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School walkability index: Application of environmental audit tool and GIS

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A R T I C L E I N F O

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Environmental audit

A B S T R A C T

Introduction: Active school travel is an important way to promote children's physical activity, but it requires supportive environments that can safely and comfortably accommodate children's walking and biking. Few existing indices explicitly consider school neighborhood environmental factors related to children's walking to school. In this study, we used a street audit tool and Geographic Information System (GIS) to evaluate walkability near low-income elementary schools in Seattle, WA.

Methods: The audit-based school walkability index was developed based on all street segments (n = 841) within a 0.4 km network buffer from each study school (n = 18). The GIS-based school walkability, a combination of road connectivity, vehicular traffic exposure, and residential density, was also measured in a 2 km network buffer around each school. The participants were individuals aged 8–11 years (n = 315) who participated in the Walking School Bus randomized controlled trial project. Mixed-effects logistic and linear models were used to examine the association of the index's representations of the built environment with children's school travel mode (walking or biking to school 1+ times per week) and with objectively measured moderate-to-vigorous physical activity (MVPA, average weekday minutes during the 90-min before-school period). These associations were tested with the total sample as well as the subsample of children living within 1.5 km from their schools.

Results: The audit-based school walkability index (WI) was positively associated with both active commuting to school among the subsample living within 1.5 km from their schools and with children's before-school MVPA among the subsample and the total sample. The GIS-based school WI showed significant associations with children's before-school MVPA but no relationships with active school travel among the subsample and the total sample.

Conclusion: The audit-based school walkability index can be used as a complementary tool for measuring walkability near low-income elementary schools along with existing GIS-based school walkability index.

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1. Introduction

Active school travel (AST), such as walking or biking to/from school, is a promising means to promote physical activity and potentially reduce obesity among school-aged children (Mehdizadeh et al., 2017). Unfortunately, recent decades have seen a steep decline in walking to and from school among school-aged children (McDonald et al., 2011). Safe Routes to School (SRTS) programs, which first received federal funding by the United States Congress in 2005, have been shown to effectively increase the number of children who walk or bike to school (Stewart et al., 2014). Among the key factors associated with AST behaviors are the characteristics of the built environment related to safety and walkability. Issues of inequity and risks associated with AST have also emerged. For example, low-income children face greater risks of being injured as pedestrians while engaging in AST, compared to those from more affluent families (Gavin and Pedroso, 2010). Many low-income schools have problems with safety and walkability in their surrounding neighborhoods, such as a long distance to school, shortage of sidewalks, high traffic volume, and lack of safe places for students to walk or bicycle (He and Giuliano, 2018; Macdonald et al., 2016; McDonald, 2008). Increasing evidence suggests that built environmental approaches to promote AST require population and context-specific strategies (Carver et al., 2019; Evers et al., 2014; Rothman et al., 2015). Addressing walkability around schools where low-income children reside can contribute to not only increasing AST and physical activity but also addressing health equity (Macdonald et al., 2016).

Despite some promising results from SRTS and other related efforts, the proportion of students using AST modes remains low in most schools. The home-to-school distance is one of the most important environmental barriers to AST, with those living further from school being less likely to actively travel to school (Duncan et al., 2016; McDonald, 2008; Mitra and Buliung, 2012). However, there is little consistency across studies in terms of the feasible/optimal distance to consider for promoting AST. Panter et al. (2011) found that 2 km would be a feasible distance for children aged 9–10 years to actively commute to school. Wilson et al. (2018) only considered children living within 1.6 km from school by excluding those who were bus eligible. Schlossberg et al. (2006) also showed that those who lived within 1.6 km of the school were the most likely to walk. Most relevant to this study and based on United States national data on children 5–13 years old, McDonald (2008) suggested 1–2 km to maximize walking to school. As a walkable home-to-school distance is a prerequisite for AST promotion, careful consideration of distance thresholds, which may vary across populations and settings, is needed in empirical studies dealing with environment-AST relationships.

Along with the home-to-school distance, built environments may directly and indirectly influence school travel factors. Traffic and safety concerns are frequently reported as important barriers to AST (Panter et al., 2010). According to McMillan (2005)'s conceptual framework of an elementary-aged child's travel behavior, certain urban forms such as vacant lands or high volume of traffic, may increase parents' fear of criminal or traffic danger, which in turn may prompt parents to not allow their child to walk to school and play outdoors. On the other hand, urban design features, including the presence of shade trees and better aesthetics, also encourage active travel to school (Larsen et al., 2012). Mitra (2013) proposed the behavioral model of school transportation, suggesting that urban design features (e.g., aesthetics and physical qualities of streetscapes) help increase pedestrian comfort and the attractiveness of travel route for children.

Another major issue in built environment-AST studies is related to the measurement of the built environment. Recent years have witnessed a rise in development and use of walkability indices, particularly for adults, which are typically measured using the Geographic Information System (GIS). The studies generally include measures of land use mix and density, street/sidewalk connectivity, crash/crime rates, traffic, slope, land cover, and other environmental variables to measure the degree to which an area can provide opportunities to walk (Grasser et al., 2016; Hajna et al., 2013). However, these measures of adult-based walkability may not be salient for school-aged children (Panter et al., 2008). Two efforts directly attempted to develop and employ a school walkability index (WI) that considered the specific circumstances of children although this index has not been tested in the United States context. Giles-Corti et al. (2011) developed the WI by considering road connectivity and traffic exposure. Building on their WI, Christiansen et al. (2014) included an additional variable, residential density, to construct a school WI. Their study of 14 schools in Southern Denmark found a significant association with children's AST. The two school walkability indices calculated the results for each of their built environment factors and then standardized the results by calculating the z-scores. The z-scores for all of the factors were then summed to produce a composite score.

