



Neighborhood built environment associated with cognition and dementia risk among older adults: A systematic literature review

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ABSTRACT

Cognitive impairment associated with aging is a serious and growing public health problem. This systematic literature review contributes to better understanding the current state of knowledge on the roles of neighborhood environments in supporting cognitive health in later life. Literature search was carried out in 2020 using the seven databases most relevant to the topic. This review was restricted to peer-reviewed observational and quantitative studies that focused on 1) community-dwelling older adults as target populations; 2) neighborhood built environments as independent variables; and 3) cognition or dementia as outcome variables. Thirty-seven studies published between 1989 and 2020 met the inclusion criteria. The neighborhood built environment domains covered in these included urbanity/rurality, land use, neighborhood physical disorder, transportation infrastructure, urban design, and urban nature. Neighborhood resources and green space exposure were most frequently studied and linked to cognition-related outcomes. Neighborhood built environment was shown to be more pertinent to older adults' global cognition, memory, and dementia. Physical activity showed a mediating role between neighborhood built environment and cognition. The effect of neighborhood built environment on cognitive function was stronger among older women and those with disabilities or lower socioeconomic status. Evidence on the relationship between neighborhood built environment and cognition/dementia among older adults is moderate. Our findings highlight the need for more standardized and longitudinal measures of neighborhood built environment and high-sensitivity cognitive tests that capture the specific and relevant domains of cognition, to facilitate further exploration of the mediating and moderating effects of neighborhood built environment with cognition/dementia in older adults. This review offers insights for future research and policy efforts toward creating communities to support cognitive health and aging in place.

1. Introduction

The world population is aging rapidly. Older adults aged 65 and above was expected to increase to about 1.5 billion worldwide by 2050 (World Health Organization, 2011). Most developed countries including the US have been experiencing a considerable increase in older populations for several decades (He et al., 2016). Such growth has accompanied many public health concerns including dementia. Dementia is not an inherent part of aging, but it mostly affects older adults (Centers for Disease Control and Prevention, 2019). It is a syndrome characterized by a significant decline in a wide range of cognitive abilities such as memory, executive function, and language, which is severe enough to affect an individual's abilities to perform daily activities. There are about 50 million individuals living with dementia worldwide and this

number is projected to reach to 132 million by 2050 (World Health Organization, 2017). In the US, Alzheimer's disease, the most typical type of dementia, is the fifth leading cause of death for older adults aged 65 and older, with 121,499 recorded deaths in 2019 (Alzheimers 'Alzheimer's Association, 2021). Alzheimer's and other dementia in the US are expected to cost about \$355 billion in 2021, adding considerable burdens to the affected families, caregivers, and the health care systems (Alzheimers 'Alzheimer's Association, 2021). Cognitive health is a fundamental determinant of successful aging in place. Given the continuously increasing prevalence of cognitive problems and their comorbidities, it is important to identify modifiable features that can help maintain or promote cognitive functions of older adults (Barnett et al., 2018). Compared to some of the individual factors, such as demographics and genes that are difficult or impossible to change,

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neighborhood environments such as land use, sidewalks, and parks are more readily modifiable through interventions (Rodriguez et al., 2008).

According to the Alzheimer's Association (2021), about 70 percent of people with dementia in the US are living in communities, instead of care facilities. Local communities and neighborhoods hold stronger significance among older people as places for a sense of belonging and for maintaining autonomy and self-contentment (Forsund et al., 2018). There has been a significant increase in the number of studies exploring neighborhood environmental impacts on older adults' cognitive health in the past decade. Based on the socio-ecological model, people's cognitive health can be influenced by the dynamic interactions between individual, societal, and environmental factors (Bronfenbrenner, 1977). A previous literature review of the geographical/physical environmental impacts on cognition found that greenness, level of urbanization, environmental complexity, traffic, and noise were potential predictors of cognitive health in later life (Cassarino and Setti, 2015). The authors of this review paper indicated that environments affected cognition not only directly by exposing people to different levels of cognitive load and multisensory stimulation in close relation to attention and memory performance, but also indirectly by influencing neighborhood socioeconomic status or personal lifestyle behaviors such as physical activity and social engagement (Cassarino and Setti, 2015). Empirical studies also found that living in a dense neighborhood with easy access to local destinations and services can enable more physical activity, which, in turn, benefits cardiometabolic health and helps protect against cognitive decline (Bancroft et al., 2015; Cerin et al., 2020). Older adults tend to be more vulnerable to neighborhood barriers, stressors, or hazards due to their declining physical functioning (related to mobility, daily living, etc.). They also tend to have extended duration of exposure to their neighborhood environments as most do not work outside their home and rely more on proximally located neighborhood resources for social interactions (Glass and Balfour, 2003). Drawing on Lawton's person-environment fit (P-E fit) perspective, supportive living environments can increase older adults' competence in coping with stress (Lawton, 1983; Nahemow and Lawton, 1973). Many empirical studies grounded on the P-E fit model have consistently shown that disadvantaged neighborhoods with limited resources and opportunities for socially-derived cognitive stimulation can expedite cognitive decline, while neighborhoods with sufficient opportunities for social and cognitive activity participation can help promote cognitive health in older adults (Aneshensel et al., 2011; Conroy et al., 2010; Luo et al., 2019).

