift towards higher temperature ranges (Ballester, Giorgi, & Rodó, 2010) and greater rainfall variability (Min, Zhang, Zwiers, & Hegerl, 2011). Populations will experience heat stresses more frequently and will need to look for environments with less thermal discomfort. This challenge requires a better understanding of the relationships between climate, built environment and physical activity.

Adverse weather conditions have been shown to be a barrier to physical activity (Tucker & Gilliland, 2007). Daily step counts in Japanese older people peaked at mean daily temperatures of 17°C and decreased with increasing precipitation and shorter daylight hours (Togo et al., 2005). Longitudinal studies of young adults in Qatar and Brazil found decreasing physical activity was correlated with increasing average temperature, humidity and rainfall, particularly during summer (Al-Mohannadi et al., 2016; Martins, Reichert, Bielemann, & Hallal, 2017). In Chicago, (United States) adults with arthritis had lower overall activity levels for lower daylight, higher rainfall, and cold (< -6.67°C) and hot (≥ 23.89°C) mean daily temperatures (Feinglass et al., 2011). The same study, however, found hot weather was associated with more minutes of moderate-to-vigorous physical activity (Feinglass et al., 2011). Objective physical activity levels have also been found positively associated with minimum temperature and daylight among older adults in Scotland and United Kingdom (Witham et al., 2014; Wu et al., 2017). These results suggest the physical activity-temperature relationship may vary by context; however, the different study populations and methodologies prevent cross-study comparisons and drawing of conclusive evidence.

Greenspaces have been found to be associated with better health outcomes, including those related to all-cause mortality, cardiovascular disease, and mental health among others (Gascon et al., 2016; Nieuwenhuijsen, 2018; Nieuwenhuijsen et al., 2017). Physical activity conducted in greenspaces may contribute to these health outcomes by reducing stress levels and benefiting mental health. There is only mixed evidence, however, of the effects of greenspace on physical activity levels (Bancroft et al., 2015; Mytton, Townsend, Rutter, & Foster, 2012; Nieuwenhuijsen, 2018; Triguero-Mas et al., 2017). A systematic review found positive results among 40% of studies, and weak or no relationship among 56% of studies (Lachowycz & Jones, 2011). Yet, greenspaces are hypothesized to promote physical activity as common destinations for recreational activity and indicators of accessibility to park spaces or outdoor areas (Bancroft et al., 2015; Bedimo-Rung, Mowen, & Cohen, 2005; Kruize et al., 2019). Studies using global positioning systems and accelerometers have reported momentary increases in physical activity when children enter into green areas such as parks (Almanza et al. 2011).

Vegetation contributes to urban temperature regulation with a cooling effect extending 200m to 500m (Ca, Asaeda, & Abu, 1998; Hamada & Ohta, 2010). Urban greenery could affect apparent temperatures through processes such as evapotranspiration (which transforms sensible heat into latent heat by evaporating liquid water into water vapour), shading from tree cover, and regulation of air movements and heat exchange (Bowler, Buyung-Ali, Knight, & Pullin, 2010). A meta-analysis on urban greenery found that parks reduced urban air temperatures by 1°C on average, with larger parks and trees possibly having a greater effect (Bowler et al., 2010). In London, a recent study found that heat-related mortality was modified by urban vegetation levels, whereby neighbourhoods with the highest tree cover and vegetation had lower odds of heat-related mortality

(Murage et al., 2020). The cooling effect of greenspaces may further promote the physical activity conducted in those spaces.

Although both meteorological conditions and surrounding greenness can affect physical activity, few studies have assessed a potential synergy of spatial and temporal impacts on physical activity. Two studies in the United States have focused on the effects of meteorological conditions on the use of greenspace for physical activity via aggregated trail counts at the hourly and daily levels, and found temperatures peaked at 24°C average or 28°C max temperatures, respectively (Burchfield, Fitzhugh, & Bassett, 2012; Wolff & Fitzhugh, 2011). A repeated cross-sectional survey in the UK found evidence that temperature, windspeed, and daylight affected the physical activity levels during visits to green environments, particularly parks (Elliott et al., 2019). In terms of residential neighbourhood greenspace, higher weekly temperature and quality of residential neighbourhood greenspace were found to be associated with self-reported weekly physical activity in Paris (Chaix et al., 2014). Increasing percentage of residential neighbourhood greenspaces, however, seemed to have a negative association during sunnier weather and positive association during rainier weather for self-reported non-work-related physical activity in the UK (Cochrane et al., 2009). These findings indicate possible interactions between surrounding greenness and meteorological conditions in the associations with physical activity. These previous studies were limited because they focused on destination-specific natural environments, and their control of temporal concurrence of the meteorological conditions and the greenspace use was limited. Therefore, an analysis that includes continuous monitoring of the weather, location and physical activity level during people's daily life is needed, to increase the sensitivity to weather changes within a day (Burchfield et al., 2012; Prins & van Lenthe, 2015) and to capture the large variation in people’s physical activity locations and thus understand whether individuals apply compensatory mechanisms to these adverse weather and environmental conditions.