GIS-based walkability features have been widely used to predict individual physical activity (Cruise et al., 2017; Lefebvre-Ropars et al., 2017; Manaugh and El-Geneidy, 2011). However, GIS-based measures of a built environment (e.g., road connectivity, traffic exposure, and residential density) often do not account for the route-specific and place-specific features that directly influence children's walking behavior (Lee et al., 2013; Pikora et al., 2007). Certain street-level and micro-scale built environments, including sidewalk quality and aesthetics, have been shown to affect children's comfort and safety for walking and biking to school. For example, Timperio et al. (2006) found that poor lighting or steep roads along the route to school were negatively associated with children's walking/biking to school. Zhu and Lee (2009) found that the presence of bus stops along the route to school was negatively associated with the choice of children's school travel mode choice. Kerr et al. (2006) also found that parental concerns and neighborhood aesthetics were associated with AST. The likelihood of walking to school was shown to be positively associated with the presence of street trees (Larsen et al., 2009), and parent's perception of the safety and convenience of walking (Zhu and Lee, 2009).

Given the association between micro-scale environments and children's walking and physical activity, several audit instruments have also been developed to target children and school commuting. One example is the International Study of Childhood Obesity, Lifestyle and the Environment (ISOLE) school audit tool, developed to measure school environments correlated with children's physical activity (Broyles et al., 2015). This instrument includes walking provision (pavements, traffic calming, road safety), sports and play facilities (playground surfaces, drinking fountains), and aesthetics (trees for shade, noise, graffiti). Another example is the Texas Childhood Obesity Prevention Policy Evaluation (T-COPPE) school environmental audit tool, developed to measure walkability and safety of the school campus and streets around the school (Lee et al., 2013). It includes three audit components: street, map, and campus audits. The street and map audits are designed to assess streets adjacent and near schools, while the school site audit is designed to assess outdoor environments within the school property. These two tools have been found to have adequate inter-rater and test-retest reliability (Broyles et al., 2015; Lee et al., 2013).

Despite the development of environmental audit instruments for children, few attempts have been made to build an audit-based school WI for children and to test the effects of the WI on AST and before-school physical activity. Audit instruments collect a large number of detailed data at the street level, and therefore present significant challenges to data processing (e.g. cleaning, selecting, aggregating, scoring, etc.) to extract valid and efficient indices that are appropriate for statistical analyses.

This paper aims to test both the audit-based school WI and the GIS-based school WI for their roles in predicting AST and before-school moderate-to-vigorous physical activity (MVPA). For the GIS-based school WI, we used an existing WI which included road connectivity, traffic exposure, and residential density for 2 km buffers around schools. Due to the lack of available audit-based school WIs, we developed our own index drawing from the items included in the modified T-COPPE instrument based pm 0.4 km buffers around schools. The development of our audit-based school WI has been guided by the previous literature addressing the street-level variables that are important for children's walking to school behaviors (Braza et al., 2004) and by the Behavioral Model of Environment, a spatial model used to conceptualize and organize built environmental factors related to outdoor physical activity such as walking and biking (Moudon and Lee, 2003). The main research questions of this paper are as follows:

- What are the key components that need to be included in the audit-based school WI?
- Is there an association between the audit-based school WI and children's AST or before-school MVPA?
- Is there an association between the GIS-based school WI and children's AST or before-school MVPA?

2. Methods

2.1. Study design and sample

As part of the Walking School Bus (WSB) randomized controlled trial (RCT), baseline data on 1) self-reported transportation mode to school and 2) accelerometer-determined physical activity were collected from the students attending 22 elementary schools, primarily serving low-income families in the greater Seattle (n = 18) and Houston (n = 4) area. Only the 18 Seattle schools were selected for the present study because they underwent street audits, which was not collected in Houston. From the 18 schools, students who reported their mode of commuting to school or recorded adequate accelerometry wear time were included in the study, which resulted in 315 students aged 8–11 years with a total of 1304 participant days. Students were eligible to participate in the WSB RCT if they were physically capable of walking to and from school and lived within a 1-mile network buffer of school or if their parents committed to regularly dropping them off at a WSB stop within the 1-mile walk zone. In our study, the associations of the walkability indices with children's AST or MVPA were tested with the total sample and a subsample of students based on their home-to-school distance at 1.5 km for walking, which was consistent with previous literature as an acceptable distance for school commuting (D'Haese et al., 2011). Thus, our final sample size was 315 students, with the subsample of 224 students living within 1.5 km from their school.

2.2. Audit-based school walkability index

Each street segment (n = 841) within a 0.4 km buffer from 18 schools was examined using the field audit tool administered by a trained auditor. Auditors completed a minimum of 6 h of field training and a subsequent certification process to ensure consistency and validity of the data collected by different auditors. Audits were conducted between January and April 2014–2016. For this present study, a total of 25 items from the modified T-COPPE instrument were selected based on their documented and potential correlation with walking and/or walking to school behavior, being modifiable through environmental and policy interventions, and being readily observed from the public streets. Such environmental variables along the street segments were assessed for three domains: (a) land uses and housing types, (b) street characteristics (e.g. school zones, sidewalks, amenities), and (c) neighborhood perceptions (e.g., surveillance, street maintenance). This instrument was tested to have acceptable inter-rater (k = 0.84, ICC = 0.60) and test-retest reliability (k = 0.90, ICC = 0.77). More detailed information about the audit instrument and its development processes are described elsewhere (DELETED for blind review).