Built environment (BE), most generally, refers to the human-made physical surroundings (Saelens and Handy, 2008). For the scope of this literature review, neighborhood built environment (NBE) includes the domains of urbanity/rurality, land use, neighborhood physical disorder, transportation infrastructure, urban design, and urban nature. Despite the growing interest in neighborhood environments and cognitive health, to our knowledge, only a small number of review articles have synthesized the current evidence on NBE impacts on cognition/dementia in older adults (Besser et al., 2017; Wu et al., 2015b). One review article, published in 2015, focused on community environment and cognitive function of older adults and classified community environment into two categories: compositional and contextual. It indicated that the majority of the existing studies used compositional measures (e.g. neighborhood socioeconomic status, deprivation index) with limited exploration of contextual measures, the actual settings of a neighborhood (e.g. land use, greenness, food environment) (Wu et al., 2015a). Another relevant review study, published in 2017, identified six studies that examined NBE and cognition, and concluded that the NBE-cognition association was still a nascent field of research that needs further exploration (Besser et al., 2017). Going beyond the previous reviews, we include a large number of new studies on NBE and cognition/dementia through 2020, consider multiple domains of NBE and its measures, and provide a more comprehensive discussion on the specific domains of cognitive function that are associated with different NBE

features. By providing a comprehensive synthesis of the current evidence on the modifiable features of NBE associated with cognition and dementia risk in older adults, our review provides empirical supports for intervention programs and policy initiatives aimed at changing NBE to protect and promote cognitive health of older residents. We expect this study to provide a suggestive direction for researchers, policy-makers, and practitioners on developing strategies to prevent cognitive decline and promote healthy aging in place among older adults. By drawing the evidence from multiple disciplines (e.g. public health, medicine, epidemiology, environment, gerontology), it also brings attention to the importance of interdisciplinary and multi-sectoral/agency collaborations including public health, urban planning and transportation fields/sectors in identifying effective NBE strategies that can contribute to cognitive health and healthy aging among older residents.

2. Methods

2.1. Search strategy

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline (Moher et al., 2009). The three main domains of interest were searched using pre-defined key words and subject headings: built environments (e.g. population density, land use, walkability, street connectivity, nature, parks), cognitive function and dementia (e.g. cognition, Alzheimer's disease, dementia), and older adults (e.g. aged, elderly, senior, later life). The detailed search terms can be found in [Supplementary Table 1](#). A series of systematic literature searches was conducted in September 2020 using seven databases most relevant to the scope of this review including MEDLINE Complete (Ebsco), Academic Search Ultimate (Ebsco), SPORTDiscus (Ebsco), Global Health (Ovid), Embase (Ovid), APA PsycINFO (Ebsco), and CINAHL Complete (Ebsco). Papers published through September 25, 2020, were considered in these searches. We also reviewed the references and citations of the selected studies using Web of Science and Google Scholar to identify additional eligible records. We limited our search to peer-reviewed academic journals or conference papers written in English.

2.2. Eligibility criteria

We screened studies based on the following inclusion criteria: (1) community-dwelling older adults; (2) NBE as an independent variable; and (3) cognition or dementia (e.g., cognitive function, cognitive decline, cognitive impairment, and risk of dementia) as outcome variables. We excluded studies that were: (a) not focusing on BE; (b) not at neighborhood scale (e.g. the studies measuring BE at a larger scale such as region, town, or city); (c) not targeting community-dwelling older adults; (d) focusing on unrelated outcome variables (e.g. general mental health, psychological cognition); (e) not observational and quantitative (e.g. review articles, technical reports); (f) conference paper abstracts or study protocols; and/or (g) not in English. The age threshold used to define older adults varied across studies, and therefore we included studies that the author(s) described their study population as older adults.

2.3. Study selection

The retrieved citations from the database searches were imported into Covidence – a standard online platform for Cochrane reviews (Babineau, 2014). Duplicates were automatically removed in Covidence. Two reviewers performed the title and abstract screening and the full text assessment independently, based on the eligibility criteria described above. Any inconsistencies found during this process were solved by discussing with a third reviewer until an agreement was reached.

2.4. Data extraction

A data extraction template was pre-developed to systematically extract the data from each study, which included: first author, publication year, published journal, field of publication, study design, study location and setting, study participants (e.g. sample size, age, gender, dementia restriction), NBE measures, spatial unit of analysis, confounding variables, outcome variables, moderators and mediators, statistical analyses, and findings on the NBE-cognition/dementia association. Two reviewers completed the data extraction independently and a third reviewer joined the process to discuss and resolve inconsistencies.

2.5. Quality assessment

We evaluated the methodological quality of each included study using a pre-established assessment rubric (Supplementary Table 2) which was adapted from several published quality assessment tools (Effective Public Health Practice Project, 1998; National Institutes of Health, n.d.; Zhong et al., 2020). The assessment rubric contained four domains: (1) study design, (2) selection bias, (3) data collection methods, and (4) statistical analyses. We classified the included studies into three categories based on the total score ranging from 0 to 9: high-quality (scores of 7–9), moderate-quality (scores of 4–6), and low-quality (scores of 0–3). Two reviewers evaluated the quality of each included study independently and a third reviewer helped resolve inconsistent evaluations.

