

# Cognitive Function of Elderly Persons in Japanese Neighborhoods: The Role of Street Layout

Mohammad Javad Koohsari, PhD<sup>1,2</sup>, Tomoki Nakaya, PhD<sup>3</sup>, Gavin R. McCormack, PhD<sup>4</sup>, Ai Shibata, PhD<sup>5</sup>, Kaori Ishii, PhD<sup>1</sup>, Akitomo Yasunaga, PhD<sup>6</sup>, and Koichiro Oka, PhD<sup>1</sup>

American Journal of Alzheimer's Disease & Other Dementias<sup>®</sup>  
2019, Vol. 34(6) 381-389  
© The Author(s) 2019



Article reuse guidelines:  
sagepub.com/journals-permissions  
DOI: 10.1177/1533317519844046  
journals.sagepub.com/home/aja



## Abstract

**Objectives:** The aims of this study were to examine (a) associations of two metric and space syntax measures of street layout with the cognitive function of Japanese older adults and (b) the extent to which objectively assessed physical activity mediated such associations. **Methods:** Cross-sectional data from 277 older adults who lived in Japan were used. Street layout attributes were objectively calculated for each participant's geocoded home location. The Mini-Mental State Examination was used to evaluate cognitive function. Physical activity was objectively assessed with accelerometers. **Results:** There was a statistically significant negative association between street integration and the odds of having cognitive impairment. Objectively assessed physical activity did not attenuate this relationship. **Conclusions:** Our findings provide unique evidence regarding the importance of the topological aspects of street layouts in (re)designing neighborhoods to support mental illness.

## Keywords

urban design, mental illness, elderly, ageing, built environment, cognitive impairment

## Introduction

Cognitive impairment is one of the most common age-related health problems among the elderly population. For example, a clinical review showed that 10% to 20% of adults aged 65 years and older have mild cognitive impairment.<sup>1</sup> With the rise in an aging population globally,<sup>2</sup> the prevalence of cognitive impairment is expected to grow substantially. While individual-focused interventions remain important in preventing and treating cognitive impairment, there has been growing interest in population-focused interventions such as the role of the surrounding architectural and neighborhood physical environment in supporting the cognitive function of older adults.<sup>3-7</sup> Previous studies suggest that two types of community-level environment measures, including compositional (eg, deprivation index) and contextual (eg, green space) characteristics, might be important for cognitive function in the elderly population.<sup>5</sup> Recent evidence also shows modest positive associations exist between physical activity supportive neighborhood design and access to destinations and older adults' cognitive function.<sup>3</sup> The hypothesis is that the exposure to the surrounding built environment influences the cognitive health of elderly persons. For instance, a recent study conducted in the United Kingdom found an association between higher land use mix (ie, having access to a variety of destinations within an area) and lower odds of cognitive impairment in older adults.<sup>8</sup> A study in Ireland found

that living in a more densely populated area was associated with better cognitive performance.<sup>9</sup>

Street layout—the way streets are connected to each other within an area—is one of the key neighborhood design elements.<sup>10</sup> There is inconclusive evidence regarding whether or not street layout can influence older adults' cognitive function.<sup>11-13</sup> For example, a study conducted in the United States found that living in areas with more connected street layouts, measured by intersection density, was associated with worse cognition among the elderly population.<sup>11</sup> In contrast, a recent study conducted in Singapore found that higher street

<sup>1</sup> Faculty of Sport Sciences, Waseda University, Tokorozawa, Japan

<sup>2</sup> Behavioural Epidemiology Laboratory, Baker Heart and Diabetes Institute, Melbourne, Australia

<sup>3</sup> Graduate School of Environmental Studies, Tohoku University, Sendai, Miyagi, Japan

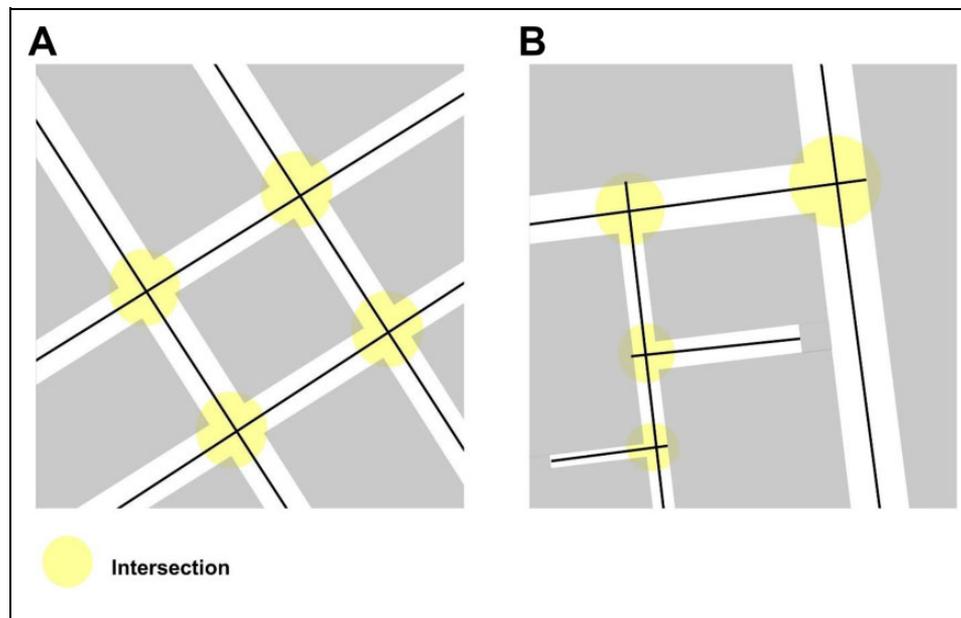
<sup>4</sup> Department of Community Health Sciences, Cumming School of Medicine, University of Calgary, Calgary, Alberta, Canada