To calculate the audit-based school WI, we digitalized all audit-based school built environmental information in ArcGIS 13.0 and created the school-level variables. We then conducted mixed-effect logistic regressions between each school-level audit variable and children's AST after adjusting for demographic and distance variables. We selected potential indicators to be included in the audit-based school WI based on having a consistent direction of the associations in both the subsample and the total sample analyses regardless of their statistical significance. Due to multicollinearity problems among the selected indicators (n = 14), we created a composite estimate of the audit-based school WI using principal components analysis using the z-score of each variable. After using orthogonal varimax rotation, the factors having eigenvalues greater than one were extracted. Finally, regression-based factor scores were summed up to construct the audit-based school WI.

2.3. GIS-based school walkability index

The GIS-based school WI was calculated for a 2 km network buffer from each school, which has been validated in previous studies

(Christiansen et al., 2014; Giles-Corti et al., 2011). The GIS-based school WI was constructed adopting principal components analysis based on the z-score of three macro-scale built environment components: 1) road connectivity, 2) vehicular traffic exposure, and 3) residential density. Road connectivity was calculated as the ratio between the 2 km pedestrian street network buffer area and the 2 km Euclidian buffer area. Vehicular traffic exposure referred to the ratio of busy or large streets as compared to all of the streets. Residential density was calculated as the number of residential units in the 2 km pedestrian network buffer around each school divided by the total area of the buffer. We used the street and pedestrian pathway dataset from the Washington State Department of Transportation and parcel-based land use data from the King County Department of Assessments.

2.4. Outcome variables

Two outcomes were considered in this study: self-reported AST and objective measures of physical activity. The travel mode to school was captured from a self-reported commute mode survey for each valid accelerometer day. Students answered the question, "How did you get to school today?" and they were instructed to choose the single best response from the seven choices: rode school bus, rode metro bus, came by carpool, came by car, walked with an adult, walked without an adult, or biked. Such self-reports of student

Table 1
Components of audit-based school walkability.

Variable	Description	Subsample	Total sample	Final
		Direction [a]		
Land Use				
L01. Density of multi-family housing	Number of street segments having multi-family housing units/total number of street segments	(+)	(+)	(+)
L02. Density of park	Number of street segments having parks/total number of street segments	(+)	(+)	(+)
L03. Density of vacant land	Number of street segments having vacant housings or vacant lands/total number of street segments	(-)	(-)	(-)
Street Characteristics				
S01. Density of sidewalk	Number of street segments having at least one side of the sidewalks/total number of street segments	(+)	(+)	(+)
S02. Sidewalk completeness rate	Number of street segments having absolute completeness/total number of street segments having sidewalks	(+)	(-)	
S03. Flat sidewalk rate	Number of street segments having flat sidewalks/total number of street segments having sidewalks	(+)	(-)	
S04. Wide sidewalk rate	Number of street segments having 4+ feet sidewalk width/total number of street segments having sidewalks	(+)	(-)	
S05. Sidewalk buffer rate	Number of street segments having sidewalk buffer/total number of street segments having sidewalks	(+)*	(+)	
S06. Sidewalk connectivity rate	Number of street segments having connected sidewalks on both directions/total number of street segments having sidewalks	(+)†	(+)	(+)
S07. Density of uneven surface [b]	Number of street segments having uneven surface/total number of street segments	(+)	(+)	(+)
S08. Density of trashes on the street	Number of street segments having trashes/total number of street segments	(-)†	(-)*	(-)
S09. Density of graffiti	Number of street segments having drainage problems/total number of street segments	(-)	(-)	(-)
S10. Density of drainage problems	Number of street segments having drainage problems/total number of street segments	(-)	(+)†	
S11. Street light density	Number of street lightings/total length of street segments (100 feet)	(+)	(+)	(+)
S12. Density of traffic calming devices	Number of street segments having any traffic calming devices (e.g., speed bump, roundabout)/total number of street segments	(+)	(-)	
S13. Noise from factories/dogs	Number of street segments having a little or a lot of noise from factories and barking dogs/total number of street segments	(-)	(+)	
S14. Density of bus stop	Number of street segments having bus stop/total number of street segments	(-)	(-)	(-)
S15. Density of street tree	Number of street segments with street trees along the public right of way/total number of street segments	(+)*	(-)	
S16. Density of marked crosswalks	Number of street segments with marked crosswalks/total number of street segments	(+)	(+)†	(+)
Neighborhood Perceptions	(1: poor, 2: fair, 3: good, 4: very good, 5: excellent)			
N01. Surveillance	Average surveillance (easily observed from the windows, porches, or gardens) score	(+)	(-)	
N02. Maintenance	Average maintenance (free of cracks, holes, overgrown grass/weeds, etc.) score of street	(+)*	(+)	(+)
N03. Cleanness	Average cleanliness (free of litter, rubbish, broken glass, etc.) score of street	(+)†	(-)†	
N04. Safety	Average safety score of walking and biking	(+)*	(+)	(+)
N05. Comfort	Average comfort score of walking and biking	(+)	(-)	
N06. Visual quality of street	Average score of the visual quality of the street, buildings, and trees/vegetation	(+)*	(+)	(+)

