Urban form metrics for promoting walking: Street layouts and destinations

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Abstract

There is evidence that higher street connectivity and availability of destinations can support walking behavior. However, the availability of data and comparability between previous studies remains a challenge. Based on a large Canadian adult sample, this study examined the associations between street layout and walking behaviors and explored whether objectively-measured destinations may mediate these relationships. This study used data from 12,378 adults from Alberta's Tomorrow Project (ATP), a prospective cohort study conducted in Alberta, Canada. Walking behaviors were obtained by questionnaires. Street layout and destination measures were calculated objectively. Covariate-adjusted multivariate linear models estimated the associations between the space syntax street integration and duration of transport and leisure walking. The mediation effects of the availability of destinations in these associations were tested by the structural equation modelling. Street integration was significantly positively associated with transportation walking (b=0.01, 95% CI 0.00, 0.01, $p = 0.01$) (indirect effect). The availability of destinations partially mediated this association. Using the natural movement theory in space syntax, our study provides insights into using street layouts as a primary measure to (re)design the built environment to support walking.

Keywords: Science-based urban design, Built environment; Healthy urban design; Street configuration; Urban form.

1. Introduction

Being physically active has many physical and mental health benefits. Nevertheless, many people are too physically inactive to gain these health benefits. Socioecological models suggest that physical activity behaviors are shaped by numerous biological, family, political, and built environment factors. Among these factors, the built environment can encourage physical activity among many people over an extended duration [1]. The built environment can support physical activity by providing people with opportunities that support walking and which makes walking an automatic or preferred choice [2].

Various built environment elements are found to be associated with walking behavior. Notably, existing evidence suggests that increased neighborhood street connectivity and availability of destinations can support walking behavior [3]. For example, improving destination access was linked to higher levels of physical activity over time [3]. Previous studies have incorporated perceived and objective neighborhood street layout and destination measures. Perceived measures have been obtained by asking people how they perceive and feel about their surrounding street layouts and the availability of or proximity to destinations. Objective measures of street layouts and destinations are commonly calculated via auditing tools or geographic information systems (GIS). Notably, recent studies have employed new objective measures of street layouts applying space syntax theory in relation to walking [4]. Space syntax is a concept and method to analyse the spatial configuration of the built environment [5]. Street integration, a main measure in space syntax, was associated with increased walking for transport in several previous studies conducted in different countries [6-8]. Space syntax detects street network topology that cannot be properly measured by conventional street connectivity measures, such as intersection density and block sizes [7].

The ‘natural movement’ is one of the central theories in space syntax, which indicates the capacity of the street layout itself to attract pedestrian flow [9]. According to this theory, highly integrated streets can influence walking through the co-existent destinations on such streets. This theory suggests that destination availability may mediate relationships between street layout and walking behaviors [10]. Nevertheless, only a few studies have formally tested this mediation effect [7, 11, 12]. These studies were also limited in several important ways. Two of these studies included only the perceived availability of destinations [7, 12]. The perceived availability of destinations in the neighborhood may not correspond with objective measures of destination availability [13]. The other study used Walk Score® as a substitution for the availability of destinations in the neighborhood [11]. However, Walk Score® incorporates other built environment features and not just proximity or availability of destinations (e.g., population density, intersections, block size). Destinations are also weighted based on their proximity (distance) and importance [14]. Additionally, these previous studies only focused on transportation walking, and no studies have examined the mediation effects of destinations in the relationships between street layout and leisure walking. It is likely that different types of walking have their unique built environment correlates.

Therefore, based on a large Canadian adult sample, this study examined the associations between street layout and walking behaviors and explored whether objectively-measured destinations may mediate these relationships. Our hypothesis is that the availability of destinations is the mediator for the observed street layout and walking relationships.

2. Methods

2.1. Data collection and study participants

This study used secondary cross-sectional data from Alberta's Tomorrow Project (ATP), a prospective cohort study conducted in Alberta, Canada, to explore the causes of cancer and other non-communicable diseases [15]. Alberta province covers a large geographical area of about 640,000 km^2 with a population density of 6.4 people per km^2 [16]. The detailed study design and recruitment procedure are described elsewhere [15, 17]. In summary, between 2000 to 2008, a random sample of Alberta residents without a history of cancer and no plans to leave Alberta within the next year were invited to participate in the initial recruitment phase through random digit dialling (n=63,486). Among them, 31,072 participants were registered after providing informed consent and submitting a health and lifestyle questionnaire. In 2008, those enrolled between 2000 and 2007 were invited to complete a follow-up health and lifestyle survey (n= 20,707). This cross-sectional study analyses data from urban-dwelling adult participants (age <65 years old) who completed the 2008 health and lifestyle follow-up survey. The University of Calgary Conjoint Health Research Ethics Board approved this analysis (REB19-1992).