Comprehensive studies of the potential interactions between greenspace and meteorological conditions may benefit from personal monitoring technologies that provide detailed data on individual-level behaviours. Recent studies on physical activity have focused on objective measurements using pedometers, accelerometers, or heart rate monitors. Smartphone accelerometer applications have been validated for their accuracy and are increasingly used as convenient instruments in population studies (Hekler et al., 2015; Presset, Laurenczy, Malatesta, & Barral, 2018). Smartphones, with their GPS and accelerometery services, enable this concurrent objective measurement of time- and location-specific physical activity, which may help better explain linkages between temperature, surrounding greenness, and physical activity.

This paper describes the results of assessing the synergetic effects of apparent temperature and surrounding greenness on physical activity in four European cities, using objective personal measures in a subsample of participants from the Positive Health Effects on the Natural Outdoor Environment in Typical Populations of Different Regions in Europe (PHENOTYPE) Project (Nieuwenhuijsen et al., 2014).

Methods

Study setting & design

Data were obtained from a smartphone-based monitoring study, recruited from a random sample of participants residing in four cities: Barcelona (Spain), Stoke-on-Trent (United Kingdom), Doetinchem (The Netherlands), and Kaunas (Lithuania) in the PHENOTYPE project (Nieuwenhuijsen et al., 2014;

Smith et al., 2017; Triguero-Mas et al., 2017). All study participants of the PHENOTYPE project questionnaire (N=3946) were invited to participate in this smartphone study, with the aim of recruiting around 100 participants per city. The study inclusion criterion was to be able to walk 300 m on level ground. In total, the subsample smartphone study recruited 431 participants: 109 in Barcelona (10.4% of invited participants from that city), 49 (4.7%) in Stoke-on-Trent, 111 (12.9%) in Doetinchem, and 112 (11.2%) in Kaunas. In Stoke-on-Trent, participation was further boosted through randomised mail invitations and opportunistic sampling (n = 50) (Triguero-Mas et al., 2017).

Each participant was instructed to wear a smartphone installed with the CalFit mobile application for seven consecutive days during the May - December 2013 study period. During this time, the smartphone was to be removed only during charging, sleeping or when performing activities that could damage the smartphone (i.e. aquatic activities). The Calfit application, which has been validated against the Actigraph accelerometer (Donaire-Gonzalez et al., 2013), used accelerometer motion sensor and global positioning system (GPS) receivers to collect data on participant physical activity and geographical location. More details of the study protocol can be found at (Nieuwenhuijsen et al., 2014; Triguero-Mas et al., 2017). Ethical approval was obtained from each city's corresponding authority: Clinical Research Ethics Committee of the Municipal Health Care (CEIC PS-MAR), Spain (2012/4978/I); Staffordshire University Faculty of Health Science ethics committee, United Kingdom; Medical Ethical Committee of the University Medical Centre Utrecht, Netherlands; Lithuanian Bioethics Committee, Lithuania (2012-04-30 Nr.6B-12-147).

Outcome: Physical activity

Physical activity was estimated using Metabolic Equivalent of Task (MET), which is a measurement quantifying the energy expenditure of activities using the resting metabolic rate (3.5 ml O_2/kg/min) as the basic unit (Jette, Sidney, & Blumchen, 1990). A conversion equation from Freedson, Melanson, and Sirard (1998) was adapted for transforming the acceleration intensity of the raw Calfit accelerometer count data into METs. This process is elaborated more in the original paper (Donaire-Gonzalez et al., 2013). The METs at the minute level were then averaged to produce Average hourly MET. Non-wear time of smartphone data was removed from the dataset, defined as episodes of 40 or more consecutive minutes with the accelerometer's vertical axis below 0.3g (Donaire-Gonzalez et al., 2013; Triguero-Mas et al., 2017). A valid hour was defined as having both physical activity counts and surrounding greenness counts for over 30 minutes within the hour. Only waking hours (6:00 to 23:59) were included in the analysis. A valid user was defined as having at least four days with a minimum of 10 valid hours per day during the waking hours.

Exposure: Apparent temperature

Meteorological records were obtained for year 2013 from the respective nearest local meteorological stations: Zona Universitària in Barcelona (41.379 °N, 2.105 °E), Keele University in Stoke-on-Trent (52.999 °N, 2.268 °W), Hupsel in Doetinchem (52.067 °N, 6.500 °E), and Kaunas station in Kaunas (54.883 °N, 23.835 °E). Apparent temperature was calculated from temperature and relative humidity (Ballester, Robine, Herrmann, & Rodo, 2011; Sensirion, 2006). Centering was conducted on apparent temperature for each city to reduce correlations and possible collinearity issues in the quadratic term.