Note: **$p < 0.01$, *$0.01 \le p < 0.05$ †$0.05 \le p < 0.1$; (+) positive association; (-) negative association; [a] mixed-effects logistic regression after adjusting for home-to-school distance, demographics (age, sex, race), household income, and obesity; and [b] S07. Density of uneven surface: a consistent positive association in both the subsample and the total sample but being exclude due to its theoretical irrelevance; **Bold** indicates the selected final variables given consistent direction of the associations.

travel to school have been previously validated (Mendoza et al., 2010). The AST mode outcome (i.e., walked with an adult, walked without an adult, or biked) was captured as walking or biking to school one or more days per week. Although active commuting 1+ times a week does not represent a high percentage of active trips, it has been used to characterize AST in national reports of US children's school travel mode by the US Centers for Disease Control and Prevention (Centers for Disease Control Prevention, 2002; 2005). Moreover, similar measures of AST have been used in previous literature (Babey et al., 2009; DeWeese et al., 2013; Voorhees et al., 2010).

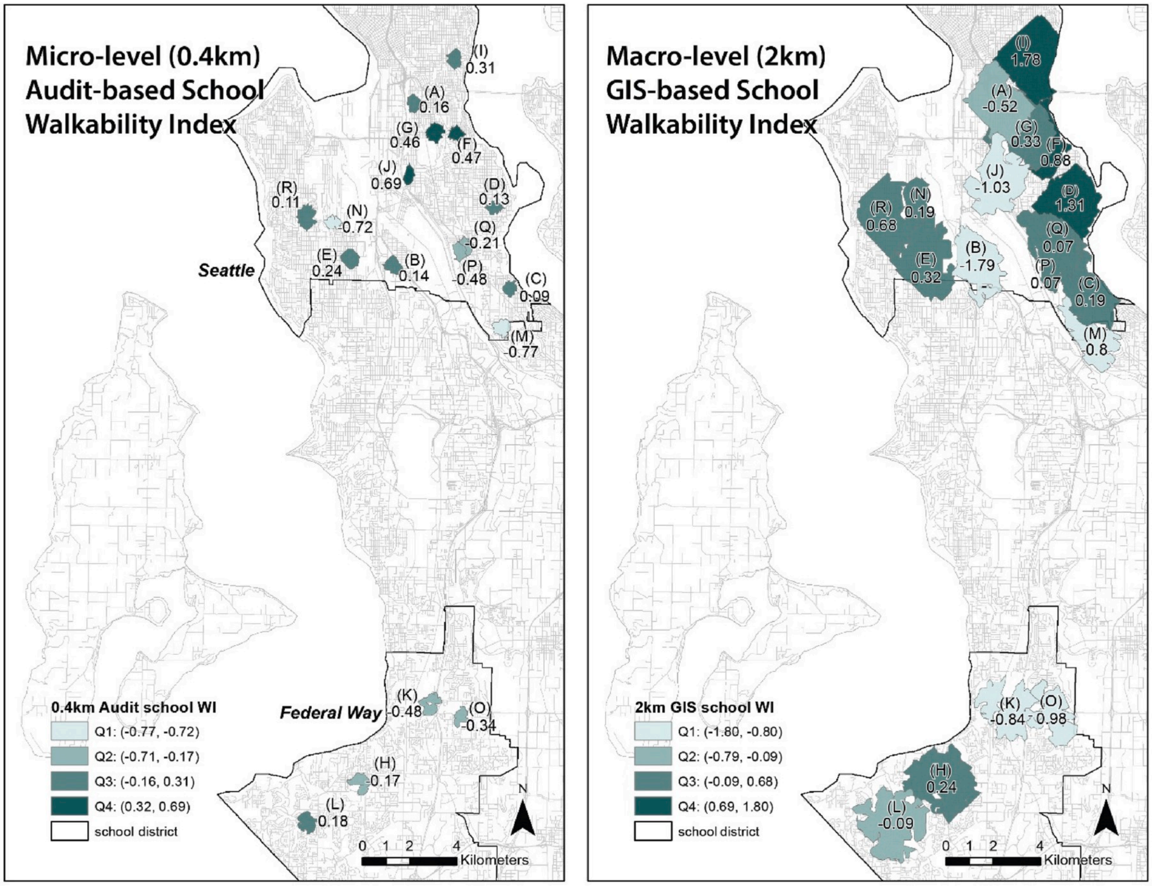
The physical activity variable was measured objectively based on accelerometry. Each child wore the ActiGraph GT3X + accelerometer device for one week. In this study, we used average minutes of MVPA during a 90-min before-school period each weekday to capture potential physical activity during the morning commute to school. We included accelerometry data from participants who had at least 30 min or more of wear time during a 90-min before-school period.

2.5. Covariates

Socio-demographic covariates were collected by parent-completed survey and included age, gender, race/ethnicity, and household income. Weight status (body mass index percentile) was calculated from measured height and weight and dichotomized (underweight or normal vs. overweight or obese) because of the skewed distribution. We calculated the network distance from home to each school for the analyses of the AST outcome and additionally included the accelerometer wear time for the analyses of MVPA outcome.