<sup>5</sup> Faculty of Health and Sport Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

<sup>6</sup> Faculty of Liberal Arts and Sciences, Bunka Gakuen University, Tokyo, Japan

## Corresponding Author:

Mohammad Javad Koohsari, PhD, Faculty of Sport Sciences, Waseda University, 2-579-15 Mikajima, Tokorozawa, Saitama 1192, Japan.  
Email: javad.koohsari@baker.edu.au



**Figure 1.** Two street layouts with the same intersection density but with different street patterns.

connectivity was associated with better cognitive function in older adults.<sup>12</sup> This observed inconsistency of the effects of street layout on older adults' cognitive function arises because few studies yet exist on this topic. For instance, a recent systematic review found only six studies examining the associations of the neighborhood built environment attributes with cognition among older adults, and only one of them included street layout measures.<sup>3</sup> Additionally, the previous studies used different types of street layout measures in relation to cognitive function. Street layout can be conceptualized by two types of measures: metric and space syntax measures. Metric measures, such as intersection density and link–node ratios, are limited to local and discrete features of a street layout,<sup>14</sup> and they cannot detect how streets are topologically related to each other within a layout. Space syntax measures can evaluate topological aspects of a street pattern, which may be more closely related to how humans navigate within a street network.<sup>15</sup> Figure 1 shows two street layouts with similar metric measures of intersection density, but totally different street patterns. While these two types of measures may be related to each other, they refer to distinctive aspects of street layouts.<sup>16</sup> However, no study has simultaneously analyzed these measures in relation to the cognitive impairment of older adults.

Furthermore, street layout can significantly impact the physical activity of residents; well-connected areas can reduce the walking distances between destinations and provide residents with route choices to traverse between destinations.<sup>17,18</sup> Recent studies have also shown that local destinations are more likely to be located in well-integrated areas, which can further support active travel and physical activity.<sup>19,20</sup> Therefore, physical activity is assumed to be one pathway through which the built environment may influence older adults' cognitive function. Walkable built environments, defined as physical environmental attributes supporting people to be physically active, provide

opportunities for older adults to walk and to socially interact within their surrounding environment, which promotes cognitive function.<sup>8,21</sup> For example, a study among adults aged 50 and older found that physical activity partially mediated the positive associations between the availability of institutional resources, such as schools, libraries, and community centers, and cognition among the white respondents.<sup>21</sup> Nevertheless, to our knowledge, there is only one study that has investigated the mediation effects of walking in the associations between street layout with cognitive function among the elderly population.<sup>13</sup> Watts et al<sup>13</sup> examined the associations between street layout and cognitive function and decline over a 2-year period among a sample of 64 older adults with and without mild Alzheimer's disease. The mediation effects of walking in these relationships were also tested. They found a significant association between higher street integration and cognitive decline in healthy elderly persons over a 2-year period, which was not fully explained by walking. However, the authors used a self-reported walking measure, which may be subject to recall bias.

Therefore, this study aimed to examine: (a) the associations of two metric and space syntax measures of street layout with the cognitive function of older Japanese adults and (b) the extent to which objectively assessed physical activity mediated such associations.

## Methods

### Study Participants and Procedures

Cross-sectional data collected in 2013 from a larger epidemiological study, which aimed to identify social and environmental determinants of health behaviors and outcomes among Japanese older adults, were used in this study. A total of 3000 older residents (65–84 years old) living in Matsudo city, Chiba

Prefecture, Japan, were randomly selected from the government registry of residential addresses, and an invitation letter was posted to them. Of these, 951 agreed to participate in the main study, and 349 also took part in an on-site examination, which was conducted in several health centers across Matsudo city (October to December 2013). During the 2-hour on-site examination, the participants were asked to fill in a paper-based self-administered questionnaire regarding their sociodemographic information. A trained research team member assessed the participants' cognitive function. A book voucher (¥1000) was given to all participants to compensate them for their time. Written informed consent was obtained from all participants. The study was approved by the institutional ethics committee of Waseda University (2013-265) and by the institutional review board of Chiba Prefectural University of Health Sciences (2012-042).

## Measures

**Cognitive function.** The Mini-Mental State Examination (MMSE) was used to evaluate cognitive function.<sup>22</sup> The MMSE is a widely used instrument to screen for cognitive impairment, particularly in older adult populations.<sup>23</sup> The instrument has 30 items, which evaluate five areas of cognitive function including orientation, registration, attention and calculation, memory, and language. The MMSE score ranges from 0 to 30, with higher scores indicating better cognitive function. Several cutoff points for MMSE such as 23 of 24 or 24 of 25 have been used in previous studies to detect dementia.<sup>24</sup> Since MMSE cutoff points are affected by participants' age, education level, and health status, a cutoff value of 25 or lower has been applied to evaluate mild cognitive impairment in healthy older population.<sup>8,25,26</sup> Consistent with these studies and considering our participants were relatively healthy and educated, cognitive impairment was defined as an MMSE score of 25 or lower.