3. Results

3.1. Identification of studies

Fig. 1 presents the literature search and selection process. A total of 24,753 records were identified through the initial search in seven databases using the pre-identified key words and subject headings described earlier. After excluding 10,075 duplicates and 14,576 irrelevant records from the title and abstract screening, 102 records remained for the full-text review. We further removed 72 studies based on the exclusion criteria and identified 30 eligible studies. Another seven studies were identified by checking the citations and references of the 30 eligible studies, which brought the total number to 37. **Table 1** presents the quality assessment results of the 37 eligible studies. Of the 37 studies, the majority ($n = 27$; 73.0 %) were in the moderate-quality category, followed by the high-quality category ($n = 7$; 18.9 %) and

the low-quality category ($n = 3$; 8.1 %). The detailed data extraction results of the 37 studies are presented in Supplementary Table 3.

3.2. Characteristics of the reviewed studies

Table 2 shows the general characteristics of the 37 identified studies published between 1989 and 2020. Among the 37 studies, 34 studies were published since 2015 and only one study was published before 2000. NBE-related studies showed a trend of rapid growth from 2015 to 2020. The top three countries with the largest number of studies were the U.S. ($n = 13$; 35.1 %), the U.K. ($n = 7$; 18.9 %), and China ($n = 5$; 13.5 %). **Fig. 2** presents the total number of publications by study year and location. Two major fields of publication were medicine ($n = 13$; 35.1 %) and public health ($n = 12$; 32.4 %). In terms of the study design, cross-sectional studies ($n = 24$; 64.9 %) were more common, but 13 studies (35.1 %) used a longitudinal design. For the study settings, urban settings ($n = 16$; 43.2 %) were more popular studied, compared to rural or suburban settings ($n = 8$; 21.6 %). Sample size varied greatly across studies, ranging between 64 and 2,165,268, and the majority had a sample size of greater than 400 ($n = 31$; 83.8 %). As for the age cut-off for older adults' inclusion, almost half ($n = 17$; 45.9 %) of the studies used the age of 65 as a threshold for older adults' inclusion, followed by the age of 45 ($n = 7$; 18.9 %), the age of 50 ($n = 5$; 13.5 %), the age of 55, ($n = 4$; 10.8 %), and the mean age of the studied cohort ($n = 4$; 10.8 %). In terms of the definition of a neighborhood, 19 (51.4 %) studies used spatial boundaries (e.g. 0.5-mile, 1-mile buffer) around participants' home; 15 (40.5 %) studies relied on administrative boundaries (e.g. U.S. Census tracts, Census blocks, and U.K. postcodes); one (2.7 %) study (Estrella et al., 2020) used a subjective definition based on the self-report of where daily routines were performed, such as shopping, visiting friends or going for religious activities; and two (5.4 %) studies did not provide a clear definition of the neighborhood used in their studies.

3.3. Variables examined in the review studies

3.3.1. Neighborhood built environment variables and measures

The NBE variables examined in the reviewed studies were grouped into six domains (**Table 2**): (1) urbanity/rurality ($n = 4$; 10.8 %); (2) land use ($n = 15$; 40.5 %); (3) neighborhood physical disorder ($n = 5$; 13.5 %); (4) transportation infrastructure ($n = 11$; 29.7 %); (5) urban design ($n = 4$; 10.8 %); and (6) urban nature ($n = 13$; 35.1 %). Urbanity/rurality usually reflects development intensity or complexity of a living environment (Wörn et al., 2017). The urbanity/rurality domain in our reviewed studies contains community size and residential density. Community size was measured by population density or the number of residents within a community. Residential density was captured by the number of addresses within a certain area or the mix of housing types in a neighborhood (e.g. a large proportion of single-family housing indicated low residential density). The land use domain covered neighborhood physical resources availability, accessibility, destination density, walkability, and land use mix. The neighborhood resources included a wide range of local amenities, basic infrastructure, and services for daily life, such as community centers, health care services, recreational facilities, libraries, churches, schools, and food stores. Destinations covered social engagement places (e.g. entertainment), institutional destinations (e.g. libraries, schools, and churches), and utilitarian destinations (e.g. barbers and grocery stores). The neighborhood physical disorder domain included composite variables, such as physical disorder index and street disrepair index, which were created by combining multiple individual disorder items (e.g. graffiti, litter, noise, vacant buildings). The transportation infrastructure domain contained measures related to traffic safety, public transit, residential distance to roads, street integration, street connectivity, intersection density, infrastructure for walking and cycling, road tidiness, and handicapped access. Urban design covered aesthetics and pleasantness, streetscape/public

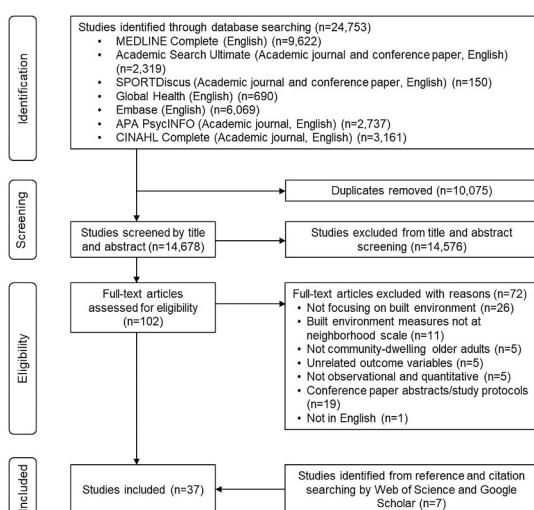


Fig. 1. Flow chart of the literature search process.

Table 1

Quality assessment of the reviewed studies (N = 37).

