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Weather conditions as cross-sectional moderators of the associations between the physical environment and walking behavior in the Netherlands

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ABSTRACT

There is increasing evidence that people's walking behavior is linked to the physical environment to which they are exposed. However, whether this association is moderated through local weather conditions is largely unclear. Based on Dutch National Travel Survey data, we applied latent class analysis to determine co-occurring weather conditions and used Tobit regression model to examine whether and, if so, to what extent weather conditions moderated the associations between the physical environment and different walking patterns on weekdays and weekends. We found that in warm and dry weather conditions on weekdays, people living nearby bus stops were more likely to walk to public transit. However, the same correlation was not found on weekends. In inclement weather (i.e., warm, very windy, rainy), people were less likely to walk to public transit. In warm, windy, and slightly rainy conditions, address density was negatively related to recreational walking. On weekends, people were more likely to walk for leisure outside the residential neighborhood (e.g., large open spaces, parks) in warm and dry conditions. Our results indicate that the combined impact of weather and the physical environment needs to be taken into account in walking infrastructure planning.

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Active travel behavior; built environment; the Netherlands; walking; weather

1. Introduction

Walking as an everyday activity contributes to individuals' daily physical activity (Van Cauwenberg et al., 2018; Wang et al., 2016). Not only person-level characteristics but also the conditions of the physical environment (i.e., the natural and built environmental settings) to which people are exposed seem to play a role in walking engagement (Lam et al., 2022; Sallis et al., 2006), which are probably stratified into transport-related and recreational walking.

Reviews suggest, for example, that transport-related walking is positively associated with population density, and street network configuration, and land-use mix, while recreational walking seems to be positively related to the esthetic design of the surroundings and the share of green space and blue space (Barnett et al., 2017; Feuillet et al., 2016). These findings indicate that the relationships between the physical environmental attributes and walking behavior may vary across different walking trips.

Weather conditions also seem to affected active travel (i.e., walking and/or cycling) (Böcker et al., 2019; Delclòs-Alió et al., 2019); whereas extreme weather appears to be barriers to traveling actively (Liu et al., 2014). In the Dutch context, for example, Sabir (2011) found that adverse weather (e.g., heavy rain, strong wind) correlates with visiting closer destinations for shopping and leisure activities. Böcker and Thorsson (2014) showed that, wind speed and precipitation were inversely related to cycling behavior, while Heinen et al. (2011) found that the quantity and duration of rain are inversely associated with cycling. Helbich et al. (2014) found that temperature played a minor role in Rotterdam's inner city compared to more open and remote areas, while Durand et al. (2017) found no associations. This is probably because that the same cold temperature in the city is more bearable than in the country due to the urban heat island (UHI) (Steeneveld et al., 2011). As such, decisionmakers and urban planners may adjust their policies to accommodate induced travel demand in different weather conditions (Böcker et al., 2013).

Despite the mounting evidence on how the physical environment affects walking, several limitations can be identified. First, the majority of studies disregard weather conditions or operationalize them as a single covariate (Liu et al., 2017; Wang et al., 2021). However, each weather condition is likely to have different effects when incorporated individually in transport models, while in reality weather conditions co-occur and are thus correlated (Clifton et al., 2011; Phung & Rose, 2007).

Second, few studies have a focus on the impacts of the physical environmental attributes and weather conditions on walking behavior simultaneously. The physical environment is thought to mitigate or enhance the influence of weather

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(Durand et al., 2017). Some places (e.g., larger green spaces) are perceived as more walkable in pleasant weather conditions (Ball et al., 2008). Further, people possibly choose different travel modes in different weather conditions, even though they live in a similar physical environment. The associations between the physical environment and walking are plausibly moderated by different weather conditions. For example, people perceive a neighborhood as more walkable in good weather, while low temperatures likely increase their private car use. However, the relationships between the physical environment, weather conditions, and walking behavior may be more complex than previously assumed. It is thus necessary to examine how associations between physical environmental attributes and walking behavior possibly vary with different weather conditions.

Third, peoples' reactions to different weather conditions also vary across walking types. Temperature, for example, was found to be rather irrelevant for commuting trips compared to non-commuting trips (Liu et al., 2015). Some walking types (e.g., transit-related walking) seem to be less influenced by inclement weather conditions than others (e.g., leisure walking) (Saneinejad et al., 2012). Besides, the time of the walking trip (e.g., weekdays vs. weekends) also plays a role. For example, people (particularly commuters) appear to be less sensitive to weather conditions on weekdays due to non-discretionary travel than on weekends (Liu et al., 2015, 2017). However, it remains unclear how the physical environmental characteristics shape different walking types (purpose or day of the week) in different weather conditions. Such interaction effects should be examined further in a structured way, as this may offer insights into the possible moderation effects of weather conditions on the relationships between the physical environmental attributes and different walking patterns.