**Physical activity.** Physical activity was objectively assessed using Active style Pro model HJA-350IT (Omron Healthcare, Kyoto, Japan) accelerometers (74.0 × 34.0 × 46.0 mm; 60 g). The detailed algorithm and validation of this type of accelerometer have been described elsewhere.<sup>27,28</sup> The accelerometer device was set to calculate the number of steps and intensity of movement every 10 seconds. Participants wore the accelerometer on their waist for at least 7 days, except when sleeping or during water-based activities (eg, bathing, showering, and swimming). Those who wore the accelerometer for ≥4 days (including 1 weekend day), with at least 10 h/d of wear time, were eligible for this study.<sup>29</sup> Nonwear periods were defined as any sequence of at least 60 minutes of zero counts, with allowance for up to 2 minutes of observations of less than 50 counts per minute.<sup>29</sup> The daily average time spent on light physical activity (LPA; >1.5 to <3.0 metabolic equivalent tasks) and moderate-to-vigorous physical activity (MVPA; ≥3.0 metabolic equivalents) was calculated. These metabolic equivalent levels were similar to those used in previous observational studies of older

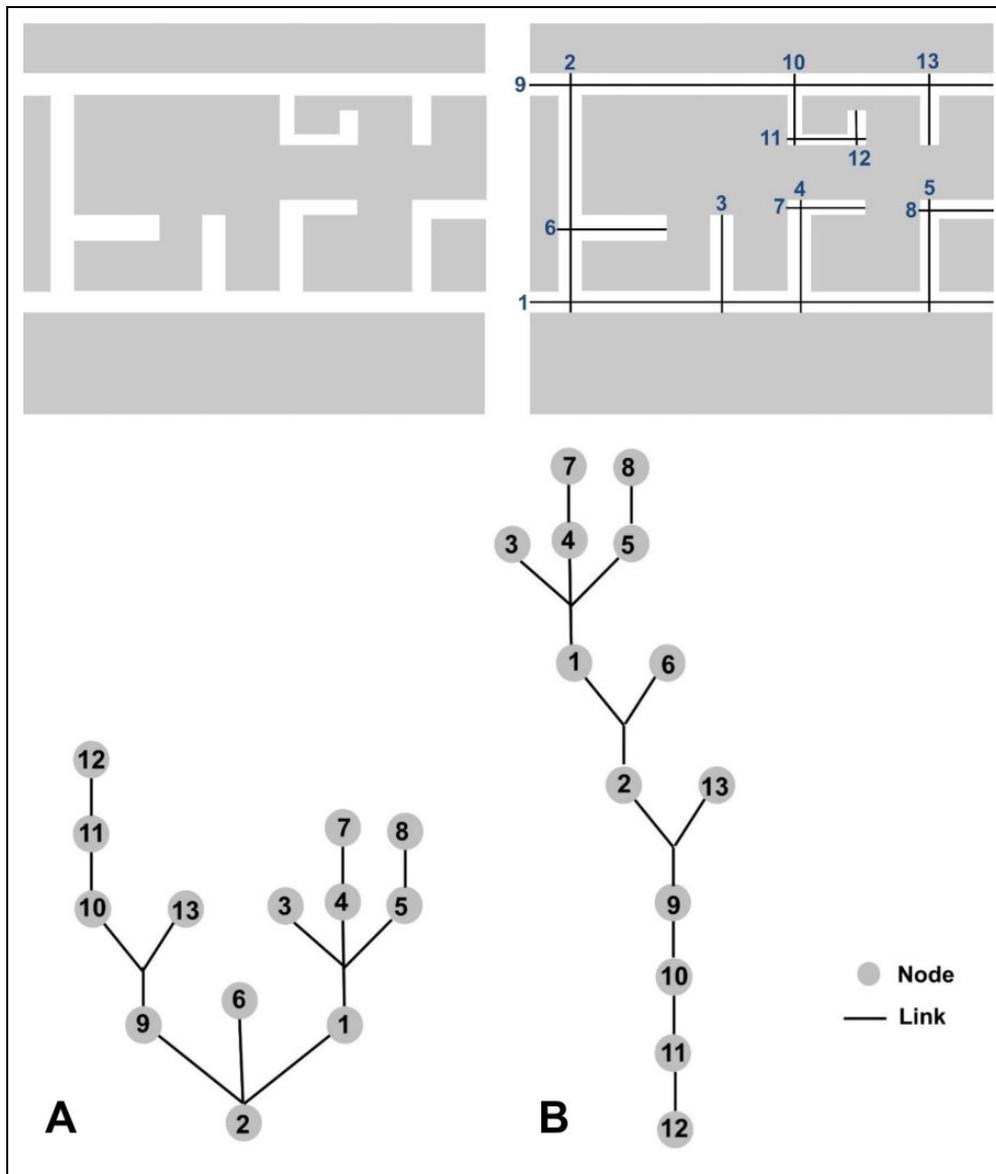
adults.<sup>30,31</sup> The Active Style Pro accelerometer can distinguish between locomotive and household activities.<sup>32</sup> Since locomotive physical activities such as walking and jogging are more likely to be related to street layouts compared with household activities, the former was included in this study.