	Study design	Selection bias		Data collection methods		Statistical analyses	Total score	Quality
		Sampling	Sample size justification	Outcome variables	BE variables			
Astell-Burt et al. (2020)	2	2	0	1	1	2	8	High
Bastos et al. (2015)	0	2	0	1	0	1	4	Moderate
Besser et al. (2019)	0	1	0	1	1	2	5	Moderate
Besser et al. (2018)	0	1	0	1	1	1	4	Moderate
Brown et al. (2018)	0	1	0	1	1	1	4	Moderate
Cassarino et al. (2020)	0	0	1	1	1	1	4	Moderate
Cassarino et al. (2018)	0	2	0	1	1	1	5	Moderate
Chen et al. (2017)	2	2	0	1	1	2	8	High
Cherrie et al. (2018)	2	2	0	1	1	1	7	High
Cherrie et al. (2019)	2	2	0	1	1	1	7	High
Clarke et al. (2012)	0	2	0	1	1	1	5	Moderate
Clarke et al. (2015)	2	1	0	0	0	1	4	Moderate
de Keijzer et al. (2018)	2	1	0	1	1	2	7	High
Estrella et al. (2020)	0	1	0	1	1	1	4	Moderate
Finlay et al. (2020)	0	2	0	1	1	2	6	Moderate
Guo et al. (2019)	0	0	0	1	1	1	3	Low
Katayama et al. (2020)	0	0	0	1	1	1	3	Low
Koohsari et al. (2019)	0	2	0	1	1	1	5	Moderate
Lee and Waite (2018)	0	2	0	1	1	1	5	Moderate
Luo et al. (2019)	2	1	0	1	0	1	5	Moderate
Magaziner and Cadigan (1989)	0	2	0	1	0	1	4	Moderate
Ng et al. (2018)	0	1	0	1	1	1	4	Moderate
Paul et al. (2020)	2	1	0	1	1	2	7	High
Saenz et al. (2018)	0	2	0	1	1	1	5	Moderate
Sharifian et al. (2020)	2	2	0	1	0	1	6	Moderate
Tani et al. (2019)	0	1	0	1	1	2	5	Moderate
Watts et al. (2015)	2	0	0	1	1	1	5	Moderate
Wellenius et al. (2012)	2	1	0	1	1	2	7	High
Wörn et al. (2017)	2	1	0	1	1	1	6	Moderate
Wu et al. (2020)	0	1	0	1	1	1	4	Moderate
Wu et al. (2017a)	0	2	0	1	1	1	5	Moderate
Wu et al. (2015a)	0	1	0	1	1	1	4	Moderate
Wu et al. (2017b)	0	2	0	1	1	2	6	Moderate
Yuchi et al. (2020)	0	1	0	1	1	2	5	Moderate
Zaheed et al. (2019)	0	1	0	1	0	1	3	Low
Zhu et al. (2019)	2	1	0	1	1	1	6	Moderate
Zhu et al. (2020)	2	1	0	1	1	1	6	Moderate

Note: High-quality: total scores of 7–9; Moderate-quality: total scores of 4–6; Low-quality: total scores of 0–3.

space quality, and residential environment quality. Streetscape/public space quality was evaluated based on whether the public spaces were in good or poor conditions. Residential environment quality was an aggregated measure developed based on four major NBE aspects including physical disorder, maintenance of private spaces, design of defensible spaces, and natural features. Urban nature included measures related to green space/park area and park availability at childhood, adolescent, or adulthood.

Among the 37 studies, the majority ($n = 29$; 78.4 %) relied on objective measures alone to capture NBE; six studies (16.2 %) used subjective measures alone; and two studies (5.4 %) employed both objective and subjective measures. Neighborhood urbanity/rurality, captured by population density (Cassarino et al., 2018), number of residents within a neighborhood (Saenz et al., 2018), or residential density (Ng et al., 2018; Wörn et al., 2017), was objectively measured based on the Census or other governmental data. Two studies utilized street or visual images audits to objectively evaluate the quality of NBE surrounding residences (Clarke et al., 2015; Wu et al., 2017a). The geographical Information System (GIS) was widely used as an objective measurement tool to capture specific BE features, such as destinations density (Besser et al., 2018, 2019; Ng et al., 2018), land us mix (Ng et al., 2018), availability of healthy food stores (Tani et al., 2019), accessibility of local amenities (Wu et al., 2020), residential proximity to major roads (Chen et al., 2017; Wellenius et al., 2012; Yuchi et al., 2020), intersection density (Koohsari et al., 2019), street connectivity (Ng et al., 2018; Watts et al., 2015), street integration (Watts et al., 2015), and availability of green spaces (Cherrie et al., 2018, 2019; Clarke et al., 2012; Wu et al., 2020). Walkability was objectively measured either by

developing composite indices such as the walkability index (a weighted combination of street connectivity, land-use mix, and residential density) (Ng et al., 2018) or by Walk Score, calculated based on the distance to the frequently used destinations nearby such as grocery stores and retails (<https://www.walkscore.com/>) (Guo et al., 2019; Katayama et al., 2020). The Normalized Difference Vegetation Index (NDVI) (Rhew et al., 2011), a satellite image-based vegetation index, was widely utilized to objectively measure urban nature (Brown et al., 2018; de Keijzer et al., 2018; Paul et al., 2020; Yuchi et al., 2020; Zhu et al., 2019, 2020). Among the eight studies using subjective measures of NBE based on respondents' perceptions, two studies (Estrella et al., 2020; Ng et al., 2018) adopted questions from validated survey scales including the Neighborhood Environment Walkability Scale (NEWS) (Brownson et al., 2009) and Mujahid et al. (2007), while the other six studies (Cassarino et al., 2020; Luo et al., 2019; Magaziner and Cadigan, 1989; Sharifian et al., 2020; Tani et al., 2019; Zaheed et al., 2019) relied on questions that were developed on their own.