2.2. Measures

Walking behaviors. Two types of walking behaviors, transport and leisure walking, were obtained using the International Physical Activity Questionnaire (IPAQ) Long Form [18]. The IPAQ offers reliable and valid estimates of different walking behaviors [18]. Participants reported the number of days in the past seven days that they engaged in transport and leisure walking for at least 10 minutes. Subsequently, participants provided information on the duration of these walking activities within a typical day. The weekly duration of each walking activity was calculated by multiplying the number of days engaged in the activity by the minutes per day for that specific activity.

Destinations. Participants' 6-digit residential postal codes were geocoded using the CanMap Postal Code Suite (Desktop Mapping Technologies Inc.; DMTI). Due to the confidential nature of participants' health data, complete household street address information was not available. However, a previous study showed that Canada's geocoded urban postal codes could effectively estimate household geographical location [19]. Using GIS [ArcGIS Pro 2.2] (ESRI, US), the availability of destinations was assessed by determining the total count of destinations within a 400m radius (circular buffer) of geocoded 6-digit residential postal codes of participants. A 400m buffer was selected because it is the approximate distance travelled by 5-10 minutes of walking [20]. The seventy-six Standard Industrial Classification codes of business destinations from the DMTI Spatial CanMap Enhanced Points of Interests data was used to represent business destinations. These Standard Industrial Classification codes corresponded to Retail Trade, Finance, Insurance, Real Estate, Services, and Public Administration (e.g., department stores, restaurants, barbershops, and schools). An acceptable agreement has been reported between these Standard Industrial Classification codes and field observation in Canadian context [21].

Street integration. The street integration measure of space syntax was computed for each street segment, considering the influence of all other street segments within a 1.6 km distance. Axwoman [22] and Depthmap [23] were used to calculate the street integration obtained from the CanMap Streetfiles and Route Logistics street data files (DMTI Spatial Inc.).

Sociodemographic characteristics. Participants reported several sociodemographic characteristics, including age, sex, current marital status, highest education level, general health status, number of children <18 years old in the household, current employment status, and annual household income. Participants were also asked about their mobility abilities using a 1-3 scale (1= no problem in walking, 2= some problems in walking, and 3= confined to bed). Those who were unable to walk (confined to bed or missing answer) were removed from the analysis (n=18).

2.3. Statistical Analysis

Summary statistics, such as percentages, means, and standard deviations (SD), were computed to describe the characteristics of walking behaviors, street integration, availability of destinations, and covariates. Due to the positively skewed distributions of the two walking duration variables, natural log transformations were applied to improve the distributional properties of the data. Covariate-adjusted multivariate linear models estimated the associations of the space syntax street integration with the duration of transport and leisure walking (path c – total effect). The mediation effects of the availability of destinations in these associations were tested by structural equation modelling (SEM). The type of mediation effect (i.e., no, partial, or full) was determined using the post-estimation “medsem” package in Stata [24] and Zhao et al.’s recommendations [25]. This package allows for comprehensive SEM analysis, including mediation analysis. It estimates and assesses the significance of the direct and indirect effects in the mediation model. The "medsem" package is a widely used tool in the field and follows recommendations by Zhao et al [25] for mediation analysis. The Monte Carlo simulation (5000 replications) was applied to check the statistical significance of the indirect effects (path a × path b) [24]. The mediation effect was measured as a ratio to determine the relative magnitude of the mediation effect. Specifically, the ratio of the indirect effect (path a × path b) to the total effect (path c) was calculated. This ratio provides insights into the proportion of the total effect that is mediated through the availability of destinations [24]. Before the regression analysis, the street integration and availability of destinations variables were standardised (i.e., z-scores). For all point estimates (Beta(B): linear regression), 95% confidence intervals were estimated. Analyses were conducted using Stata 15.0 (Stata Corp., College Station, TX, USA), and the significance level was set at $p < 0.05$.

3. Results

A total of 12,378 participants had complete data on covariates, street integration, and destinations. Approximately 62% of them were women (n=7,651), 78% were married or had live-in partners, 40% had some or entire technical college training, 41% reported very good general health status, 68% had no children in their households, 63% were employed full-time, and 48% reported an annual household income of >$100,000. Of this sample, 7,314 and 7,429 participants who reported over 10 min/week and less than 1,260 min/week of transport or leisure walking were included in the regression and mediation analysis (Table 1). The selection of 1,260 minutes per week as a threshold for outliers was similar to previous studies which used self-reported physical activity questionnaires [26, 27]. These participants reported 181.5 and 180.2 weekly minutes of transport and leisure walking, respectively. Table 2 shows the participants' neighborhood street layout and destination attributes. The correlation between the space syntax street integration and availability of destinations were 0.22 ($p < 0.01$) and 0.23 ($p < 0.01$) among those participants who reported transport and leisure walking, respectively.