Exposure: Surrounding greenness

Contact with surrounding greenness was measured through hourly average Normalized Difference Vegetation Index (NDVI). NDVI captures the level of vegetation or greenness on a scale with minimum/maximum values of -1 and +1. Cloud-free Landsat 8 satellite images (resolution 30mx30m) during the study period were used to create NDVI maps for each city area. The maps were then used to assign NDVI values for every GPS point location obtained from Calfit smartphone data of the participants, which were then summarized per hour to obtain the total average hourly NDVI. The variable was further categorized into city-specific NDVI quartiles.

Covariates: Precision variables

For the other meteorological covariates obtained from the meteorological records, rainfall was transformed into a binary variable (zero; non-zero rainfall), while windspeed remained as a continuous variable. Daily dawn and dusk times were obtained for each city from the 'suncalc' R package (Thieurmel & Elmarhraoui, 2019), and these times were rounded to the nearest hour to create a binary variable of sky darkness (no; yes).

Residential surrounding greenness was measured as mean residential NDVI within 300m circular buffer, which is commonly used in international studies to assess the natural greenness participants would have been exposed to near their home (Kruize et al., 2020).

To control for time trend and seasonality, month (reference: September), day of week (ref: Monday), hour of day (ref: 1 pm of each time zone), and public holiday were included in the analyses. The following sociodemographic variables were linked from the PHENOTYPE project survey data of each participant and also included as potential precision variables: gender (ref: male), age (ref: 26-45; 18-25; 46-65; 66-75), education level (ref: university degree or higher; secondary school/ education (up to 18 years); no education or primary school only), chronic disease status (ref: no; yes), and dog ownership (ref: no; yes), employment (ref: employed; unemployed or retired), having children under age 12 (no; yes), meeting physical activity guidelines (no; yes as estimated in the survey questionnaire), and perceived income (enough; comfortable; not enough).

Statistical analysis

We conducted a linear mixed model for each city separately, to assess the effects of apparent temperature and surrounding greenness on physical activity (hourly average MET), controlling for other meteorological, time-related, and demographic variables. A random effect of participant in the intercept was included to consider within-participant correlation. As the outcome variable average MET per hour was highly right-skewed, it was log transformed to be properly modelled. A preliminary model used Generalized Additive Models (GAMs) to visualize the relationship between temperature and physical activity at different quartiles of NDVI while accounting for the significance of terms in a linear model. Then, a main model was fitted with an interaction term between apparent temperature and surrounding greenness, using a linear or quadratic apparent temperature term in each NDVI quartile as appropriate. The interaction term allowed the association of temperature and physical activity to vary across the different greenness levels.

We tested whether the interaction between temperature and greenness was different across cities. Using a single model and data from all cities, the joint effect of temperature and greenness was allowed to be different across cities by including interaction terms of city. Then, using ANOVA, such a model was compared with the same model but excluding the interactions terms involving city (i.e. null hypothesis of equal pattern of the effect in all cities). Statistical significance level was set at 0.05. All analyses were conducted using R version 3.5.2 (R Core Team, 2018), including the "lme4" package.

Because the outcome was log transformed, model results were interpreted in terms of the median or, equivalently, the geometric mean of the average MET per hour. Specifically, a c unit increase in the covariate of interest is associated to a percentage change in the median of the outcome $\Delta M\% =$

$100(e^{\beta c} - 1)\%$, where β is the coefficient of interest in the model (Barrera-Gómez & Basagaña, 2015). For binary variables, *c = 1*, whereas for continuous variables *c* was set at the interquartile difference. To characterize the relationships under the model with quadratic temperature and interaction effects, two measures were computed. The optimal temperature for the quadratic effect was derived as $T_o = -(\beta_1 + \gamma_1) / (2(\beta_2 + \gamma_2))$, where β_1 and β_2 are the coefficients for the linear and quadratic terms for temperature, respectively, and γ_1 and γ_2 are the coefficients for the corresponding interaction terms with greenness variable. As a measure of the effect adjusted by precision variables included in the model, the percentage change (%) in the MET median associated with a departure of +/- T degrees from the optimal temperature was ΔM% derived as $= 100(e^{(\beta 2 + \gamma 2)T^{\wedge}2} - 1)\%$. In the case of non-significant quadratic effect of temperature, $\beta_2 = 0$ for ΔM%, marking the percentage change in MET median associated with T degrees increase in apparent temperature. 95% confidence intervals were computed using 100,000 Monte Carlo simulations in the case of T_o. In the case of no interactions (i.e. assuming that T_o is independent of greenness), $\gamma_1 = \gamma_2 = 0$ in previous formulas for T_o and ΔM%.

Sensitivity analyses

Sensitivity analyses were conducted to assess the following effects on the main model: (1) other potential modifiers of the association between hourly apparent temperature and physical activity, (2) the removal of month from the main model, (3) the effect of distance from the weather stations, and (4) the effect of transportation options. Additional sensitivity models assessed (5) the effect of percentile apparent temperature, (6) the effect of a separate greenspace indicator: contact with greenspace, and (7) the effect of employment on the physical activity patterns, via stratification. More information can be found in Appendix B.