3.3.2. Cognition related outcome variables and measures

The examined outcome variables were classified into three categories: overall cognitive function ($n = 27$; 73.0 %); domain-specific cognitive function ($n = 12$; 32.4 %); and dementia ($n = 11$; 29.7 %). The overall cognitive function included global cognition, cognitive change/decline over time, cognitive vulnerability (cognitive failures in attention, memory, and motor function, and the level of sensitivity to the surrounding sensory stimulus), and cognitive impairment. The domain-specific cognitive function covered memory (e.g. episodic memory, immediate and delayed memory recall, and working memory), sensation

Table 2

Characteristics of the identified studies (N = 37).

Study characteristics	No.	%
Publication year (1989–2020)		
1989–1999	1	2.7 %
2000–2020	36	97.3 %
Field of publication		
Environment	3	8.1 %
Aging	9	24.3 %
Medicine	13	35.1 %
Public Health	12	32.4 %
Theory applied		
Not mentioned at all	22	59.5 %
Just mentioned	5	13.5 %
Used to guide the study	10	27.0 %
Study design		
Cross-sectional	24	64.9 %
Longitudinal	13	35.1 %
Region of study location		
North America	16	43.2 %
Europe	11	29.7 %
Asia	9	24.3 %
Other regions	3	8.1 %
Study setting		
Urban only	9	24.3 %
Suburban only	1	2.7 %
Urban and rural	7	18.9 %
Not specified/general	20	54.1 %
Sample size (64–2,165,268)		
<400	6	16.2 %
≥400	31	83.8 %
Gender		
Female only	2	5.4 %
Both male and female	35	94.6 %
Age cut-off for older adults' inclusion		
Aged 45+	7	18.9 %
Aged 50+	5	13.5 %
Aged 55+	4	10.8 %
Aged 65+	17	45.9 %
Mean age of a cohort	4	10.8 %
Definition of neighborhood		
Administrative boundary	15	40.5 %
Spatial boundary	19	51.4 %
Subjective boundary	1	2.7 %
No clear definition	2	5.4 %
Neighborhood built environment		
<i>Neighborhood built environment measures</i>		
Objective measures alone	29	78.4 %
Subjective measures alone	6	16.2 %
Both objective and subjective measures	2	5.4 %

Table 2 (continued)

Study characteristics	No.	%
Neighborhood built environment domains		
Urbanity/rurality	Ob = 3; Both = 1	4 10.8 %
Land use	Ob = 12; Sub = 2; Both = 2	15 40.5 %
Neighborhood physical disorder	Ob = 2; Sub = 3	5 13.5 %
Transportation infrastructure	Ob = 9; Sub = 1; Both = 1	11 29.7 %
Urban design	Ob = 2; Sub = 2	4 10.8 %
Urban nature	Ob = 13	13 35.1 %
Cognition/dementia outcomes		
<i>Cognition/dementia outcome measures</i>		
Subjective measures by self-report alone		1 2.7 %
Objective measures by cognitive tests alone		26 70.3 %
Objective measures by diagnosis alone		7 18.9 %
Objective measures by both cognitive tests and diagnosis		3 8.1 %
<i>Cognition/dementia outcome domains</i>		
Overall Cognitive function		27 73.0 %
Global cognition	Ob-T = 18	18 48.6 %
Cognitive change/decline over time	Ob-T = 9	9 24.3 %
Cognitive vulnerability	Sub = 1	1 2.7 %
Cognitive impairment	Ob-T = 6	6 16.2 %
Specific cognitive function		12 32.4 %
Memory	Ob-T = 12	12 32.4 %
Sensation and perception	Ob-T = 2	2 5.4 %
Motor skills and construction	Ob-T = 1	1 2.7 %
Attention and concentration	Ob-T = 5	5 13.5 %
Processing speed	Ob-T = 6	6 16.2 %
Language/verbal skills	Ob-T = 8	8 21.6 %
Executive function	Ob-T = 4	4 10.8 %
Dementia	Ob-T = 1; Ob-D = 10	11 29.7 %

Note: Ob = objective measures only; Sub = subjective measures only; Both = both objective and subjective measures; Ob-T = objective measures by cognitive testing; Ob-D = objective measures by diagnosis.

and perception (e.g. recognition and orientation), motor skills and construction (e.g. visuospatial and constructional), attention and concentration, processing speed, language and verbal skills (e.g. verbal fluency and verbal learning), and executive function (e.g. problem solving and reasoning) (Harvey, 2019). Memory (n = 12; 32.4 %) and language/verbal skills (n = 8; 21.6 %) were most frequently examined and linked with NBE. Among the 37 studies, eight studies (21.6 %) examined both the overall and domain-specific cognitive function; almost half of the studies (n = 18; 48.6 %) examined overall cognitive function alone; and three studies (8.1 %) examined domain-specific cognitive function alone.