INSERT TABLES 1 & 2 ABOUT HERE

The associations between space syntax street integration and duration of leisure and transportation walking are shown in Table 3. Street integration was significantly positively associated with transportation walking (b=0.03, 95% CI 0.00, 0.05, p = 0.03). No significant association was observed between street integration and leisure walking.

The mediation effects of the availability of destinations for associations between street integration and walking outcomes are shown in Table 3. The indirect effect of street integration on transportation walking through the availability of destinations was significant (b=0.01, 95% CI 0.00, 0.01, p = 0.01). The association between street integration and transportation walking was fully mediated by the availability of destinations, accounting for 29% of the total effect.

INSERT TABLE 3 ABOUT HERE

4. Discussion

This was one of the few studies that formally tested the mediation effects of destinations in the observed associations between street layout and walking. In line with three previous studies [11, 12, 28], we found a mediation effect between street integration and transportation walking through the availability of destinations. Our study extends previous findings by including objectively-measured destinations and investigating different types of walking (transportation and leisure walking).

We found that street integration was positively associated with transportation walking. This finding is consistent with several previous studies that have found street connectivity supportive of transportation walking [29, 30]. It was hypothesised that well-connected street layouts influence transportation walking by providing short distances and multiple routes to traverse between destinations [31]. Our study provides empirical evidence that the availability of destinations can be another pathway through which highly integrated street layouts can impact transportation walking. There are two key difficulties in using destination data in the research on the built environment and health. First, land-use data at the parcel level are commonly challenging to acquire or unobtainable in high or low-income countries [32]. Second, different types of destinations were included in the previous studies to test the relationships between destinations and walking behavior. This potentially impedes collating and summarising the previous findings on the role of the availability of destinations in promoting walking behaviors. Our results imply that in addition to reflecting connectivity, the street layout measured using street integration reflects the availability of destinations, indicating the validity of using the street layout measures for predicting walking behavior with no need for destination measures.

There was no significant association between street integration and leisure walking. This is consistent with the body of research showing no associations between built environment elements and leisure walking. For example, a longitudinal study found no significant associations between the changes in several built environment attributes and leisure walking [33]. It has been suggested that the correlates of walking behavior may differ based on the walking purpose [29]. As a discretionary activity, leisure walking may depend less on built environment elements than transportation walking. Additionally, several built environment attributes, such as aesthetics and safety from traffic and crime, may be important for recreational walking [34]. Future studies are needed to explore distinctive correlates of walking stratified by the purpose of walking.

These findings have several implications for urban design, planning, and public health practice. First, urban designers and planners should acknowledge the importance of destination accessibility in promoting transportation walking. Designing well-connected street layouts that provide easy access to a variety of destinations, such as retail stores, recreational facilities, and educational institutions, can enhance transportation walking opportunities. Second, integrating street layout design with destination planning can lead to more activity-friendly urban environments. By strategically locating destinations along highly integrated street layout, urban designers can further encourage walking behavior as a means of transportation. Finally, public health initiatives targeting transportation walking can prioritize interventions that focus on improving street connectivity and improving availability of destination.

This study had some limitations. Causal relationships cannot be concluded from our findings because this is a cross-sectional study. There were also temporal differences between data sources for calculating street layout and destination measures however, previous evidence suggests that built environment features remain relatively stable in the short-term [35]. For example, a Canadian study has shown stability of several built environment attributes, including population density, street connectivity, and the availability of retail outlets over a 3-7 years period of time [35]. Our sample included adults <65 years of age residing in urban areas, thus our findings may not generalize to older adults or non-urban populations. Further, our analysis included participants who reported at least some participation in walking for leisure or walking for transport, therefore our estimates do reflect initiate of these behaviors (i.e., doing no walking to undertaking any walking). While our study included a commonly used and validated tool for measuring walking, self-report physical activity tools nevertheless have limitations with regard to reporting and memory bias. Moreover, the IPAQ does not measure context specific (e.g., neighborhood) walking, and therefore some of walking reported may have occurred outside the geographical boundaries used for our street integration and destination measures potentially attenuating the magnitude of the associations estimated.

5. Conclusions

The role of urban design in facilitating walking behavior has been investigated in many studies. However, the availability of data and comparability between previous studies remains a challenge. Through the space syntax natural movement theory, our study provides insights into using street layouts as a primary measure to (re)design the built environment to support walking. Further studies in other geographical contexts are needed to confirm our findings.