Results

Descriptive statistics

The PHENOTYPE smartphone data had an overall of 31,788 valid hourly observations between May and December 2013 from 352 participants who were included in the final analysis (Barcelona: n = 95, 87.2% of participants; Stoke-on-Trent: n = 79, 79.8%; Doetinchem: n = 94, 84.7%; Kaunas: n = 84, 75.0%). A comparison was conducted between the included and excluded participants of the final analysis (Appendix A, Table A1). Excluded participants had lower education in Barcelona, were more likely to meet active guidelines in Stoke-on-Trent, were more likely to self-report poorer health and have chronic disease in Doetinchem. The demographic results in Kaunas were comparable between excluded and included participants.

Table 1 displays the summary statistics, while Table 2 show the participant demographics of the study (additional information can be seen in Appendix A, Table A2). Average MET per hour was practically invariant across the four cities (mean: Barcelona 2.04; Stoke-on-Trent 1.97; Doetinchem 1.98; and Kaunas 2.02). Apparent temperature had similar distributions for Stoke-on-Trent (mean 10.0°C, SD 6.3), Doetinchem (12.4°C, SD 7.2) and Kaunas (12.4°C, SD 7.5), while Barcelona had a higher and narrower range of temperatures (23.2°C, SD 4.0). Rainfall was less prevalent in Barcelona (2.8% of the study period) compared with the other three cities (10.3-15.8%), while windspeeds averaged 2.3 m/s to 3.1 m/s across the four cities. Sky darkness was more prevalent in in Stoke-on-Trent (26.5% of hours) and Doetinchem (23.7%) compared with Barcelona (17.9%) and Kaunas (18.7%).

For all cities, the correlation between apparent temperature and surrounding greenness was low ($r \leq 0.1$). The median of hourly average NDVI was the highest in Doetinchem (0.5; IQR 0.4, 0.6), followed by Kaunas (0.5; IQR 0.4, 0.5), Stoke-on-Trent (0.4; IQR 0.3, 0.5) and lowest in Barcelona (0.2; IQR 0.2, 0.3) (see Appendix A, Figure A1). Average residential NDVI was lowest in Barcelona (mean = 0.2) compared with the other cities (ranging from 0.5 to 0.6).

Table 1. Summary findings

Variables	Barcelona, SP	Stoke-on-Trent, UK	Doetinchem, NL	Kaunas, LI	Chi-square test, p-value
Observations (Total = 31788)	8978	6769	8894	7147	
Physical Activity					
Average hourly MET, mean (SD)	2.04 (0.80)	1.97 (0.80)	1.98 (0.91)	2.02 (0.74)	<0.001
Meteorological					
Station name (elevation m)	Zona Universitària (79 m)	Keele University (179 m)	Hupsel (30 m)	Kaunas (77 m)	
Apparent temperature, mean (SD) C°	23.23 (4.00)	10.03 (6.27)	12.42 (7.16)	12.43 (7.46)	<0.001
Rainfall cases, non-zero (%)	253 (2.80)	842 (12.40)	1407 (15.80)	733 (10.30)	<0.001
Non-zero rainfall, mean (SD) mm	1.13 (2.73)	0.88 (1.25)	0.80 (1.28)	1.42 (2.35)	<0.001
Windspeed, mean (SD) m/s	2.29 (1.12)	3.00 (1.52)	3.13 (1.82)	3.04 (1.64)	<0.001
Sky darkness, hours (%)	1608 (17.90)	1791 (26.50)	2108 (23.70)	1338 (18.70)	<0.001
Surrounding Greenness					
NDVI Quartiles, city-specific					<0.001
Quartile 1 Lowest	[-0.06, 0.15)	[0.05, 0.32)	[0.01, 0.38)	[0.03, 0.37)	
Quartile 2	[0.15, 0.20)	[0.32, 0.41)	[0.38, 0.47)	[0.37, 0.45)	
Quartile 3	[0.20, 0.26)	[0.41, 0.49)	[0.47, 0.56)	[0.45, 0.51)	
Quartile 4 Highest	[0.26, 0.81]	[0.49, 0.79]	[0.56, 0.83]	[0.51, 0.77]	
Residential NDVI within 300m, mean (SD)	0.21 (0.09)	0.49 (0.09)	0.56 (0.10)	0.54 (0.07)	<0.001