Taken together, given these three research gaps, it is imperative to better understand how weather conditions moderate physical environment-walking behavior relationships for designing weather-resilient walking environments. To address these knowledge gaps, while building upon our previous work (Gao et al., 2020), we examined (1) whether weather conditions moderate associations between the physical environment and three walking patterns, namely non-transit related walking, transit-related walking, and recreational walking, and, if so, (2) how these moderation effects are different across weekdays and weekends. Our hypothesis was that more walkable environments diminish the negative effect of weather conditions on walking.

2. Materials and methodology

2.1. Data source

The Dutch National Travel Survey from 2010 to 2014 was pooled in this study (CBS, 2015). Recorded data included people's travel behavior (i.e., travel modes per trip stage, travel purposes, and start and end time of each trip) on the survey day as well as socioeconomic characteristics. Respondent's residential location was allocated to a 4-digit number at the postal code level, which enabled us to enrich the travel survey data with characteristics of the residential environment. Eligible for study inclusion were respondents aged ≥18 years ($N = 129{,}142$). We excluded respondents with missing data of socioeconomic characteristics ($N = 25{,}446$) and those without postal code information ($N = 11{,}398$). In total, our sample comprised 92,298 respondents. About 79.8% of the trips were recorded on weekdays and 20.2% on weekends.

2.2. Variables

2.2.1. Walking duration as the outcome variable

The walking duration was defined as the number of minutes a respondent walked for each type of walking per day. Three patterns of walking durations were classified by trip purposes (i.e., non-transit-related, transit-related, and recreational walking). Non-transit-related walking represents walking to and from work, stores, or services. Transit-related walking refers to walking trips to public transit. Recreational walking refers to walking for pleasure (e.g., walking the dog).

2.2.2. Weather conditions as moderators

The moderators used in this study were the weather conditions on the survey day. The daily weather data was accessed from the Royal Netherlands Meteorological Institute (KNMI, 2017). Three typically used weather-related variables were taken from thirty-three weather stations located throughout the Netherlands: (a) daily average wind speed (in m/s), (b) daily precipitation sum (in mm), and (c) daily maximum air temperature (in °C) (Wang et al., 2021).

2.2.3. Physical environment

Characteristics describing the built environment per postal code area were selected based on the previous study (Ewing & Cervero, 2010) and were depended on data availability (CBS, 2012, 2014a, 2014b). The built environment was operationalized through the following variables: Address density (1000 addresses per km^2) was calculated as the average number of residential addresses per postal code area. Land-use diversity was measured via the Shannon entropy index based on residential, commercial, manufacturing, leisure, and public utilities (e.g., park, police office, clinic, or hospital). The index ranges from 0 to 1, where a higher index value represents a more even distribution across all kinds of land use within a residential area (Cervero & Kockelman, 1997). We also included the number of street intersections per km^2 (Kadaster, 2012), the number of bus stops within each postal code area, and the destination accessibility such as Euclidean distance to the closest train station, restaurant, and supermarket(in km). In terms of the natural environment, we considered the percentage of green space (e.g., agricultural areas, parks) and also the share of water bodies. Both variables were extracted from the 2012 Dutch land-use database, which has a spatial resolution of 25 m (Hazeu et al., 2014).