**Covariates.** Participants reported the following sociodemographic information: age, gender, educational attainment (tertiary or higher, below tertiary), and their number of chronic diseases (based on medical professional diagnosis). Accelerometer wear time was also included as a covariate.

**Street layout.** Two street layout measures, the intersection density and the space syntax measure of street integration, were included in this study. The intersection density was calculated as the ratio of 3-way or more intersections per km<sup>2</sup> using geographic information systems software. The space syntax measure of street integration refers to how streets are topologically related to each other within a network.<sup>33</sup> The first step in calculating a space syntax measure of street integration is drawing "axial lines." Axial lines refer to the longest and shortest sight lines of people moving in an urban environment that entirely covers that space.<sup>34</sup> Space syntax uses the basics of graph theory in quantifying the axial line map; each axial line refers to a "node" in a graph connected to its adjacent lines by "links." A "justified graph" contains all nodes and links for a specific space (axial line), called the root space.<sup>35</sup> Compared with less integrated streets, more integrated streets require fewer turns (ie, changing directions) to reach other streets in that network and have a shallow graph.<sup>36</sup> Figure 2 shows an example of an axial line map for a neighborhood and the justified graphs for two spaces (axial lines) in the network. Segment 2 is more integrated compared to segment 12, because it can be reached with fewer turns from other streets. Street integration was calculated using Axwoman<sup>37</sup> and the University College London DepthMap.<sup>38</sup> Data from Digital Map (Basic Geospatial Information) 2015 was used to calculate these street layout measures. Both street layout measures were calculated within an 800 m network-based buffer around each participant's geocoded home address. This buffer was chosen to be consistent with previous studies examining environmental correlates of older adults' health behavior and outcomes.<sup>39,40</sup>

## Statistical Analysis

Descriptive statistics, including frequencies and measures of central tendency and variation (ie, means, standard deviations [SD]), were estimated for sociodemographic, cognitive function, and physical activity variables. Multivariable binary logistic regression and generalized linear (gamma distribution with log link function) models were used to examine associations between street layout attributes and cognitive impairment and objectively assessed physical activity variables. All models were adjusted for covariates and each street layout attribute was included in a separate model. Those participants (n = 10) who were unable to engage in physical activity were



**Figure 2.** A hypothetical neighborhood (left) and its axial lines (right; numbers represent segment names). Justified graphs using axial line 2 (A) and axial line 12 (B) as the root space.

identified by the following short form-8 (SF-8) item and excluded from the analysis<sup>41</sup>: “During the past 4 weeks, how much did physical health problems limit your physical activities (such as walking or climbing stairs)?” Street layout attributes were standardized (ie, Z-scores) prior to the analysis. Analyses were conducted using Stata 15.0 (Stata Corp, College Station, Texas), and the level of significance was set at  $P < .05$ .

## Results

### Characteristics of Study Participants

After excluding those with invalid or missing accelerometer and cognitive function data and those who were unable to engage in physical activity, data from 277 participants were analyzed. Table 1 shows the characteristics of the study

sample. The mean age was 74.6 years, just over one-third (37.5%) were female, just over one-third (37.5%) had completed a tertiary or higher education, and approximately 37.5% reported having two or more chronic diseases. The mean (SD) length of accelerometer wear time was 15.0 (1.4) h/d. The average (SD) accelerometer-based LPA and MVPA were 0.8 (0.4) and 0.5 (0.4) h/d, respectively. A total of 43 (15.5%) participants had cognitive impairment ( $MMSE \leq 25$ ).

### Associations Between Street Layout Measures and Cognitive Impairment

Table 2 reports associations between the street layout attributes and cognitive impairment. Adjusting for covariates, there was a significant association between higher street integration and

**Table 1.** Characteristics of Study Participants.<sup>a</sup>

Variable	Mean (SD) or n (%)	
	Total (N = 277)	Cognitive Impairment <sup>b</sup> (n = 43)
Age (years)	74.6 (5.4)	75.5 (5.5)
Gender		
Women	104 (37.5)	16 (37.2)
Men	173 (62.5)	27 (62.8)
Education		
Tertiary or higher	104 (37.5)	10 (23.3)
Below tertiary	169 (61.0)	32 (74.4)
Number of chronic diseases		
None or one	173 (62.5)	25 (58.1)
Two or more	104 (37.5)	18 (41.9)
Accelerometer wear time (min/d)	898.4 (87.1)	886.9 (118.8)
Accelerometer-based LPA (min/d)	45.7 (23.6)	41.9 (24.2)
Accelerometer-based MVPA (min/d)	29.7 (25.0)	25.8 (23.7)

Abbreviations: LPA, light physical activity; MVPA, moderate-to-vigorous physical activity; SD, standard deviation.

<sup>a</sup>n = 277.

<sup>b</sup>Mini-Mental State Examination ≤ 25.

lower odds of having a cognitive impairment (odds ratio [OR]: 0.66, 95% confidence interval [CI]: 0.46, 0.95, *P* = .03). This association remained significant even after adjusting for LPA or MVPA. Adjusting for all covariates, there was no significant association between intersection density and cognitive impairment.