Table 2. Participant demographics

Variables	Category	Barcelona, SP	Stoke-on-Trent, UK	Doetinchem, NL	Kaunas, LI	Chi-square test, p-value
N of Participants		95	79	94	84	
Gender	Female (%)	48 (50.5)	45 (57.0)	53 (56.4)	43 (51.2)	0.751
Age (%)						<0.001
	18-25	16 (16.8)	8 (10.1)	0 (0.0)	12 (14.3)	
	26-45 (ref)	40 (42.1)	34 (43.0)	18 (19.1)	13 (15.5)	
	46-65	33 (34.7)	27 (34.2)	55 (58.5)	50 (59.5)	
	66-75	6 (6.3)	10 (12.7)	21 (22.3)	9 (10.7)	
Education (%)						<0.001
	High (ref)	55 (57.9)	37 (46.8)	45 (47.9)	65 (77.4)	
	Medium	31 (32.6)	41 (51.9)	49 (52.1)	18 (21.4)	
	Low	9 (9.5)	1 (1.3)	0 (0.0)	1 (1.2)	
Dog ownership	Yes (%)	22 (23.2)	28 (35.4)	21 (22.3)	52 (61.9)	<0.001
Chronic disease	Yes (%)	24 (25.3)	21 (26.6)	36 (38.3)	32 (38.1)	0.103

Preliminary model

The preliminary GAM models demonstrated a curvilinear relationship between apparent temperature and physical activity in NDVI quartile 4 of Stoke-on-Trent and Doetinchem, while other quartiles and other cities had linear relationships. A quadratic term was selected for Quartile 4 for the two cities, whereas linear terms were used in the other quartiles of each city.

Main model

Surrounding greenness levels significantly interacted with apparent temperature in the linear mixed model of each city (see Figure 1 and Table 3). While physical activity was mostly found independent of temperature at the lowest NDVI level, the relationship was significantly positive or curvilinear at higher NDVI levels. When comparing between cities, the hypothesis of equal pattern of the joint effect of apparent temperature and NDVI on MET was rejected.

In Stoke-on-Trent (n = 6769) and Doetinchem (n=8894), the quadratic effect of apparent temperature was significant at the highest NDVI Quartile 4, with downward parabolic effects. For Stoke-on-Trent, the estimate of optimal temperature at NDVI Quartile 4 was 15.2°C (95%CI: 11.2°C, 24.9°C), with a -4.1% change in median MET (95% CI: -7.0%, -1.1%) at +-10°C departure from optimal temperature. For Doetinchem, the optimal temperature at NDVI Quartile 4 was 14.6°C (95%CI: 11.7°C, 17.5°C) and associated with a -4.1% change in median MET (95% CI: -5.9%, -2.3%) for +-10°C departure from optimal temperature.

For the linear effects, in Barcelona (n = 8978) a 10°C increase in temperature was found associated with 4.0% increase in median MET in NDVI Quartile 2 (95% CI: 0.1%, 8.1%). In Stoke-on-Trent, a significant positive linear association was found for NDVI Quartile 3, with 5.5% increase in median MET (95% CI: 1.9% 9.2%). In Doetinchem, a significant negative linear association was found for NDVI Quartile 1, with -3.7% change in median MET (95% CI: -5.8%, -1.6%). In Kaunas (n = 7147), a 10°C increase in temperature was found associated with 4.3% (95% CI: 1.4%, 7.3%), 3.1% (95% CI: 0.2%, 6.0%), and 4.6% (95% CI: 1.7%, 7.7%) increase in median MET for Quartiles 2, 3, and 4, respectively.

Among the meteorological covariates, rainfall (-2.8%, 95% CI: -4.9%, -0.7%) and a 2.3 m/s increase of windspeed (-1.4%, 95% CI: -2.4%, -0.3%) was negatively associated with average MET in Kaunas (see Appendix A, Table A3). Sky darkness was negatively associated with average MET in Stoke-on-Trent (-4.7%, 95% CI: -7.1%, -2.3%). The model also adjusted for residential NDVI of 300 m buffer, month, day of week, hour of day, public holiday, gender, age, education, chronic disease, dog ownership, and participant ID as random effect. Other demographical variables, such as having children under age 12 (no; yes), employment (ref: employed; unemployed or retired), meeting physical activity guidelines (no; yes as estimated in the survey questionnaire), and perceived income (enough; comfortable; not enough) were considered as potential precision variables but not found to improve the model.