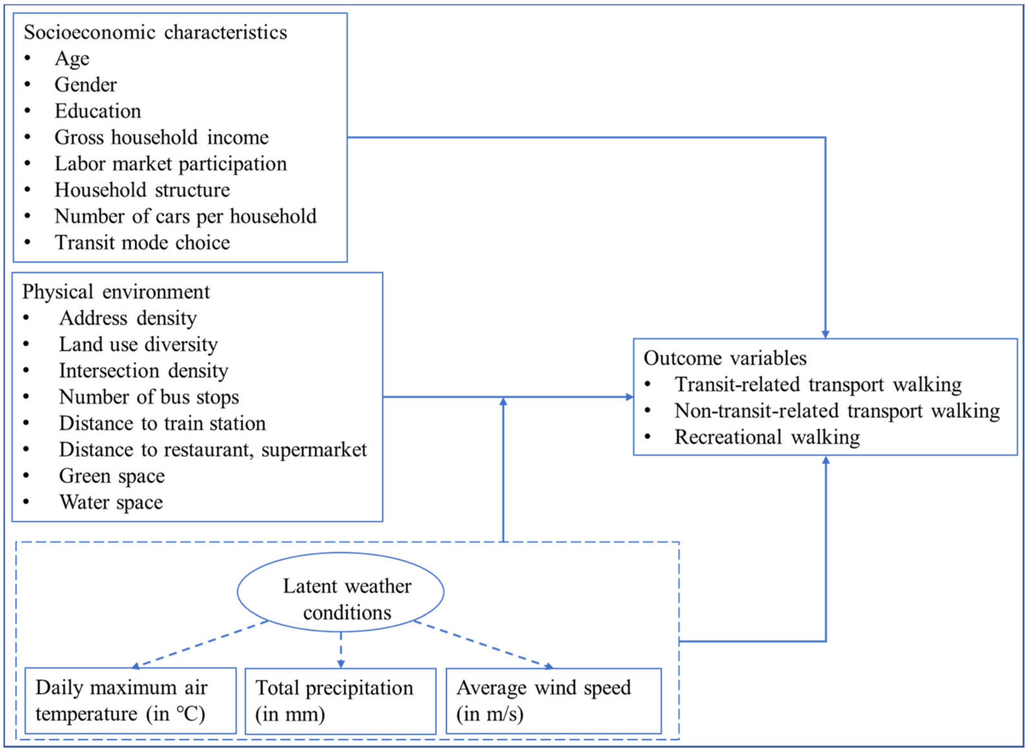

Figure 1. Conceptual model.

2.2.4. Control variables

We included the following person-level and household-level variables as control variables (Gao et al., 2020). We grouped age into 18–24, 25–34, 35–64, and ≥65 years. Gender was dichotomous. Annual household income and individual education level were divided into three levels (low, medium, and high). Social participation was classified into part-time work (12–30 h/week), work (≥30 h/week), student, unemployed, and retired. The household structure was stratified into a single-person family, couple with/without children, and single parent with children.

2.3. Statistical analyses

Descriptive statistics summarized the data. To examine multicollinearity, we computed Pearson correlation coefficients between the covariates. Correlations larger than ±0.8 have been labeled as problematic (Freedman et al., 1991).

Latent class analysis (LCA, McCutcheon, 1987) was used to determine mutually exclusive latent classes and class memberships. A latent class cannot be directly measured, but it can be derived from observed indicators, which in the present research were maximum air temperature, precipitation, and average wind speed. To obtain the most suitable number of latent classes, we constructed different models with a various number of latent classes and compare the model fits (Gerassis et al., 2019; Ton et al., 2020). We used the Bayesian information criterion (BIC) scores and log-likelihood values as fit criteria. A lower BIC score and a higher log-likelihood value indicate a better goodness-of-fit.

We then fitted Tobit regression models to assess the moderating effects of the latent weather condition classes on the physical environment–walking relationships. As the outcome variables (i.e., the duration of the different walking types) are supposed to be positive while having a substantial proportion of zeros, we deemed Tobit regressions suitable. Separate models were estimated for each walking type, stratified by weekdays and weekends. Continuous covariates were z-scored due to the varying units, and for categorical ones, the first category served as the reference category. Figure 1 shows the conceptualization of our analysis. Statistical analyses were conducted in Stata 16.

3. Results

3.1. Descriptive statistics

The walking duration across the respondents was, on average, 10.92 min/day on weekdays (standard deviation [SD] ± 30.12 and 14.95 min/day at weekends (SD ± 40.03). Among all participants, on average, more for public transit (1.23 min/day [SD ± 7.13]) on weekdays than on weekends (0.80 min/day [SD ± 7.20]). Respondents were engaged in more non-transit-related walking (5.15 vs. 4.19 min/day) and recreational walking (9.01 vs. 5.49 min/day) on weekends than on weekdays. Of the sample, on weekdays, 15.6% reported non-transit-related walking (26.85 min/day [SD ± 39.24]), 10.2% reported recreational walking (53.98 min/day [SD ± 48.86]), and 5.7% reported transit-related walking (21.68 min/day [SD ± 21.37]). On weekends, 17.3% of participants reported non-transit-related walking (29.79 min/day [SD ± 41.68]), 13.3% reported recreational walking (67.59 min/day [SD ± 68.47]), and 3.2% reported transit-related walking (24.67 min/day [SD ± 31.76]). Table 1 shows additional summary statistics for each variable.

Table 1. Descriptive statistics.