**Associations Between Objectively Assessed Physical Activity and Cognitive Impairment**

Objectively measured LPA and MVPA were not significantly associated with cognitive impairment (OR: 0.99, 95% CI: 0.98-1.01, *P* = .46; OR: 0.99, 95% CI: 0.98-1.01, *P* = .41, respectively).

**Associations Between Street Layout Measures and Objectively Assessed Physical Activity**

Table 3 shows the results of the associations between street layout attributes and the objectively assessed LPA and MVPA. Adjusting for covariates, neither the intersection density nor

**Table 2.** Multivariable Logistic Regression Estimate Associations (OR and 95% CI) Between Street Layout Attributes and Cognitive Impairment.<sup>a</sup>

Street Layout Attributes (Z-Scores)	Cognitive Impairment <sup>b</sup>			
	Model 1 OR (95% CI)	Model 2 OR (95% CI)	Model 3 OR (95% CI)	Model 4 OR (95% CI)
Intersection density	0.93 (0.66-1.30)	0.90 (0.64-1.27)	0.89 (0.63-1.25)	0.90 (0.64-1.26)
Street integration	0.69 (0.49-0.98) <sup>c</sup>	0.66 (0.46-0.95) <sup>c</sup>	0.63 (0.44-0.92) <sup>c</sup>	0.64 (0.44-0.92) <sup>c</sup>

Abbreviations: CI, confidence interval; OR, odds ratio.

<sup>a</sup>Model 1: Unadjusted; only one street layout variable was included per each model. Model 2: Adjusted for individual sociodemographic and health information factors (age, gender, education, and number of chronic diseases); only one street layout variable was included per each model plus covariates. Model 3: Adjusted for individual sociodemographic, health information factors (age, gender, education, and number of chronic diseases), and light physical activity; only one street layout variable was included per each model plus covariates. Model 4: Adjusted for individual sociodemographic, health information factors (age, gender, education, and number of chronic diseases), and moderate-to-vigorous physical activity; only one street layout variable was included per each model plus covariates.

<sup>b</sup>Mini-Mental State Examination ≤ 25.

<sup>c</sup>*P* < .05.

**Table 3.** Multivariable Generalized Linear Regression Estimate Associations (Coefficient and 95% CI) Between Street Layout Attributes and Objectively Assessed Physical Activity.<sup>a</sup>

Street Layout Attributes (Z-Scores)	Model 1 <sup>b</sup> (95% CI)	Model 2 <sup>c</sup> β (95% CI) <sup>d</sup>
Intersection density	-0.05 (-0.11 to 0.01)	0.01 (-0.08 to 0.10)
Street integration	-0.05 (-0.12 to 0.01)	-0.06 (-0.17 to 0.03)

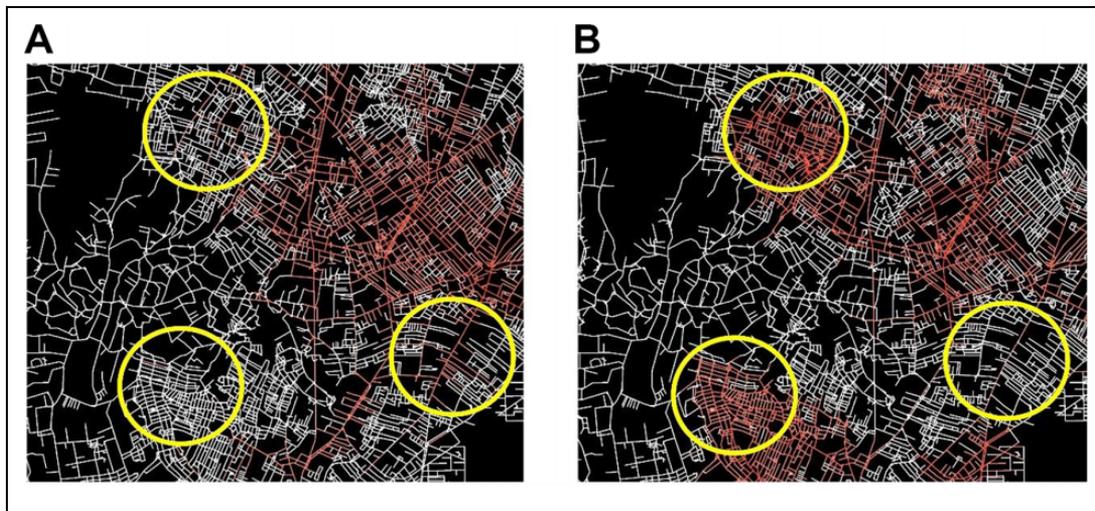
Abbreviation: CI, confidence interval.

<sup>a</sup>All models adjusted for individual sociodemographic information factors (age, gender, educational attainment) and accelerometer wear time; only one street layout variable was included per each model plus covariates.

<sup>b</sup>Light physical activity.

<sup>c</sup>Moderate-to-vigorous physical activity.

<sup>d</sup>β = regression coefficients for standardized street layout variables.



**Figure 3.** Three areas with different values of local and global street integration: (A) global street integration; (B) local street integration (darker red lines show higher integration values).

the street integration was significantly associated with LPA or MVPA.