2.6. Statistical analysis

Two sets of analyses were also estimated to determine if the audit and GIS-based school WIs represented the built environment with respect to children's AST and MVPA outcomes. We used mixed-effects linear modeling for the physical activity outcome, and mixed-effects logistic modeling for the commute mode outcome after including school as a random factor in all models to account for cluster



Note: School Code: (Alphabet)

Fig. 1. Geographical location of each school and distributions of walkability indices.
Note: School Code: (Alphabet).

sampling. As distance could play a determining role in environment-AST associations (Panter et al., 2008), we tested the associations of walkability indices with children's AST and MVPA among the subsample living within 1.5 km from their school and the total sample without considering the home-to-school distance. All statistical analyses were conducted using Stata SE 15.0 (Stata Corp, College Station, TX).

3. Results

4. Table 1 shows the 14 final variables for the audit-based school WI based on positive or negative associations between each variable and children's AST in the subsample and the total sample, along with the list of 25 components of the audit-based school walkability identified in the modified T-COPPE instrument. The results of the correlation test between each audit-based school walkability indicator and children's AST after adjusting for socio-demographics, obesity, and home-to-school distance are shown in Supplementary Table 1. Although one variable, density of uneven surface, showed a positive association with children's AST, we decided to drop this variable due to its theoretical irrelevance. Thus, the potential 14 potential audit-based school walkability indicators considered in this study were: density of multi-family housing, density of park, density of vacant land, density of sidewalk, sidewalk buffer rate, sidewalk connectivity rate, density of trashes of the street, density of graffiti, street light density, density of bus stop, density of marked crosswalks, maintenance, safety, and visual quality of street. Spearman correlation matrix of the 14 variables was reported in Supplementary Table 2, and the results of the principal component analysis were reported in Supplementary Table 3. Five factors accounting for 86% of the total variance were finally identified from the modified T-COPPE instrument.

The resulting geographic distribution of audit- and GIS-based walkability indices at the school level was shown in Fig. 1. The number of street segments within the 0.4 km buffer from school ranged from 15 to 87 (Table 2). The audit-based school WI values ranged from -0.8 to 0.7, and the GIS-based school WI was from -1.8 to 1.8 with higher scores indicating higher walkability. The correlation between the audit-based school WI and GIS-based school WI was positive but lower, Pearson's $r = 0.24$, $p < 0.001$. The comparison between the audit-based school WI and the GIS-based school WI, based on their results from the streets around schools in our study communities, showed a weak linear relationship.

Table 3 shows the overall characteristics of the study variables. The 315 students considered in this study were fairly evenly split in gender (48% female, 52% male) and age in years (28% eight, 33% nine, 31% ten, and 8% eleven). The average age of the participants was 9.2 years (SD = 0.9). The participants generally came from low-income households (38% had less than $30,000 annual income and 32% had from $30,000 to $60,000 annual income) and most of them were Non-Hispanic White (76%), and more racially diverse than King County as a whole (Non-White: 32% and median household income: $83,571) based on the 2010 US Census data. Less than one out of ten (9.8%) of the students were obese or overweight. About half of the students reported walking or biking to school at least one day a week. More than half (62%) of the students who lived less than 1.5 km from school walked or biked to school. The average wear time of participants during the 90-min before-school period was 74.4 min (SD 14.5). Among them, the average MVPA during the 90-min before-school period was 4.5 min (SD 3.3) while average minutes of sedentary and light activities were 50 (SD 20.3) and 21.3 (SD 13.4) respectively. Finally, the average home-to-school distance among all participants was 1.5 km.

Table 4 presents models using the subsample and the total sample, to test the associations of the audit-based school WI with AST (1+ times per week) and children's MVPA (minutes per 90-min interval before-school on weekdays) after controlling for socio-demographic and home-to-school distance variables. Each model showed significant associations of children's AST with the distance from home to school. Home-to-school distance is the primary factor ($p < 0.001$) linked with children's AST at least once a week.

Table 2
Index comparison by school.

School Name	Participants attending the school	Number of Street Segments	Audit (0.4 km)		GIS (2 km)	
			Index	Rank	Index	Rank
School A	16	67	0.16	7	-0.52	13
School B	29	38	0.14	8	-1.79	18
School C	18	34	0.09	11	0.19	9
School D	24	37	0.13	9	1.31	2
School E	9	55	0.24	5	0.32	5
School F	13	39	0.47	2	0.88	3
School G	12	87	0.46	3	0.33	7
School H	16	66	-0.17	12	0.24	6
School I	30	74	0.31	4	1.78	1
School J	20	46	-0.48	16	-0.84	16
School K	18	30	0.69	1	-1.03	17
School L	11	63	0.18	6	-0.09	11
School M	12	33	-0.77	18	-0.80	14
School N	13	19	-0.72	17	0.19	8
School O	17	15	-0.34	14	-0.98	15
School P	23	36	-0.48	15	-0.18	12
School Q	15	57	-0.21	13	0.07	10
School R	19	45	0.11	10	0.68	4

Spearman's correlation $r = 0.24$, $p=<0.001$.

Table 3
Descriptive statistics of variables.