	Categories	Percentage or mean (SD)	
		Weekdays ($N = 73{,}729$)	Weekends ($N = 18{,}569$)
Dependent variables			
Overall walking duration (min)		10.90 (30.12)	14.95 (40.03)
Transit-related walking (min)		1.23 (7.13)	0.80 (7.19)
Non-transit-related walking (min)		4.19 (18.30)	5.15 (20.66)
Recreational walking (min)		5.49 (22.55)	9.01 (33.94)
Socio-demographics			
Age	18–24	6.43%	6.28%
	25–34	14.02%	14.51%
	35–64	59.21%	59.00%
	65+	20.34%	20.20%
Gender	Female	51.33%	51.28%
	Male	48.67%	48.72%
Education	Low	5.21%	5.44%
	Medium	60.38%	60.25%
	High	34.41%	34.30%
Gross household income	<20k euro	31.22%	31.32%
	20k–40k euro	58.34%	57.81%
	>40K euro	10.44%	10.87%
Labor market participation	Work (12–30 h)	17.70%	17.86%
	Work (≥30 h)	44.51%	43.58%
	Student	3.45%	3.52%
	Unemployed	11.94%	12.67%
	Retired	22.40%	22.37%
Household structure	Single-person HH	17.71%	17.46%
	Couple without children	37.77%	37.00%
	Couple with children	40.02%	40.89%
	Single parent with children	4.50%	4.65%
Number of cars per household	No car	10.51%	11.19%
	1 car	52.76%	53.12%
	≥2 cars	36.73%	35.69%
Physical environment			
Address density (1000 addresses per km^2)		1.32 (1.58)	1.49 (1.71)
Land use diversity		0.61 (0.16)	0.60 (0.16)
Crossing density (N/km^2)		104.39 (80.35)	111.28 (80.42)
Number of bus stops		17.68 (11.56)	18.19 (11.46)
Distance to a supermarket (km)		0.97 (0.80)	0.90 (0.69)
Distance to a restaurant (km)		0.91 (0.77)	0.82 (0.63)
Distance to the train station (km)		6.33 (7.94)	5.17 (5.87)
Percentage of green space (%)		55.23%	51.95%
Percentage of water bodies (%)		4.08%	4.28%
Weather conditions			
Daily max. air temperature (°C)		13.69 (7.36)	13.83 (7.43)
Daily precipitation sum (mm)		2.16 (4.65)	2.24 (4.58)
Daily average wind speed (m/s)		4.23 (2.03)	4.18 (2.04)

Table 2. Weather characteristics per latent class for weekdays and weekends.

Latent class	Weather characteristics
A	Very warm, windy, and very rainy
B	Moderately warm, very windy, and rainy
C	Warm, light winds, and dry
D	Moderately warm, windy, and light rain

3.2. Latent weather classes

We examined 1–5 latent classes, where a lower value of both the BIC and the log-likelihood indicates a better fit. Also, despite of the lowest values of the BIC and the log-likelihood, a 5-class model would not be rational, as one of the classes is less than 1% of the sample. Therefore, considering the interpretability and sample size of each class, a 4-class model was selected. The labels for each latent class were identified based on the share of different meteorological variables (Table 2).

Figure 2 compares the weather variables' means and standard deviations (SDs) across the four latent weather classes. There are distinct differences across the classes. However, the SD of daily precipitation classes B, C, and D exceeded their means. Specifically, the coefficient of variation of class C is large (i.e., SD/mean = 1.99). This suggests that these latent classes may also contribute to the variability in weather.

Figure 3 shows that on both weekdays and weekends, the largest share of walking duration, regardless of the type of walking, was during warm, light winds, and dry weather conditions (class C). In particular, people engaged in more recreational walking. People were less likely to walk in very warm, windy, and very rainy conditions (class A).

3.3. Weather classes as moderators of the physical environment–walking associations

Table 3 shows the results of the moderation analysis, on weekdays, in good weather (classes C and D), a positive correlation between the number of nearby bus stops and walking to public transit was observed. In inclement weather (i.e., warm, very windy, and rainy conditions; class B), people had a lower likelihood to walk for public transit, while the shorter distance to the nearest supermarket encouraged longer transit-