## Discussion

This study examined associations between neighborhood designs, characterized by different street layouts, and the cognitive impairment of Japanese older adults. We found that the different types of street layout measures, metric and space syntax, have distinctive associations with cognitive function. No association was observed between the intersection density and cognitive function. However, those who lived in areas with more integrated street layouts (as assessed by the space syntax measure of street integration) were less likely to have cognitive impairment compared with those who lived in less integrated areas. This finding is in contrast with the only previous study that has examined the association of the space syntax measure of integration with cognitive function in the elderly population.<sup>13</sup> The study by Watts et al<sup>13</sup> found that higher street integration was associated with cognitive decline in healthy older adults. The authors discussed that neighborhoods with greater integration may have more traffic flow, which deters residents from walking. They also mentioned that more integrated areas are cognitively easier to navigate but offer more initial choices which can be a barrier for self-initiation of walking. However, they used a different type of street integration measure. While “local” street integration at 800 m was applied in our study, Watts et al<sup>13</sup> applied a “global” street integration measure. Street integration can be calculated by considering all other streets in the network (global) or by limiting the calculation to streets within a certain distance (local).<sup>42</sup> Therefore, an area can have a high local but low global, street integration, and vice versa (Figure 3). These two measures of street integration may have distinctive relationships with behavior. For example, local integration was found to be associated with pedestrian flow,<sup>43,44</sup> but global integration was correlated with vehicle

movement.<sup>45</sup> Our findings provide unique preliminary evidence regarding the importance of street integration at local scale on the cognitive function of older adults.

Several previous studies have shown that areas with a higher intersection density and more integrated streets are conducive for physical activity and walking.<sup>46-49</sup> However, in this study, no associations were found between street layout attributes and objectively assessed physical activity. Assuming that older adults’ walking is mainly recreational in nature,<sup>50</sup> our results are consistent with some studies that show no or negative associations between well-connected streets and recreational walking.<sup>14,51</sup> Walking is assumed to be one of the pathways through which walkable neighborhood attributes, such as well-integrated street layouts, may influence cognitive function.<sup>21</sup> However, we found no attenuation effects of objectively assessed LPA and MVPA in the associations between street integration and cognitive impairment. This finding implies that street integration may influence cognitive function through mechanisms other than walking. A recent study conducted in the United States found that neighborhood retail areas tend to be associated with improved cognition of older adults.<sup>11</sup> Several previous studies have also shown that retail destinations tend to be located in more integrated street layouts.<sup>52,53</sup> Older adults who lived in more integrated areas may have better access to retail areas and have more opportunities to socially interact and spend time within their neighborhood. In addition, over time, people tend to minimize their angular deviations while traversing within a network because they intend to unintentionally minimize their brain navigation processing.<sup>15</sup> A more integrated street pattern can allow residents to take cognitively simpler journeys compared with a less integrated pattern because residents need less angular deviations for navigation within the former. Such an integrated street layout was found to be highly correlated with residents’ spatial cognition of their neighborhoods.<sup>54</sup> Thus, building and maintaining an updated cognitive image of a neighborhood with a less

integrated pattern may be difficult for elderly persons, and ultimately, this can be a barrier for them to interact with their neighborhood. Future studies are needed to comprehensively examine multiple pathways in the relationships between well-integrated streets and cognitive function among the elderly population.

This study has some limitations. Similar to other cross-sectional studies, we are unable to draw causal relationships between variables. While MMSE was applied in most of the previous neighborhood-based studies, its limitations should be considered, including being nonspecific and having poor specificity in detecting mild cognitive impairment.<sup>3,55</sup> Only one MMSE cutoff point was used, which was informed by previous studies.<sup>8,25,26</sup> Data from only one city were used in this study, which could have limited the generalizability of our findings. A strength of this study is the use of two objectively assessed street layout attributes. While not context-specific, the use of accelerometers for assessing the physical activity intensities is also considered a strength.

## Conclusions

This study contributes to the evidence of how street layout, a key urban design element, may influence the cognitive function of older adults and explored the mediation effects of objectively assessed physical activity in this relationship. Since the majority of previous studies come from sprawled areas in Western countries, it is unclear how the dense and compact street layouts in Asian cities may affect cognitive impairment in the elderly population. Studies in Asian cities can provide the international field with evidence for how extreme levels of street layouts can be beneficial or detrimental for the mental illness of older adults. Our findings provide unique preliminary evidence regarding the importance of the topological aspects of street layouts in (re)designing neighborhoods to support mental illness.

## Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: M.J.K. was supported by a JSPS Postdoctoral Fellowship for Research in Japan (#17716) from the Japan Society for the Promotion of Science. T.N. was supported by the JSPS KAKENHI (#JP15H02964). K.O. is supported by the MEXT-Supported Program for the Strategic Research Foundation at Private Universities, 2015-2019 the Japan Ministry of Education, Culture, Sports, Science and Technology (S1511017).