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Table 1. Characteristics of study participants

Variable	Total (n=12,378)	Reported transport walking (n=7,314)	Reported leisure walking (n=7,429)
	Mean (SD) or N (%)	**Mean (SD) or N (%)**	**Mean (SD) or N (%)**
Age (years)	52.2 (7.0)	52.3 (7.0)	52.2 (7.0)
Sex			
Women	7651 (61.8)	4520 (61.8)	4832 (65.0)
Men	4727 (38.2)	2794 (38.2)	2597 (35.0)
Current marital status			
Married or not married, but living with someone	9697 (78.3)	5676 (77.6)	5966 (80.3)
Separated or divorced	1590 (12.8)	966 (13.2)	850 (11.4)
Widowed	284 (2.3)	162 (2.2)	163 (2.2)
Single, never married	807 (6.5)	510 (7.0)	450 (6.1)
Highest education level			
Some or entire high school	2526 (20.4)	1344 (18.4)	1348 (18.1)
Some or entire technical college training	4898 (39.6)	2843 (38.9)	2885 (38.8)
Some or entire university degree	3333 (26.9)	2054 (28.1)	2160 (29.1)
Some or entire university postgraduate degree	1621 (13.1)	1073 (14.7)	1036 (13.9)
General health status			
Poor or fair	941 (7.6)	510 (7.0)	426 (5.7)
Good	4111 (33.2)	2343 (32.0)	2258 (30.4)
Very good	5121 (41.4)	3083 (42.2)	3259 (43.9)
Excellent	2205 (17.8)	1378 (18.8)	1486 (20.0)
Number of children in household			
0	8379 (67.7)	4964 (67.9)	5038 (67.8)
1	1760 (14.2)	1048 (14.3)	1078 (14.5)
2	1652 (13.3)	987 (13.5)	978 (13.2)
≥3	587 (4.7)	315 (4.3)	335 (4.5)
Current employment status			
Working full-time	7812 (63.1)	4550 (62.2)	4533 (61.0)
Working part-time	1857 (15.0)	1116 (15.3)	1230 (16.6)
Home maker	803 (6.5)	460 (6.3)	518 (7.0)
Retired	1241 (10.0)	790 (10.8)	798 (10.7)
Other or not employed or student	665 (5.4)	398 (5.4)	350 (4.7)
Annual household income (Canadian Dollars)			
$0 to 49,999	1787 (14.4)	1023 (14.0)	948 (12.8)
$50,000 to 99,999	3894 (31.5)	2286 (31.3)	2276 (30.6)
$100,000 to 149,999	3196 (25.8)	1897 (25.9)	1986 (26.7)

$150,000 to 199,999	1356 (11.0)	815 (11.1)	851 (11.5)
$200,000 to 249,999	578 (4.7)	360 (4.9)	375 (5.0)
$≥250,000	763 (6.2)	468 (6.4)	510 (6.9)
Not reported	804 (6.5)	465 (6.4)	483 (6.5)
Transportation walking (min/week)	110.5 (191.1)	181.5 (192.6)	-
Leisure walking (min/week)	111.8 (176.6)	-	180.2 (173.0)

Table 2. Participants' neighborhood street layout and destinations attributes

	Total (n=12,378)	Reported transport walking (n=7,314)	Reported leisure walking (n=7,429)
	Mean (SD)	**Mean (SD)**	**Mean (SD)**
Street integration	167.4 (86.3)	172.3 (86.7)	169.1 (86.3)
Availability of destinations	8.8 (11.3)	8.9 (11.2)	8.4 (11.0)

Table 3. Estimated association between space syntax street integration and weekly duration of leisure and transportation walking with availability of destinations as a mediator

	Path a	**Path b**	**Path c'** *Direct effect*	**Path a x Path b** *Indirect effect*	**Path c** *Total effect*	**Mediator effect**[a]	**Proportion of mediation**
Effect mediation by availability of destinations	**Coefficient (95% CI)**	**Coefficient (95% CI)**	**Coefficient (95% CI)**	**Coefficient (95% CI)^**	**Coefficient (95% CI)**		**(%)**
Street integration -> transportation walking	0.22 (0.20, 0.24)*	0.04 (0.01, 0.06)*	0.02 (-0.01, 0.04)	0.01 (0.00, 0.01)*	0.03 (0.00, 0.05)*	Full	29
Street integration -> leisure walking	0.22 (0.20, 0.25)*	-0.01 (-0.04, 0.01)	-0.02 (-0.04, 0.01)	-0.01 (-0.01, 0.00)	-0.02 (-0.04, 0.00)	No	-

^95% CI based on standard errors estimated from Monte-Carlo simulations (5000 repetitions). Other CIs estimated using robust standard errors.
[a] According to the Zhao, Lynch & Chen's approach to testing mediation
*p<0.05