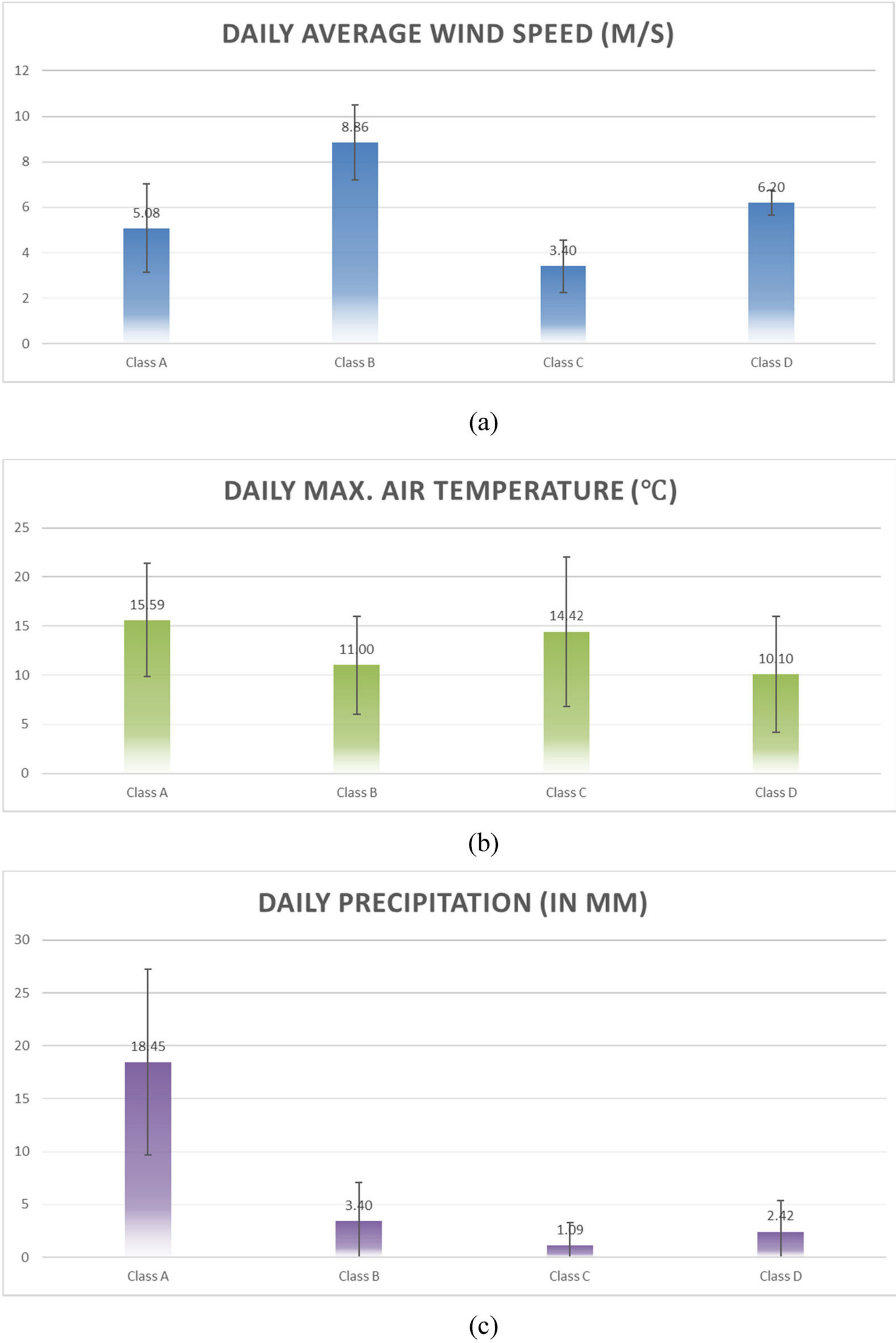

Figure 2. Weather characteristics across the latent weather classes.

related walking duration. In warm, windy, light rain conditions (class D), address density was negatively related to recreational walking. On weekends, one significant interaction appeared (Table 4). A positive association between recreational walking and distance to the closest train station was found, given warm and dry conditions (class C). No significant interactions of weather conditions on non-transit-related walking behavior were observed on weekends or weekdays.

4. Discussion

4.1. Principle findings

Our study investigated the moderating effects of weather conditions on the association between the physical environmental attributes and different patterns of walking duration and how these effects vary over weekdays and weekends. In line with previous studies (Delclòs-Alió et al., 2019; Durand