Variable	Mean/n	SD/%
Dependent Variables		
Before-school MVPA (average minutes of moderate-vigorous physical activity per 90-min measurement period per day)	4.5	3.3
Active Transportation Mode (1+ times walking/biking to school per week, n = 309)	158	51.1%
1.5 km or less than 1.5 km (n = 224)	140	62.5%
More than 1.5 km (n = 85)	17	20.0%
Independent Variables (School level)		
Audit-based school walkability index 0.4 km	-0.01	0.4
GIS-based school walkability index 2 km	-0.01	0.9
Confounding Variables		
Home-to-school distance (km)	1.45	1.8
Wearing time of accelerometer (minutes of wearing time per day)	74.4	14.5
Age		
8	88	28.0%
9	104	33.1%
10	96	30.6%
11	26	8.3%
Sex		
Female	151	48.2%
Male	162	51.8%
Race		
Asian	51	19.8%
Black	51	19.8%
Hispanic	58	22.6%
Other	37	14.4%
White	60	23.4%
Obesity		
Underweight or normal (<25)	284	90.2%
Overweight or obese (≥25)	31	9.8%
Income		
$30,000 or less	119	38.0%
$30,001 to $60,000	101	32.3%
$60,001 or more	93	29.7%

Note: SD, standard deviation.

Among those living within 1.5 km of their school, the audit-based school WI was significantly associated with AST after adjusting for gender, age, race/ethnicity, distance from home to school, and household income. The audit-based school WI revealed an increased probability of that a child will at least once a week walk or bike to school for the subsample living within 1.5 km from school (OR = 5.31, 95% CI = 1.78, 15.84). However, the audit-based school WI was not significantly associated with AST in the total sample. The

Table 4
Multilevel analyses of the associations of audit-based school WI with active commuting at and daily minutes of before-school MVPA.

	Active commuting (1+ times per week)				Daily minutes of before-school MVPA			
	≤1.5 km (n = 186)		Total (n = 255)		≤1.5 km (n = 186)		Total	
	OR	95% CI	OR	95% CI	Coef.	95% CI	Coef.	95% CI
Audit-based school WI	**5.31****	(1.78, 15.84)	1.69	(0.58, 4.90)	**2.20****	(0.61, 3.79)	**1.81***	(0.30, 3.33)
Age (ref: 8)								
9	0.89	(0.35, 2.26)	0.89	(0.42, 1.86)	**-1.00***	(-2.00, -0.01)	-0.59	(-1.50, 0.31)
10	1.14	(0.44, 3.00)	0.81	(0.37, 1.76)	-0.46	(-1.52, 0.60)	-0.26	(-1.23, 0.72)
11	1.22	(0.27, 5.40)	1.45	(0.41, 5.11)	-1.40	(-2.95, 0.15)	-0.39	(-1.85, 1.06)
Male	1.56	(0.75, 3.25)	1.12	(0.62, 2.02)	**1.10****	(0.28, 1.91)	**0.98****	(0.25, 1.71)
Race (ref: White)								
Asian	1.27	(0.41, 3.98)	0.72	(0.29, 1.78)	-0.67	(-1.93, 0.59)	-1.66**	(-2.80, -0.51)
Black	0.33	(0.11, 1.05)	0.52	(0.20, 1.37)	-1.07	(-2.41, 0.27)	-0.39	(-1.62, 0.84)
Hispanic	1.46	(0.44, 4.87)	1.37	(0.51, 3.67)	-0.51	(-1.78, 0.75)	-1.06	(-2.24, 0.11)
Other	0.46	(0.14, 1.54)	0.41	(0.14, 1.19)	-0.32	(-1.70, 1.05)	-0.93	(-2.21, 0.34)
Obesity	0.40	(0.11, 1.48)	0.45	(0.15, 1.33)	0.77	(-0.77, 2.30)	0.76	(-0.55, 2.07)
Income (ref: $30,000 or less)								
$30,001 to $60,000	0.63	(0.25, 1.59)	0.71	(0.34, 1.47)	0.17	(-0.78, 1.12)	0.35	(-0.52, 1.22)
$60,001 or more	0.53	(0.19, 1.50)	0.81	(0.36, 1.80)	-0.03	(-1.14, 1.07)	0.43	(-0.57, 1.44)
Home-to-school distance (km)	**0.03****	(0.01, 0.11)	**0.48****	(0.34, 0.69)	0.78	(-0.32, 1.89)	-0.14	(-0.34, 0.07)
Wearing time					0.02	(-0.01, 0.05)	0.01	(-0.02, 0.03)
AIC	215.37		330.67		910.06		1271.66	

Note: $^{**}p < 0.01$, $^{*}0.01 \leq p < 0.05$; **Bold** indicates significant values at $p < 0.05$; OR, Odds Ratio; and Coef., Coefficient; and AIC, Akaike information criterion.

audit-based school WI was significantly associated with more minutes of MVPA after adjusting for covariates among the subsample (Coef. = 2.20, 95% CI = 0.61–3.79) and the total sample (Coef. = 1.81, 95% CI = 0.30–3.33).

Table 5 shows the association of the GIS-based WI with AST and MVPA. The GIS-based school WI was significantly associated with children's MVPA but not with children's AST. When each index was run in the model after adjusting for gender, age, race, home-to-school distance, household income and wear time, the GIS-based school WI was significantly ($p < 0.05$) and positively associated with children's MVPA in both the subsample and the total sample. Higher scores for the GIS-based school WI was associated with more minutes of before-school MVPA for the subsample living within 1.5 km from school (Coef. = 0.40, 95% CI = 0.16–0.63) and for the total sample (Coef. = 0.29, 95% CI = 0.04–0.54).