Figure 1. Joint effects of apparent temperature and NDVI on median MET, by city

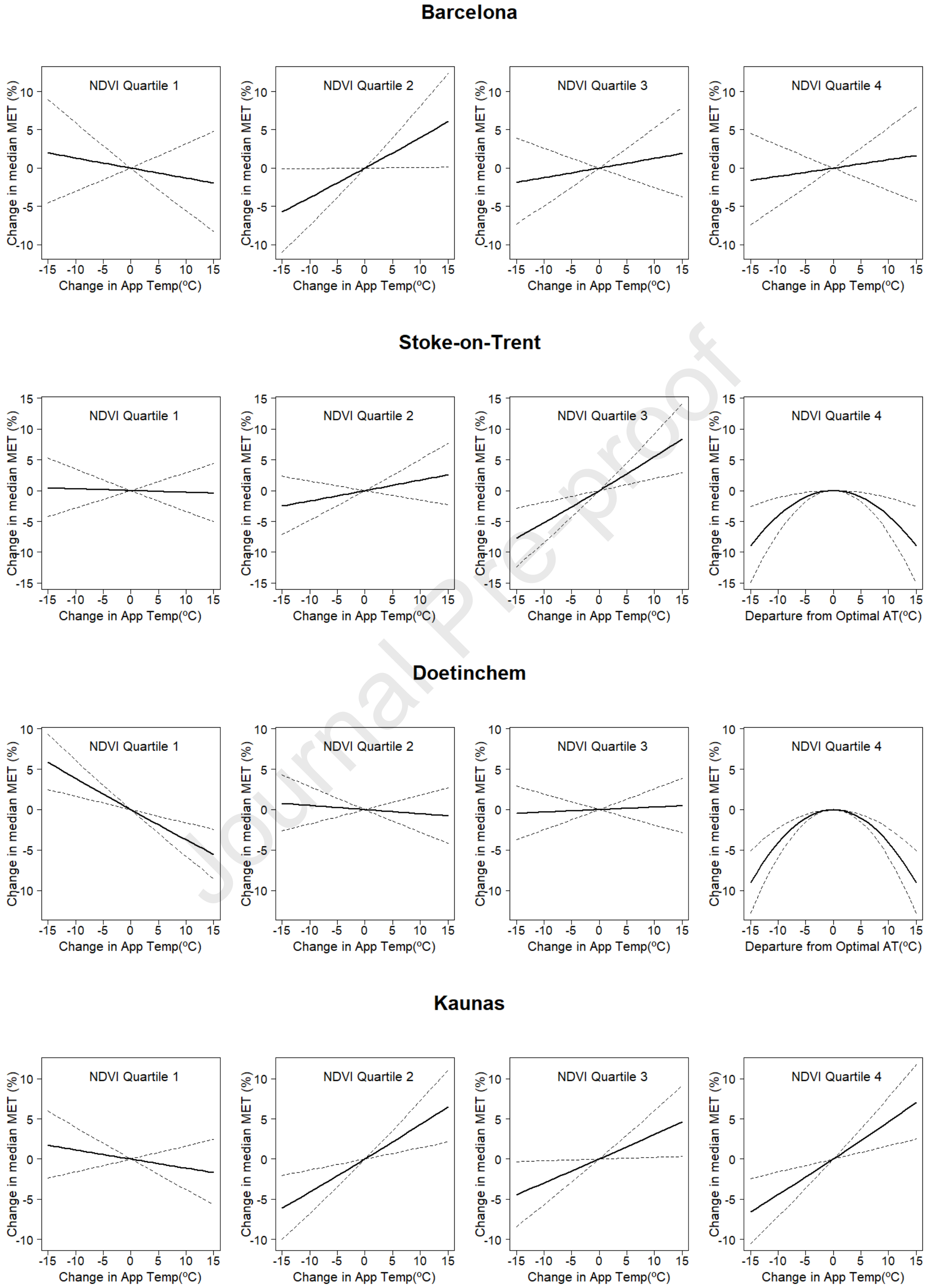

Figure 1 a) Barcelona, b) Stoke-on-Trent, c) Doetinchem and d) Kaunas

Table 3. Joint effects of apparent temperature and NDVI on median MET, by city

City	NDVI Quartile	10°C change in median of MET (%)	95% CI of Change	Sig. (p<0.05)
Barcelona				
	Q1	-1.30	-5.57, 3.16	
	Q2	4.00	0.08, 8.08	*
	Q3	1.27	-2.53, 5.21	
	Q4	1.10	-2.91, 5.27	
Stoke-on-Trent				
	Q1	-0.28	-3.39, 2.93	
	Q2	1.71	-1.53, 5.06	
	Q3	5.51	1.94, 9.20	*
	Q4 (Quadratic)†	-4.08	-6.92, -1.14	*
Doetinchem				
	Q1	-3.72	-5.77, -1.63	*
	Q2	-0.51	-2.77, 1.80	
	Q3	0.31	-1.90, 2.57	
	Q4 (Quadratic)‡	-4.12	-5.90, -2.30	*
Kaunas				
	Q1	-1.13	-3.80, 1.62	
	Q2	4.29	1.40, 7.26	*
	Q3	3.07	0.21, 6.02	*
	Q4	4.63	1.65, 7.69	*

†*Optimal temperature for Quartile 4 in Stoke-on-Trent = 15.17°C, 95% CI: 11.23°C, 24.88°C*
‡*Optimal temperature for Quartile 4 in Doetinchem = 14.64°C, 95% CI: 11.71°C, 17.46°C*
*$Footnote: Barcelona and Kaunas are reporting a linear effect in temperature; Stoke-on-Trent and Doetinchem are reporting linear effects except for Quartile 4, where a quadratic effect was used and the table reports a +/- 10°C departure from optimal temperature. Models adjusted for precipitation, windspeed, sky darkness, residential NDVI of 300 m buffer, month, day of week, hour of day, public holiday, gender, age, education, chronic disease, dog ownership, and participant ID (random effect); * p <0.05*