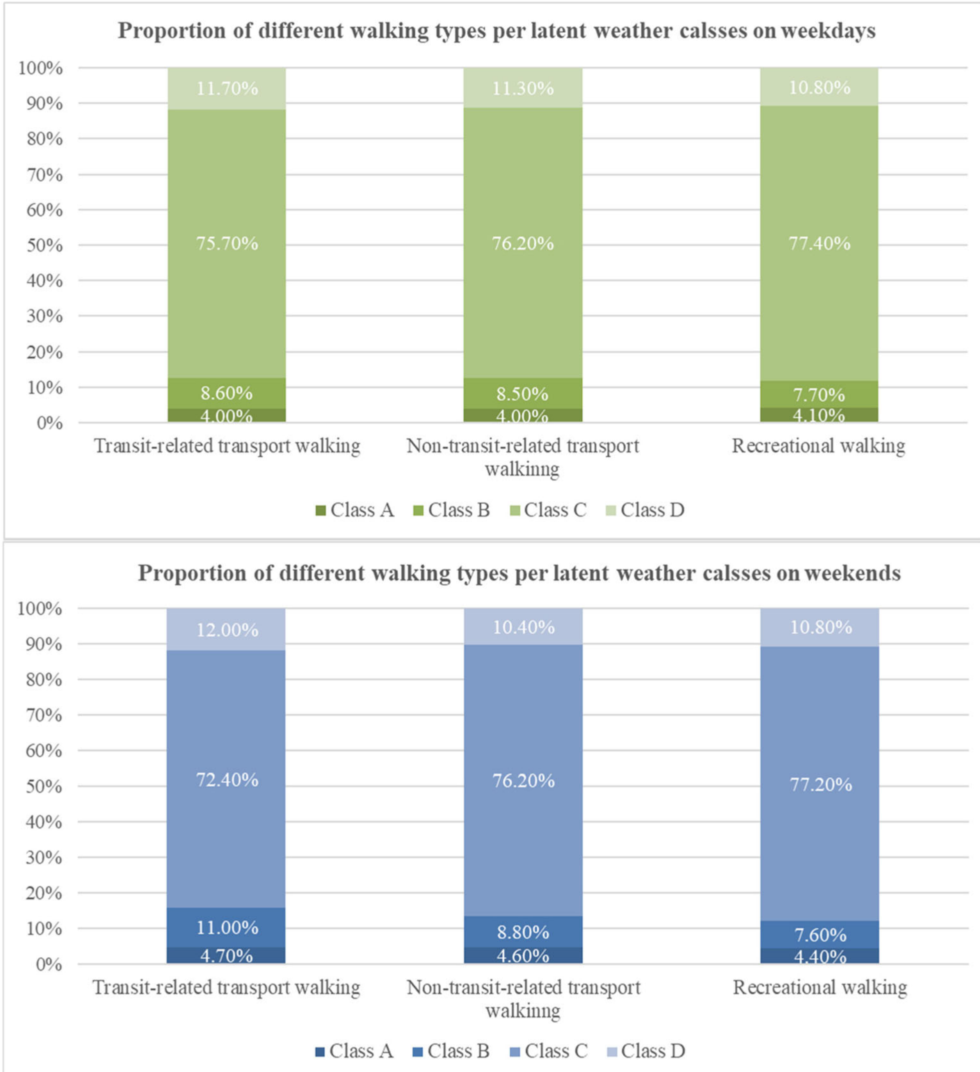

Figure 3. Proportion of different walking types per latent weather classes.

et al., 2017), our results showed that weather conditions were indeed a significant moderator.

On weekdays, people were more likely to walk to bus stops in good weather (classes C and D). Also congruent with others (Böcker et al., 2013), warmer weather and lower precipitation were positively related to daily travel behavior. On the contrary, in inclement weather (i.e., warm, very windy, and rainy conditions; class B), people were less likely to walk to public transport (bus or train), which in turn could lead to less transit use. These results suggest that heavy rain is perceived as a barrier to transit use, implying that people are more likely to switch to another travel mode (e.g., from walking/cycling to private cars). Our findings revealed that people might have different travel mode choices in different weather conditions, even though they live in the same physical environment. Regarding non-transit-related walking, in contrast to others (Liu et al., 2017; Wang et al., 2021), but confirming previous studies (Durand et al., 2017), no significant interactions between weather conditions and the physical environment were observed for non-transit-related walking; this finding was consistent for both weekdays and weekends. It seems that weather conditions are an insignificant barrier to transport-related walking. It is probably because non-transit-related walking (e.g., walking for shopping) and commuting trips are more weather resistant than other walking types. Recreational walking itself is a purpose and also a way to experience the surroundings (Hall & Ram, 2021). On weekends, people were more likely to walk for leisure outside the residential neighborhood (e.g., large open spaces, parks) in warm and dry conditions (class C). Individuals might have better access and enjoy longer leisure trips in warm weather to take train as a mode of transport. This may explain the positive relationship between distance to the closest train station and recreational walking on weekends.

Given insignificant interaction effects between weather conditions and the physical environment on non-transit-related walking, the results suggest that daily utilitarian walking (e.g., walking to the supermarket) is less sensitive to weather changes on weekdays, whereas people may engage in longer recreational walking on weekends (Gao et al., 2020). This could mean that compensation effects are at play across different types of walking when considering the role of weather conditions. These effects are different

Table 3. Moderation effects of different walking patterns on weekdays.