4. Discussion

It is important to understand safety and walkability of school neighborhood environments to develop, implement, and evaluate programs aimed at promoting children's AST and physical activity such as the Safe Routes to School program and the Walking School Bus program. The aims of the current study were to identify the micro-level environmental determinants of children's active commuting using the modified T-COPPE instrument and to develop an audit-based school WI at the school level. We then explored whether this index helped explain children's AST and MVPA. We also explored the association of an existing GIS index with children's AST and MVPA. We found that the audit-based school WI had a significant association with children's AST among the subsample living within 1.5 km from school, and it was also associated with children's before-school MVPA in the subsample and the total sample. The GIS-based school WI was only positively associated with children's before-school MVPA in the subsample and the total sample.

The audit-based school walkability index presented here was developed by using the modified T-COPPE instrument, which was designed to capture built environmental factors important for children's overall walking including walking to school. Compared to other children-related audit instruments (e.g., ISOLE), this modified T-COPPE instrument serves as an optimal tool for this study as it (a) considers the neighborhood environment near schools, (b) is designed for the United States environments, and (c) focuses on children's AST. A composite of the 14 key components from the modified T-COPPE instrument was used to develop the audit-based school WI, which was shown to be important to encourage children's AST. Although previous literature relied on parental interviews or surveys to measure the perceived built environment features related to children's walking to school (Panter et al., 2010), this study showed evidence that systematic ratings of environmental perceptions measured by trained auditors would also be helpful in understanding children's AST behaviors. These findings add to the literature that highlights the importance of site-specific environmental conditions affecting physical activity patterns of children (Lovasi et al., 2011).

It should be noted that the selected audit variables in this study reflect McMillian's (2005) and Mitra's (2013) frameworks for children's school travel behavior. The components included in the audit-based school WI, such as density of vacant land, sidewalk quality, physical disorders, density of bus stops, and safety rating, capture traffic and overall perceived safety shown to influence parents' decisions on their children's choice of transportation to school. This is supported by McMillian's (2005) framework that certain environmental features contribute to personal and traffic safety and potentially limit children's travel mode. The other components of the audit-based school WI included sidewalk connectivity and visual quality of greenery and other street elements that can influence pedestrian comfort and attractiveness, which are emphasized in Mitra's (2013) conceptual framework, the behavioral

Table 5
Multilevel analyses of the associations of GIS-based school WI with active commuting at and daily minutes of before-school MVPA.

	Active commuting (1+ times per week)				Daily minutes of before-school MVPA			
	≤1.5 km (n = 186)		Total (n = 255)		≤1.5 km (n = 186)		Total (n = 255)	
	OR	95% CI	OR	95% CI	Coef.	95% CI	Coef.	95% CI
GIS-based school WI	1.21	(0.69, 2.12)	0.97	(0.59, 1.58)	**0.40****	(0.16, 0.63)	**0.29***	(0.04, 0.54)
Age (ref: 8)								
9	0.94	(0.35, 2.50)	0.88	(0.42, 1.86)	-0.84	(-1.84, 0.15)	-0.54	(-1.45, 0.37)
10	0.99	(0.37, 2.69)	0.78	(0.36, 1.69)	-0.66	(-1.71, 0.39)	-0.37	(-1.34, 0.60)
11	0.89	(0.20, 4.05)	1.34	(0.38, 4.66)	-1.51	(-3.05, 0.04)	-0.50	(-1.96, 0.95)
Male	1.63	(0.74, 3.58)	1.12	(0.62, 2.02)	**1.24****	(0.42, 2.05)	**1.02****	(0.29, 1.75)
Race (ref: White)								
Asian	1.32	(0.39, 4.45)	0.70	(0.28, 1.73)	-0.68	(-1.94, 0.57)	**-1.65****	(-2.80, -0.50)
Black	0.35	(0.10, 1.20)	0.51	(0.19, 1.34)	-1.24	(-2.57, 0.09)	-0.53	(-1.76, 0.69)
Hispanic	1.72	(0.49, 6.08)	1.33	(0.50, 3.59)	-0.34	(-1.61, 0.92)	-1.01	(-2.19, 0.18)
Other	0.39	(0.11, 1.41)	0.40	(0.14, 1.14)	-0.37	(-1.74, 1.00)	-1.02	(-2.29, 0.25)
Obesity	0.32	(0.08, 1.31)	0.45	(0.15, 1.34)	0.64	(-0.90, 2.18)	0.75	(-0.56, 2.06)
Income (ref: $30,000 or less)								
$30,001 to $60,000	0.74	(0.29, 1.91)	0.71	(0.34, 1.47)	0.27	(-0.69, 1.22)	0.41	(-0.46, 1.29)
$60,001 or more	0.69	(0.24, 1.96)	0.83	(0.37, 1.86)	0.03	(-1.07, 1.13)	0.40	(-0.61, 1.41)
Home-to-school distance (km)	**0.04****	(0.01, 0.15)	**0.49****	(0.34, 0.69)	0.91	(-0.17, 2.00)	-0.13	(-0.34, 0.08)
Wearing time					0.02	(-0.01, 0.05)	0.01	(-0.02, 0.03)
AIC	220.83		331.55		908.21		1272.04	

Note: **$p < 0.01$, *$0.01 \le p < 0.05$; **Bold** indicates significant values at $p < 0.05$; OR, Odds Ratio; and Coef., Coefficient; and AIC, Akaike information criterions.

model of school transportation.