Sensitivity analyses

We conducted several sensitivity analyses using different temperature indicators and other adjustments, and the results were largely consistent with the primary findings (see Appendix B). When adjusting for other potential modifiers between apparent temperature and physical activity, the interaction association in Stoke-on-Trent and Doetinchem remained robust, but was no longer significant in Barcelona and Kaunas when including the AM/PM and/or age interaction. The association in Barcelona furthermore was non-significant when adjusted for car access or removing the month covariate. Distance from the weather station did not affect the interaction results, despite being statistically significant itself. Physical activity was found to peak at 66.2nd percentile temperature for Doetinchem, whereas percentile temperature no longer had a significant quadratic effect in Stoke-on-Trent. Both Stoke-on-Trent and Doetinchem found significant downward parabolic effects when assessing 100% contact with greenspace per hour (compared with 0% of contact with greenspace). When stratified by employment, the interaction effect was found among non-employed participants in Kaunas, while the other cities were influenced by employed participants.

Discussion

In this first multi-city comparative study, we found significant interaction effects between apparent temperature and surrounding greenness in the effect on physical activity among residents of four European cities. The pattern of such interaction was significantly different between the cities. For Stoke-on-Trent and Doetinchem, downward parabolic effects of apparent temperature were found for the highest level of surrounding greenness, which peaked at optimal apparent temperatures: 15.2°C and 14.6°C, respectively. A negative linear association was found at the lowest greenness level in Doetinchem, while higher greenness levels found positive linear effects in Barcelona, Stoke-on-Trent, and Kaunas. The effect in Barcelona was less robust in the sensitivity analyses.

To the best of our knowledge, the interaction effect between temperature and surrounding greenness on physical activity has not been discussed in previous literature. Previous studies assessing the temperature-physical activity relationship among elderly populations found positive associations in the UK (Alahmari et al., 2015; Sartini et al., 2017; Wu et al., 2017) and a non-significant association in Barcelona (Delclos-Alio et al., 2019). In the Netherlands, negative temperature associations have often been found in year-round studies (Böcker, Priya Uteng, Liu, & Dijst, 2019; Boutou et al., 2019; Cepeda et al., 2018; Fishman, Bocker, & Helbich, 2015), while a study found positive associations in springtime (Prins & van Lenthe, 2015). Although no studies have been conducted specifically in Lithuania or Eastern Europe, a study on self-reported physical activity in all European Union countries found that annual temperatures were positively associated with vigorous-intensity physical activity (Laverty, Thompson, Cetateanu, & Filippidis, 2018). Our findings suggest that when real-time spatial variation and greenness of participant locations is considered, the temperature effect on participant physical activity may become more well-defined. Climatic differences and locations may have influenced our results, as Stoke-on-Trent and Doetinchem seem to be more affected by high temperatures, resulting in a curvilinear association. According to the Köppen-Geiger climate classification, Stoke-on-Trent and Doetinchem have a moderate temperate climate (type Cfb), while Kaunas has a continental climate (Dfb) and Barcelona has a Mediterranean climate (Csa) (Peel, Finlayson, & McMahon, 2007). Our findings may also be aligned with the heterogeneity effect found in multi-location temperature-mortality studies, which generally found lower heat-related mortality thresholds in cities with cooler climates (Ballester et al., 2011; Hajat & Kosatky, 2010; McMichael et al., 2008; Medina-Ramon & Schwartz, 2007; Michelozzi et al., 2006), likely attributed to long-term acclimatisation and differing adaptation responses (Gasparrini et al., 2015).

However, our study also found that despite the similar meteorological conditions with other cities and a potential curvilinear temperature-physical activity pattern in the preliminary model, Kaunas found a positive linear temperature association in the interaction model instead of quadratic effects. This may be influenced by variations in outdoor spaces and physical activity culture between these cities. A larger proportion of woodland/forests and civic spaces was found for Kaunas compared to the other cities (Smith et al., 2017). More tree cover may reduce people's exposure to temperatures compared to open-air settings (Ziter, Pedersen, Kucharik, & Turner, 2019) and subsequently reduce temperature's effect on physical activity. Civic spaces may also provide large outdoor areas without much greenness, thus resulting in Kaunas' temperature associations in lower greenness levels. Physical activity in Kaunas may also differ culturally compared with the other cities, as the sensitivity analysis found non-employed participants to be more influential in the temperature-physical activity associations, as opposed to the employed participants in other cities. A recent study conducted in

Kaunas also found non-employed to be more likely to engage in self-reported physical activity compared to employed individuals (Dedele, Miskinyte, Andrusaityte, & Nemaniute-Guziene, 2019).