	Transit-related walking	S.E.	Non-transit-related walking	S.E.	Recreational walking	S.E.
The physical environment						
Address density	1.05	2.06	3.17	2.17	0.83	5.22
Land use diversity	1.21	1.94	0.90	1.81	5.53	3.70
Crossing density	1.98	2.92	−1.10	2.89	5.27	6.08
Number of bus stops	−3.56	2.02	−0.87	1.78	−4.21	3.73
Distance to train station (km)	−11.21**	3.96	−0.27	1.85	−5.28	3.69
Distance to supermarket (km)	3.04	2.83	−3.23	2.32	3.72	3.70
Distance to restaurant	−4.92	3.19	−4.42	2.30	2.63	3.51
Percentage of green space	−1.92	3.52	−4.09	3.25	7.87	6.53
Percentage of water bodies	1.15	1.64	−1.50	1.70	6.11*	3.01
Latent weather variables (ref. = class A)						
Class B	4.73	2.63	3.70	2.11	−0.59	4.32
Class C	2.99	2.26	1.27	1.76	3.97	3.56
Class D	4.13	2.53	2.72	2.01	0.33	4.09
Interaction terms (ref. = class A)						
Latent weather variables × Address density						
Class B	0.48	2.48	−0.18	2.61	−7.25	6.43
Class C	1.23	2.13	2.14	2.23	−6.65	5.40
Class D	1.53	2.38	0.98	2.50	−14.70*	6.41
Latent weather variables × Land use diversity						
Class B	1.05	2.38	0.21	2.20	−5.19	4.49
Class C	−0.65	1.99	0.12	1.86	−5.22	3.79
Class D	−2.39	2.26	−0.92	2.11	−4.76	4.30
Latent weather variables × Crossing density						
Class B	0.43	3.62	−3.91	3.61	1.16	7.65
Class C	1.16	3.01	−0.25	2.97	−5.98	6.26
Class D	1.30	3.44	0.86	3.43	2.16	7.32
Latent weather variables × Bus stops						
Class B	2.18	2.43	0.66	2.17	0.97	4.61
Class C	4.09*	2.07	1.93	1.82	2.63	3.82
Class D	4.59*	2.30	0.74	2.06	4.92	4.33
Latent weather variables × Distance to train station						
Class B	9.58*	4.22	1.35	2.11	7.59	4.19
Class C	6.01	4.02	0.48	1.91	5.66	3.79
Class D	2.40	4.40	0.03	2.14	5.66	4.21
Latent weather variables × Distance to supermarket						
Class B	−8.97**	3.74	3.07	2.72	−1.26	4.50
Class C	−2.64	2.90	0.31	2.38	−6.94	3.82
Class D	−4.70	3.37	1.09	2.69	−2.93	4.40
Latent weather variables × Distance to restaurant						
Class B	6.19	3.57	1.22	2.67	−5.28	4.27
Class C	4.70	3.26	2.09	2.36	−3.14	3.64
Class D	4.95	3.59	1.40	2.67	−3.39	4.21
Latent weather variables × Greenspace						
Class B	−0.96	4.31	−2.92	3.97	−4.97	8.14
Class C	0.73	3.62	0.21	3.34	−9.70	6.71
Class D	2.66	4.12	2.95	3.82	−6.06	7.75
Latent weather variables × Waterbody						
Class B	−1.42	2.15	3.37	2.11	−1.63	3.98
Class C	−1.71	1.69	2.39	1.74	−5.87	3.11
Class D	−2.70	2.02	0.52	2.03	−11.67**	3.88
Intercept	−49.88***	3.56	−51.01***	3.15	−203.08***	7.38

The regression models were adjusted for all the covariates given in Table 1.
*$p < 0.05$.
**$p < 0.010$.
***$p < 0.001$.

between weekdays and weekends, which also show the differing impacts of weather on transport-related walking and recreational walking. This result contrasts with Durand et al. (2017), who reported no significant associations between transport-related physical activity and weather. A possible reason for our results is that rather than examining the independent effects of weather on walking behavior, we examined the moderating effects of weather conditions on the physical environment-walking duration relationships. Moreover, physical environment-walking duration relationships are context-specific (e.g., Europe vs. North America)), so do weather conditions differ.

4.2. Limitations

Although our study was based on a large and nationally representative sample, some limitations must be emphasized. First, our latent weather classes were determined by observed daily aggregates of weather variables, which may not capture the exact weather conditions encountered during the trips. Also, the effects of weather conditions may vary significantly across seasons and locations within the Netherlands. Second, people's less accurate self-reporting of walking duration is another limitation. For example, the large share of no recorded walking duration maybe because of the misreporting of short daily walking behaviors (e.g.,

Table 4. Moderation effects of different walking patterns on weekends.