Given the different ranks and measures of audit- and GIS-based school walkability indices, it is not appropriate to simply combine two different walkability indices to create a single composite index. Instead, our findings suggest that application of walkability indices should vary depending on the specific research questions or other assessment/intervention targets. Consideration of audit-based school walkability indicators, in addition to existing GIS-based school measures, appears necessary to understand and promote children's active commuting and their before-school MVPA. In addition to the GIS index tested in the study, the audit-based school walkability index can further represent the street-level built environments near schools, especially around low-income elementary schools, important for children's travel behavior and physical activity. On the other hand, the GIS-based school WI may be appropriate for efficient and easy use by researchers and policymakers seeking assessments across multiple school neighborhoods.

It is typically less complicated to develop the GIS-based school index than an audit-based school index if raw GIS layers are available and a skilled GIS technician is available. This study showed that the 2-km GIS index was not associated with children's AST but was significantly associated with MVPA during the morning school commute period. It is interesting to note that the audit-based school WI tested in this study showed significant associations with both children's morning AST and morning MVPA. Given that the audit-based school WI assessed multiple micro-level items in a 0.4 km buffer characterizing each school's street/sidewalk features and neighborhood perceptions, it is possible that this information provides more specific details on the built environmental influences on children's AST and morning MVPA. On the other hand, the GIS-based school WI focused on macro-level items characterizing road connectivity, vehicular traffic exposure, and residential density. Thus, we speculate that these items and the larger 2 km buffer may better reflect opportunities for morning MVPA and are less relevant to the specific school travel behavior.

It is also not surprising that the home-to-school distance has a significant impact on the probability of children's active commuting at least once a week. Consistent with a previous study (Schlossberg et al., 2006), we found that students who lived less than 1.5 km from school were more likely to walk and bike to school. This is likely due to short distances being easier to walk and because school buses are typically not provided within 1 mile (1.6 km) of public schools in Seattle. Regardless of the index used or the built environment factors measured, distance often overshadows other factors in predicting whether students walk to school or not. Given the significant association between children's AST and the audit-based school WI only within the criterion of the home-to-school distance of 1.5 km from their school, it is important to note that micro-environmental interventions to promote active commuting in low-income children could be more effective when focusing on children living within 1.5 km from school.

From an engineering and planning perspective, the effectiveness of the SRTS programs makes it essential to provide transportation/planning staff with the appropriate tools to identify and prioritize the allocation of SRTS project awards. This is particularly important as funds remain scarce and need to be targeted to projects that will yield the greatest increases in AST. The indices developed in this study can support the allocation of funds in two ways: they can help rank schools according to the potential for increasing children's AST rate, and they can identify the components/indicators of the school neighborhood environment that could be changed to most effectively increase AST. In addition, this audit-based school WI can be used to identify locations that are appropriate for program-based interventions such as the WSB program.

4.1. Limitations and strengths

Several potential shortcomings of this study should be acknowledged. First, the cross-sectional design makes it impossible to make conclusions about causal relationships. In addition, the small number of schools (n = 18) and small samples per each school (mean = 17.5, SD = 5.9) reduce the power to detect associations. The composite measure of the audit-based school WI cannot be directly translated to practice or general applications but can be intended to understand the importance of audit-based school measures and associations with AST and MVPA among low-income children. Such groups are more likely to walk or bike to school and therefore are vulnerable to environmental barriers/risks as they walk or bike to school. Measures and variables selected for the audit-based school WI in relation to children's AST and MVPA require further validation and reliability testing. Parental concerns and participants' perceived environmental characteristics are also important elements that may explain commuting and PA behavior, but these factors were not included in our analyses. Further studies need to consider these parental variables and additional environmental variables (e.g. objective measures of walkability and perceived neighborhood environment characteristics). We were also unable to capture the afternoon commute time, after-school program, or playtime, which could add more daily MVPA and even walking to school may be more related to light activity, not being captured well by MVPA definition. Finally, the exclusive focus on low-income schools in King County, WA further limits our ability to generalize the findings to other settings. To the best of our knowledge, however, this is the first study to create an audit-based school WI for school neighborhoods, and to explore its potential to predict the choice of the school travel mode and physical activity levels among elementary school children. Another strength of our study is the use of both audit and GIS measurements of environmental variables as well as a validated measure of AST and objectively measured PA using accelerometry.

5. Conclusion

Our study introduced the audit-based school WI and GIS-based school WI as tools to study the impact of the built environments on children's walking to school and physical activity near low-income elementary schools. The audit-based school WI was significantly associated with children's active commuting at least once a week and with their before-school MVPA. On the other hand, the GIS-based school WI was significantly associated with children's before-school MVPA, but not with their active commuting at least once a week. The results of this study suggest that the audit-based WI can be used as a complementary tool to measure school walkability along with existing GIS-based school WI. Improving micro-level school walkability may help encourage children to walk to school, which could potentially allow children to be engaged in more physical activity. Many street-level built environments can be readily modified for improvement at a relatively low cost; thus, improving the street conditions, such as increasing sidewalk connectivity, removing trashes on the streets, and improving the visual quality of the street design could be a cost-effective approaches for SRTS programs. This information is valuable not only for researchers who are interested in promoting AST for health and mobility benefits, but also for practitioners and policymakers who are tasked with devoting limited resources to improving safety and walkability to schools.

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Author statements

Sungmin Lee: Conceptualization, Methodology, Software, Writing- Original draft preparation. Chanam Lee: Conceptualization, Validation, Writing- Reviewing and Editing. Ji Won Nam: Data curation, Visualization. Mark Abbey-Lambertz: Data curation. Jason A. Mendoza: Writing- Reviewing and Editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jth.2020.100880.

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