Table 3 presents the measurement instruments/methods used to capture each cognition/dementia outcome. Objective cognitive testing was the predominant approach to measure both overall and domain-specific cognitive function. Clinical diagnosed measures were adopted primarily in studies that dealt with dementia-related outcomes. Only one study (Cassarino et al., 2020) measured cognition based on self-reported survey. Mini Mental State Examination (MMSE) (Folstein

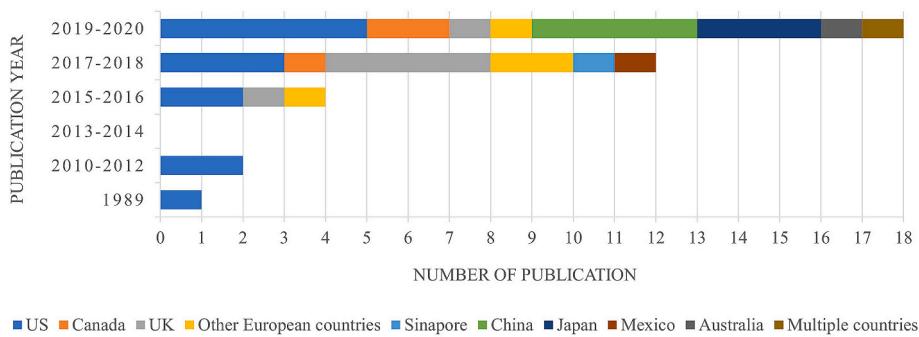


Fig. 2. Total number of publications by year and study location.

et al., 1975) and its adapted versions were the most popular cognitive tests (used in 14 studies, 37.8 %). To capture global cognition, most studies utilized a single cognitive test (e.g. MMSE), while six studies generated composite scores based on multiple cognitive tests (Clarke et al., 2015; de Keijzer et al., 2018; Estrella et al., 2020; Finlay et al., 2020; Luo et al., 2019; Watts et al., 2015).

3.4. Associations between neighborhood built environment and cognition/dementia outcomes

Table 4 shows the significant and nonsignificant associations between each NBE attribute and each cognition/dementia outcome.

3.4.1. Urbanity/rurality

Three studies reported a positive cross-sectional association between levels of urbanity and cognitive function. Specifically, Cassarino et al. (2018) found that residing in neighborhoods with medium-to-high population density was associated with better global cognition, memory, processing speed, and executive function in Irish older adults. Saenz et al. (2018) demonstrated that living in rural communities with a smaller number of residents performed worse in verbal learning, verbal memory, verbal fluency, attention, and orientation among Mexican older adults. In Wörn et al. (2017), higher residential density predicted better global cognition, processing speed, problem solving, and episodic memory among Dutch older adults. However, the positive relationship with processing speed seemed to reverse at the very high level of residential density (Wörn et al., 2017). Only one study found nonsignificant relationships between urbanity and cognition (Ng et al., 2018). There has been no evidence showing longitudinal changes in cognitive function in response to the exposure to or changes in the levels of urbanity/rurality in a neighborhood (Wörn et al., 2017).

3.4.2. Land use

Land use mix, an attribute set to indicate the diversity and integration of various types of land uses, has been a consistently strong predictor of better cognition (Ng et al., 2018; Wu et al., 2015a, 2017b). In terms of walkability, three studies highlighted the positive effects of living in a walkable neighborhood on cognitive functioning in later life (Guo et al., 2019; Katayama et al., 2020; Ng et al., 2018). The results about the relationship between the neighborhood resource availability and cognition/dementia were mixed. Some studies highlighted the positive effects of neighborhood resources on cognitive health. For example, three studies consistently found that easier access to local amenities (e.g. library, post office, healthy food store) was associated with lower dementia risk in older adults (Guo et al., 2019; Tani et al., 2019; Wu et al., 2020). Clarke et al. (2015) demonstrated that presence of community centers protected against cognitive decline over time. One US study indicated that the cognitive advantages of living in neighborhoods with more institutional resources (e.g. schools, libraries, churches) were only found for white but not African American participants (Clarke et al., 2012). This result suggested that the cultural

barriers may prevent racial/ethnic minority people from gaining a full access to neighborhood resources (Clarke et al., 2012). Some studies, on the other hand, reported nonsignificant associations between the availability of certain neighborhood resources, such as recreational centers and health care facilities, and cognitive function (Bastos et al., 2015; Clarke et al., 2012; Luo et al., 2019; Magaziner and Cadigan, 1989).

3.4.3. Neighborhood physical disorder

Three studies demonstrated that perceived neighborhood physical disorder was a significant predictor of worse cognitive performance in older age (Estrella et al., 2020; Sharifian et al., 2020; Zaheed et al., 2019). However, two studies using objective composite measures of neighborhood physical disorder did not find significant associations with cognition (Clarke et al., 2012; Lee and Waite, 2018). These studies suggested that older adults' perceptions of the neighborhood physical disorder do matter and may have more direct influence on cognitive performance outcomes.

3.4.4. Transportation infrastructure

The significant role of transportation infrastructure in affecting cognition or dementia risk among older adults has been well-documented. Three studies demonstrated the detrimental effects of living closer to major roads on cognitive performance in later life (Chen et al., 2017; Wellenius et al., 2012; Yuchi et al., 2020). Two studies found that residing in neighborhoods with accessible public transit was associated with slower cognitive decline over time (Clarke et al., 2015; Luo et al., 2019). For street connectivity, two studies reported a positive association between objectively measured street connectivity and global cognition (Ng et al., 2018; Watts et al., 2015). In terms of street integration, a measure of the number of route choices that a person has when he/she moves between places, one study demonstrated the protective effects of integrated street layouts on cognitive function (Kooohsari et al., 2019). In contrast, Watts et al. (2015) found that living in areas with high street integration was associated with poorer cognition at baseline and greater decline in verbal memory and attention over two years among healthy older adults. This finding could possibly be due to the cognitive complexity required to navigate the environment with many route choices. Traffic safety, infrastructure for walking and cycling, road tidiness, and handicapped access were not found to be associated with cognition/dementia among older adults (Clarke et al., 2015; Luo et al., 2019; Ng et al., 2018).