	Transit-related walking	S.E.	Non-transit-related walking	S.E.	Recreational walking	S.E.
The physical environment						
Address density	3.31	5.96	6.23	3.61	−26.64*	13.01
Land use diversity	1.51	6.79	4.95	3.54	2.87	7.93
Crossing density	12.46	9.58	−3.48	5.68	15.83	13.13
Number of bus stops	14.26**	5.35	−0.88	3.50	1.16	8.03
Distance to train station	3.68	12.44	−7.40	6.39	−31.93*	15.09
Distance to supermarket	−16.12	21.48	−2.80	5.10	13.80	10.49
Distance to restaurant	6.90	10.38	−4.32	5.04	−14.45	12.49
Percentage of green space	−2.27	12.72	−1.46	6.57	0.68	14.80
Percentage of water bodies	−0.31	6.48	0.51	3.26	−0.45	7.32
Latent weather variables (ref. = class A)						
Class B	9.73	10.92	7.77	4.40	15.80	10.12
Class C	6.10	9.29	4.14	3.66	19.05*	8.45
Class D	17.03	9.96	6.37	4.24	24.38*	9.63
Interaction terms (ref. = class A)						
Latent weather variables × Address density						
Class B	−1.89	7.15	−3.05	4.54	24.14	14.77
Class C	1.69	6.13	−0.24	3.75	21.09	13.29
Class D	−0.11	7.01	−2.90	4.50	17.10	15.26
Latent weather variables × Land use diversity						
Class B	−3.54	8.09	−3.03	4.45	1.55	10.07
Class C	−2.45	6.96	−4.39	3.65	−6.90	8.16
Class D	−4.42	7.84	−4.61	4.32	−11.87	9.51
Latent weather variables × Crossing density						
Class B	−12.76	11.31	1.99	6.91	−29.60	16.13
Class C	−15.63	9.85	2.80	5.84	−20.75	13.51
Class D	−16.85	11.24	4.23	6.78	−20.13	15.89
Latent weather variables × Bus stops						
Class B	−9.30	6.47	4.31	4.27	−2.54	10.05
Class C	−10.03	5.51	1.23	3.60	−0.71	8.25
Class D	−10.01	6.26	−2.41	4.17	−0.38	9.52
Latent weather variables × Distance to train station						
Class B	−19.03	16.44	7.09	7.17	19.09	17.00
Class C	−12.52	12.91	9.65	6.51	31.49*	15.33
Class D	−1.91	13.24	7.99	6.85	29.11	15.99
Latent weather variables × Distance to supermarket						
Class B	18.25	22.99	5.72	5.97	−9.60	12.42
Class C	14.78	21.68	0.23	5.25	−13.51	10.79
Class D	12.94	22.35	−5.95	6.37	−1.16	12.15
Latent weather variables × Distance to restaurant						
Class B	−9.37	13.83	4.47	5.82	22.28	13.97
Class C	−8.44	10.82	2.22	5.21	9.14	12.79
Class D	4.05	11.37	0.07	6.18	8.56	14.23
Latent weather variables × Greenspace						
Class B	−13.57	14.94	−8.05	7.86	−21.38	17.88
Class C	−6.51	13.04	−2.23	6.75	−2.99	15.19
Class D	−11.33	14.55	2.33	7.76	9.54	17.43
Latent weather variables × Waterbody						
Class B	−7.80	8.31	−1.12	4.08	0.30	9.27
Class C	0.25	6.61	−0.05	3.35	0.68	7.52
Class D	−1.43	7.78	−0.58	4.06	−5.83	9.44
Intercept	−92.43***	12.75	−58.43***	6.49	−247.85***	16.44

The regression models were adjusted for all covariates given in Table 1.
*$p < 0.05$.
**$p < 0.010$.
***$p < 0.001$.

mail retrieval or walking to the supermarket) (Turrell et al., 2014). Third, more fine-grained variables of the residential environment are recommended to provide more detailed insight into the way the environment shapes travel. Finally, as applicable to many studies (Bunds et al., 2019; Wang et al., 2021), it is difficult to infer a causal statement based on cross-sectional data.

5. Conclusions

Weather plays a critical role in shaping walking behaviors relating to the perceived comfort of the built environment, it is also a key element in walking infrastructure planning, but several studies fail to adequately assess it. By using a large and nationally representative sample, this study examined how weather conditions moderate the associations between the physical environment and people's walking behavior and examined how these effects are different among weekdays and weekends.

Our results reveal that although the physical environment appears to play a significant role in promoting walking, weather conditions nuance these associations. In particular, in warm and dry weather, distance to the nearest supermarket was adversely linked to transits-related walking on weekdays. On weekends, people living in an area closer to the train station were more likely to take a train on their day off for leisure walking, especially under good (i.e., warm and dry) weather conditions. No significant interactions between weather conditions and non-transit-related walking across the whole week (both weekdays and weekends) were observed. This finding suggests that utilitarian walking such as walking to the grocery store or for shopping) is less sensitive to weather changes. Our findings suggest that rather than focusing on a particular weather variable, it is important to consider weather conditions in a more integrated model structure.

Our findings have implications for (urban) planning policies. Transport planning strategies considering climate consequences for active travel may contribute to more desirable microclimate outcomes and affect people's weather exposure in outdoor urban environments. For example, on a neighborhood level, a climate-sensitive street design (e.g., via street trees) supports ventilation, provides shade, etc., while well-placed barriers provide shelter against precipitation and wind.

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