Overall, we found that higher levels of surrounding greenness significantly affects the relationship between temperature and physical activity, particularly at the highest level only for Stoke-on-Trent and Doetinchem. Previous studies on residential greenspace and self-reported physical activity have similarly found significant effects in the highest levels of greenness only (Astell-Burt, Feng, & Kolt, 2014; Lachowycz & Jones, 2014; Mytton et al., 2012). As NDVI measures any greenery including those found on private properties and streets (James, Banay, Hart, & Laden, 2015; Klompmaker et al., 2018), its relationship to physical activity may be affected by the location's perceived safety, accessibility, and relevance to the desired physical activity (Lee, Jordan, & Horsley, 2015; Ou et al., 2016). The effect of surrounding greenness levels may have been further confounded by indoor and outdoor locations. In Doetinchem, the lowest greenness level was associated with more physical activity in low temperatures, possibly supported by the growth of winter indoor sport options found in the Netherlands (van Bottenburg & Salome, 2010). Other cities found that physical activity was independent of temperature at the lowest greenness level. Our sensitivity analysis also consistently found temperature-physical activity associations for 100% contact with greenspace in Stoke-on-Trent, Doetinchem, and Kaunas. Physical activity conducted in higher surrounding greenness may have more likely been outdoor locations. On the other hand, temperature-physical activity associations were found at the second level of surrounding greenness but not at highest greenness levels for Barcelona. As the only coastal city in this analysis, Barcelona had a much lower distribution of surrounding greenness compared to the other three cities (Appendix A, Figure A1), and possibly a large availability of coastal areas or blue spaces for participants to engage with (Gascon et al., 2017). Future studies should further characterize the usage of locations associated with different greenness levels and examine the temperature-physical activity association for indoor and outdoor spaces.

Strengths

As far as we are aware, this is the first multi-city comparative study to examine the synergetic effect of apparent temperature and surrounding greenness on objectively measured physical activity at the hourly level. Four different cities with different cultures, climates, and greenspace characteristics were studied and all applied similar sampling protocols and exposure assessment methodology, which enabled us to draw conclusions on the variation between cities. Objective GPS and physical activity data were concurrently collected through the smartphone app, which reduced the effects of recall and self-report bias, and any timing mismatch between the participant's physical activity levels and surrounding greenness level. A broad range of participant characteristics were considered in the analyses because the smartphone data was linked to additional survey data. The analyses were controlled for time-related variables commonly used in other climate-health analyses.

Limitations

Our study was unable to determine whether the participants were located indoors or outdoors, which is highly relevant to their exposures of both meteorological conditions and surrounding greenness. The accelerometer physical activity data could not account for cycling or aquatic activities. Additionally, our analysis was unable to differentiate between different domains of physical activity (leisure, transport, occupational etc.) which may affect patterns of greenspace usage. Personal exposure to temperature and other meteorological conditions could not be detected, since meteorological data was only available from one meteorological station per city, which was sometimes located as far as 27 km away from the city center (Doetinchem). Study participants were also not limited to city boundaries during their study period. However, our sensitivity analysis of the distance to weather station demonstrated that results remained robust even after its inclusion.

Future directions

Future studies should seek to disaggregate the effects for indoor and outdoor physical activity. Characterization of participant locations can facilitate understanding about the physical activity and greenness levels connected with each place. Further information about activities conducted in each location may also be helpful. For example, park settings are venues that not only facilitate moderate-to vigorous physical activity, but also sedentary activities such as scenery viewing and picnics (Bedimo-Rung et al., 2005). On the other hand, certain indoor facilities (gyms, shopping malls etc.) may promote physical activity. Future studies can also examine the effect of temperature on physical activity at more extreme temperatures. Larger sample populations and longer study durations could provide more robust estimates. Other environmental factors such as air pollution, walkability, or built environmental variables could also be analysed to understand their impact on the temperature-physical activity relationship.

Conclusion and Implications

Our study found a synergetic effect of apparent temperature and surrounding greenness on objectively measured physical activity in four European cities. Temperature was associated with physical activity at higher levels of surrounding greenness for all cities, however this effect varied between cities. While physical activity increased with warmer temperatures at higher surrounding greenness levels for Barcelona and Kaunas, for Stoke-on-Trent and Doetinchem the association follow an expected downward parabolic with the highest level of physical activity at 15°C apparent temperature. Because a consistent methodology was employed across the cities, our findings suggest that climate heterogeneity and city-specific spatial variation in outdoor spaces, such as coastal, woodland, and civic spaces, may have contributed to the observed findings. Low greenness levels in particular may experience residual confounding such as indoor locations. Disaggregating between indoor and outdoor spaces in future studies may more clearly demonstrate the benefits of greenspace to mitigate the effect of heat stress on physical activity.

With climate change, shifting temperature ranges may increasingly affect the physical activity conducted in greener areas. Cities should make urban planning decisions to support physical activity in higher temperatures. The interaction effect between surrounding greenness and temperature on physical activity suggests that future physical activity studies should consider these two environmental factors concurrently.

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Highlights:

- Temperature-greenness interaction on physical activity has been rarely assessed
- Multi-city comparison was conducted across four European cities
- Varying temperature effect on physical activity found at higher greenness levels
- Curvilinear temp. effects found in highest greenness levels of temperate cities
- Urban planning should support physical activity in higher temperatures

Conflict of interest statement:

The authors declare they have no conflict of interest.