3.4.5. Urban design

To date, the number of empirical studies on urban design–cognition/dementia associations among older adults is still limited. Two studies reported positive effects of an aesthetic and pleasant neighborhood on the cognitive performance at older age (Cassarino et al., 2020; Ng et al., 2018). One US study also found that living in a neighborhood with well-maintained public space was associated with a slower rate of cognitive decline over time (Clarke et al., 2015). One study examined

Table 3

Cognition and dementia measurement instruments/methods.

Cognition/dementia outcomes	Measurement instruments/ methods	References ^a
Overall cognitive function		
Global cognition	Mini-Mental State Examination (MMSE) (n = 8) Adapted Chinese version of the MMSE (n = 1) Cognitive Abilities Screening Instrument (CAS) (n = 2) Moray House Test No. 12 (MHT) (n = 2) Montreal Cognitive Assessment (MoCA) (n = 1) Montreal Cognitive Assessment Survey Adaptation (MoCA-SA) (n = 1) National Center for Geriatrics and Gerontology-Functional Assessment Tool (NCGG-FAT) (n = 1) Modified version of Telephone Instrument for Cognitive Status (TICS) (n = 1) Repeatable Battery for the Assessment of Neurocognitive Status (RBANS) (n = 1) Composite Indices: generated based on the results of several different cognitive tests (n = 6)	7, 29, 2, 16, 21, 17, 27, 28, 36, 3, 4, 9, 10, 7, 19, 17, 11, 22, 12, 13, 15, 20, 14, 27
Cognitive change or decline over time	Based on the same testing approaches used in baseline and follow-up (n = 9)	29, 12, 20, 25, 27, 9, 10, 13, 36
Cognitive vulnerability	Cognitive Failure Questionnaire (CFQ) & Adult Sensory Profile and Sensory Processing Scale (ASPPS) (n = 1)	6
Cognitive impairment	Mini-Mental State Examination (MMSE) (n = 4) Adapted Chinese version of the MMSE (n = 2)	33, 18, 31, 32, 36, 37
Domain-specific cognitive function		
Memory (e.g. episodic memory, immediate and delayed memory recall, working memory)	Repeatable Battery for the Assessment of Neurocognitive Status (RBANS) (n = 1) Digit Span Forward (DSP) & Digit Span Backward (DSB) (n = 2) Cross Cultural Cognitive Examination (CCCE) (n = 1) Brief Spanish-English Verbal Learning Test (B-SEVLT) (n = 1) Consortium to Establish a Registry for Alzheimer's Disease (CERAD) (n = 2) Wechsler Memory Scale (WMS) & Free and Cued Selective Reminding Task (FCSRT) (n = 1) Hopkins Verbal Learning Test-Revised (HVLT-R) & Clock-in-the-Box Test (CIB) (n = 1) Dutch version of the Auditory Verbal Learning Test (AVLT) (n = 1) Non-standardized recall tests (n = 2)	22, 3, 4, 24, 14, 25, 35, 27, 28, 29, 7, 13, 24, 28, 29, 22
Sensation and perception (e.g. recognition, orientation)	Cross Cultural Cognitive Examination (CCCE) (n = 1) Hopkins Verbal Learning Test-Revised (HVLT-R) Recognition (n = 1)	24, 28, 22

Table 3 (continued)

Cognition/dementia outcomes	Measurement instruments/ methods	References ^a
Motor skills and construction (e.g. visuospatial, constructional)	Repeatable Battery for the Assessment of Neurocognitive Status (RBANS) (n = 1) Digit Span Forward (DSF) & Digit Span Backward (DSB) (n = 1)	4
Attention and concentration	Repeatable Battery for the Assessment of Neurocognitive Status (RBANS) (n = 1) Cross Cultural Cognitive Examination (CCCE) (n = 1) Wechsler Adult Intelligence Scale (WAIS) (n = 1) Trailmaking Test (TMT) Part A (n = 1)	22, 24
Processing speed	Digit Symbol Coding (DSC) (n = 2) Color Trail Making Test Part 1 (CTT1) (n = 1) Wechsler Adult Intelligence Scale-Revised Digit Symbol Substitution Subtest (WAIS-RDSS) (n = 1) Trailmaking Test (TMT) Part A (n = 1)	3, 4, 7, 14
Language/verbal skills (e.g. verbal fluency, verbal learning)	Coding Task (n = 1) Adapted version of the Word Fluency Test of the Multilingual Aphasia Examination (WFTMAE) (n = 1) Brief Spanish-English Verbal Learning Test (B-SEVLT) (n = 1) Cross Cultural Cognitive Examination (CCCE) (n = 1) Repeatable Battery for the Assessment of Neurocognitive Status (RBANS) (n = 1) Animal Fluency Task (AFT) (n = 2) Verbal fluency/animal naming tests (n = 3)	14, 29, 14, 24, 22, 25, 35, 7, 13, 28
Executive function (e.g. problem solving, reasoning)	Color Trail Making Test Part 2 (CTT2) (n = 1) Alice Heim 4 test of intelligence (n = 1) Trailmaking Test (TMT) Part B & Clock-in-the-Box Test (CIB) (n = 1) Raven Colored Progressive Matrices (RCPM) (n = 1)	7, 13, 28, 29
Dementia		
Dementia Incidence	Linking the cohort to the validated databases that provided information of Alzheimer's disease or other dementia (e.g. hospital record) to identify incident cases (n = 5) Entering the medical examination data into a diagnosis algorithm to identify dementia cases (n = 5) Mini-Mental State Examination (MMSE) < 24 (n = 1)	26, 8, 34, 1, 23, 30, 32, 33, 31, 5, 16