## ORCID iD

Mohammad Javad Koohsari  <https://orcid.org/0000-0001-9384-5456>

Tomoki Nakaya  <https://orcid.org/0000-0002-3827-1012>

## References

1. Langa KM, Levine DA. The diagnosis and management of mild cognitive impairment: a clinical review. *JAMA*. 2014;312(23):2551-2561.
2. United Nations Population Division. World population prospects: the 2017 revision—key findings and advance tables. Working Paper No. ESA/P/WP/2482017.
3. Besser LM, McDonald NC, Song Y, Kukull WA, Rodriguez DA. Neighborhood environment and cognition in older adults: a systematic review. *Am J Prev Med*. 2017;53(2):241-251.
4. Cassarino M, Setti A. Environment as ‘brain training’: a review of geographical and physical environmental influences on cognitive ageing. *Ageing Res Rev*. 2015;23(pt B):167-182.
5. Wu YT, Prina AM, Brayne C. The association between community environment and cognitive function: a systematic review. *Soc Psychiatry Psychiatr Epidemiol*. 2015;50(3):351-362.
6. Ferdous F, Moore KD. Field observations into the environmental soul: spatial configuration and social life for people experiencing dementia. *Am J Alzheimers Dis Other Demen*. 2014;30(2):209-218.
7. Marquardt G, Johnston D, Black BS, et al. Association of the spatial layout of the home and ADL abilities among older adults with dementia. *Am J Alzheimers Dis Other Demen*. 2011;26(1):51-57.
8. Wu YT, Prina AM, Jones A, Matthews FE, Brayne C. The built environment and cognitive disorders: results from the cognitive function and ageing study II. *Am J Prev Med*. 2017;53(1):25-32.
9. Cassarino M, O’Sullivan V, Kenny RA, Setti A. Disabilities moderate the association between neighbourhood urbanity and cognitive health: results from the Irish longitudinal study on ageing. *Disabil Health J*. 2017;11(3):359-366.
10. Marshall S. From streets to patterns. In: *Streets and Patterns*. New York, NY: Routledge; 2004:235-258.
11. Besser LM, Rodriguez DA, McDonald N, et al. Neighborhood built environment and cognition in non-demented older adults: the multi-ethnic study of atherosclerosis. *Soc Sci Med*. 2018;200:27-35.
12. Ng TP, Nyunt MSZ, Shuvo FK, et al. The neighborhood built environment and cognitive function of older persons: results from the Singapore Longitudinal Ageing Study. *Gerontology*. 2018;64(2):149-156.
13. Watts A, Ferdous F, Diaz Moore K, Burns JM. Neighborhood integration and connectivity predict cognitive performance and decline. *Gerontol Geriatr Med*. 2015;1:2333721415599141.
14. Baran PK, Rodriguez DA, Khattak AJ. Space syntax and walking in a new urbanist and suburban neighbourhoods. *J Urban Design*. 2008;13(1):5-28.
15. Hillier B, Iida S. Network and psychological effects in urban movement. Paper presented at: Proceedings of Spatial Information Theory: International Conference, COSIT, Berlin; 14–18 September 2005.
16. Hillier B, Turner A, Yang T, Park HT. Metric and topo-geometric properties of urban street networks: some convergences, divergences and new results. *J Space Syntax Studies*. 2010; 1(2):258-279.

17. Handy S, Paterson R, Butler K. *Planning for Street Connectivity: Getting from Here to There*. Chicago, IL: American Planning Association; 2003.
18. Dill J. Measuring network connectivity for bicycling and walking. Paper Presented at: Joint Congress of ACSP-AESOP2004. Washington, DC, 11-15 January 2004.
19. Koohsari MJ, Owen N, Cole R, et al. Built environmental factors and adults' travel behaviors: role of street layout and local destinations. *Prev Med*. 2017;96:124-128.
20. Koohsari MJ, Sugiyama T, Lamb KE, Villanueva K, Owen N. Street connectivity and walking for transport: role of neighborhood destinations. *Prev Med*. 2014;66:118-122.
21. Clarke PJ, Ailshire JA, House JS, et al. Cognitive function in the community setting: the neighbourhood as a source of 'cognitive reserve'? *J Epidemiol Commun Health*. 2012;66(8):730-736.
22. Folstein MF, Folstein SE, McHugh PR. "Mini-Mental State": a practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res*. 1975;12(3):189-198.
23. Kurlowicz L, Wallace M. The Mini-Mental State Examination (MMSE). *J Gerontol Nurs*. 1999;25(5):8-9.
24. Lin JS, O'Connor E, Rossom RC, Perdue LA, Eckstrom E. Screening for cognitive impairment in older adults: a systematic review for the US Preventive Services Task Force. *Ann Intern Med*. 2013;159(9):601-612.
25. Nishimura K, Ohi T, Takatsu M, et al. Associations between possession of  $\geq 20$  teeth and mild cognitive impairment in a community-dwelling elderly Japanese population: a 1-year prospective cohort study. *Ann Japan Prosthodont Soc*. 2011;3(2):126-134.
26. Jagger C, Matthews FE, Wohland P, et al. A comparison of health expectancies over two decades in England: results of the Cognitive Function and Ageing Study I and II. *Lancet*. 2016;387(10020):779-786.
27. Kurita S, Yano S, Ishii K, et al. Comparability of activity monitors used in Asian and Western-country studies for assessing free-living sedentary behaviour. *PLoS One*. 2017;12(10):e0186523.
28. Ohkawara K, Oshima Y, Hikihara Y, Ishikawa-Takata K, Tabata I, Tanaka S. Real-time estimation of daily physical activity intensity by a triaxial accelerometer and a gravity-removal classification algorithm. *Br J Nutr*. 2011;105(11):1681-1691.
29. Healy GN, Matthews CE, Dunstan DW, Winkler EA, Owen N. Sedentary time and cardio-metabolic biomarkers in US adults: NHANES 2003-06. *Eur Heart J*. 2011;32(5):590-597.
30. Gibbs BB, Brach JS, Byard T, et al. Reducing sedentary behavior versus increasing moderate-to-vigorous intensity physical activity in older adults: a 12-week randomized, clinical trial. *J Aging Health*. 2017; 29(2): 247-267.
31. Espinel PT, Chau JY, van der Ploeg HP, Merom D. Older adults' time in sedentary, light and moderate intensity activities and correlates: application of Australian time use survey. *J Sci Med Sport*. 2015;18(2):161-166.
32. Oshima Y, Kawaguchi K, Tanaka S, et al. Classifying household and locomotive activities using a triaxial accelerometer. *Gait Posture*. 2010;31(3):370-374.
33. Hillier B, Hanson J. *The Social Logic of Space*. Cambridge, England: Cambridge University Press; 1984.
34. Liu X, Jiang B. Defining and generating axial lines from street center lines for better understanding of urban morphologies. *Int J Geogr Inform Sci*. 2012;26(8):1-12.
35. Klarqvist B. A space syntax glossary. *Nordisk Arkitekturforskning*. 1993;2:11-12.
36. Hillier B, Vaughan L. The city as one thing. *Prog Planning*. 2007; 67(3):205-230.
37. Jiang B. *Axwoman 6.0: An ArcGIS Extension for Urban Morphological Analysis*. Gävle, Sweden: University of Gävle; 2012.
38. Turner A. *Depthmap 4, a Researcher's Handbook*. London, United Kingdom: Bartlett School of Graduate Studies, University College London; 2004.
39. Hess DB, Russell JK. Influence of built environment and transportation access on body mass index of older adults: survey results from Erie County, New York. *Transport Policy*. 2012; 20:128-137.
40. Kerr J, Norman G, Millstein R, et al. Neighborhood environment and physical activity among older women: findings from the San Diego Cohort of the Women's Health Initiative. *J Phys Act Health*. 2014;11(6):1070-1077.
41. Ware JE, Kosinski M, Bjorner JB, Turner-Bowker DM, Gandek B, Maruish ME. *User's Manual for the SF-36v2 Health Survey*. Lincoln, RI: Quality Metric Lincoln (RI); 2008.
42. Peponis J, Wineman J. Spatial structure of environment and behavior. In: Bechtel RB, Churchman A, eds. *Handbook of Environmental Psychology*. New York, NY: John Wiley; 2002:271-291.
43. Lerman Y, Rofè Y, Omer I. Using space syntax to model pedestrian movement in urban transportation planning. *Geogr Anal*. 2014;46(4):392-410.
44. Ozbil A, Peponis J, Stone B. Understanding the link between street connectivity, land use and pedestrian flows. *Urban Des Int*. 2011;16(2):125-141.
45. Jiang B, Liu C. Street-based topological representations and analyses for predicting traffic flow in GIS. *Int J Geogr Inf Sci*. 2009; 23(9):1119-1137.
46. Sugiyama T, Neuhaus M, Cole R, Giles-Corti B, Owen N. Destination and route attributes associated with adults' walking: a review. *Med Sci Sports Exerc*. 2012;44(7):1275-1286.
47. Kärmeniemi M, Lankila T, Ikäheimo T, Koivumaa-Honkanen H, Korpelainen R. The built environment as a determinant of physical activity: a systematic review of longitudinal studies and natural experiments. *Ann Behav Med*. 2018;52(3):239-251.
48. Barnett DW, Barnett A, Nathan A, Van Cauwenberg J, Cerin E. Built environmental correlates of older adults' total physical activity and walking: a systematic review and meta-analysis. *Int J Behav Nutr Phys Act*. 2017;14(1):103.
49. Sharmin S, Kamruzzaman M. Meta-analysis of the relationships between space syntax measures and pedestrian movement. *Transport Rev*. 2018;38(4):524-550.
50. Kruger J, Ham SA, Berrigan D, Ballard-Barbash R. Prevalence of transportation and leisure walking among US adults. *Prev Med*. 2008;47(3):329-334.
51. Koohsari MJ, Karakiewicz JA, Kaczynski AT. Public open space and walking: the role of proximity, perceptual qualities of the

- surrounding built environment, and street configuration. *Environ Behav.* 2012;45(6):706-736.
52. Omer I, Goldblatt R. Spatial patterns of retail activity and street network structure in new and traditional Israeli cities. *Urban Geogr.* 2016;37(4):629-649.
53. Rui Y, Ban Y. Exploring the relationship between street centrality and land use in Stockholm. *Int J Geogr Inf Sci.* 2014;28(7):1425-1438.
54. Kim YO, Penn A. Linking the spatial syntax of cognitive maps to the spatial syntax of the environment. *Environ Behav.* 2004;36(4):483-504.
55. Kaya D, Isik AT, Usarel C, Soysal P, Ellidokuz H, Grossberg GT. The Saint Louis University Mental Status Examination is better than the Mini-Mental State Examination to determine the cognitive impairment in Turkish elderly people. *J Am Med Dir Assoc.* 2016;17(4):370. e11-e15.