Note: a. Study references are present in [Supplementary Table 3](#).

residential environment quality using Residential Environmental Assessment Tool (REAT) which covered street level assessment in four major domains: physical disorder, territorial functioning, defensible space, and natural features. The authors found that living in a neighborhood with high REAT score was associated with higher odds of cognitive impairment in urban areas, but lower odds of being

Table 4

Associations of neighborhood built environment (NBE) with cognition/dementia outcomes.

NBE domain	NBE Attribute	Cognition/dementia outcome										
		Overall cognitive function				Domain-specific cognitive function						Dementia
		GC (n = 18)	CCD (n = 9)	CV (n = 1)	CI (n = 6)	ME (n = 12)	SP (n = 1)	MSC (n = 1)	AC (n = 5)	PS (n = 6)	LVS (n = 8)	EF (n = 4)
Urbanity/rurality (n = 4)	Community size (n = 2)	[7]*(+)				[7]*(+), [24]	[24]*(+)		[24]*(+)	[7]*(-)	[7]*(+), [24]	[7]*(-)
	Residential density (n = 2)	{[22]} ⁽ⁿ⁾ , [29]*(+)	[29] ⁽ⁿ⁾			{[22]} ⁽ⁿ⁾ , [29]		{[22]} ⁽ⁿ⁾	{[22]} ⁽ⁿ⁾	[29]*(+)	{[22]} ⁽ⁿ⁾	[29]*(+)
Land use (n = 15)	Neighborhood physical resources availability (n = 8)	[2] ⁽ⁿ⁾ , [11] [#] , [12]*(-), [12] ⁽ⁿ⁾ , [16] ⁽ⁿ⁾ , {20} [#] , {21} ⁽ⁿ⁾				[22] ⁽ⁿ⁾	[22] ⁽ⁿ⁾	[22] ⁽ⁿ⁾				[16] ⁽ⁿ⁾ , {[26]}*(-), [30]*(-)
	Accessibility (n = 2)	[16]*(+), [22] ⁽ⁿ⁾				[3] ⁽ⁿ⁾ , [4] ⁽ⁿ⁾						[16]*(-)
	Destination density (n = 3)	[3] ⁽ⁿ⁾ , [4]*(-), [15]*(+)										
	Walkability (n = 3)	[16] ⁽ⁿ⁾ , [17]*(+), [22]*(+)				[22]*(+)	[22]*(+)	[22] ⁽ⁿ⁾		[22]*(+)		[16]*(-)
	Land use mix (n = 5)	[3] [#] , [4] ⁽ⁿ⁾ , [22] ⁽ⁿ⁾ , {22}*(+)			[32] ⁽ⁿ⁾ , [33]*(-)	[3] ⁽ⁿ⁾ , [4] ⁽ⁿ⁾ , [22] ⁽ⁿ⁾ , {22}*(+)	[22] ⁽ⁿ⁾ , {22}*(+)	[4] ⁽ⁿ⁾ , [22]	[3] [#] , [4] ^{*(+)}	[22] ⁽ⁿ⁾ , {22}		[32]*(-), [33] ⁽ⁿ⁾
Neighborhood physical disorder (n = 5)	Physical disorder index (n = 5)	[11] ⁽ⁿ⁾ , {14} [#] , [19] ⁽ⁿ⁾	{25} ⁽ⁿ⁾			{14} [#] , {25}				{14} ⁽ⁿ⁾	{14} ⁽ⁿ⁾ , {25}	
	Street disrepair index (n = 1)	[19]*(-)				*(-), {35}*(-)					*(-), {35} ⁽ⁿ⁾	
Transportation Infrastructure (n = 11)	Traffic safety (n = 1)	[22] ⁽ⁿ⁾				[22] ⁽ⁿ⁾	[22] ⁽ⁿ⁾	[22] ⁽ⁿ⁾				[22] ⁽ⁿ⁾
	Public transit (n = 3)	[20] ⁽ⁿ⁾ , [2] ⁽ⁿ⁾ , [12] ⁽ⁿ⁾	{20}*(-), [12] ⁽ⁿ⁾									
	Residential distance to roads (n = 3)	[28]*(+)				[28]*(+)	[28] ⁽ⁿ⁾	[28] ⁽ⁿ⁾		[28] ⁽ⁿ⁾	[28]*(+)	[28] ⁽ⁿ⁾
	Street integration (n = 2)	[27]*(-)	[27] ⁽ⁿ⁾	[18] _{*(-)}	[27] ⁽ⁿ⁾							[8]*(-), [34] [#]
	Street connectivity (n = 2)	[22]*(+), {22} ⁽ⁿ⁾ , [27] ⁽ⁿ⁾	[27] ⁽ⁿ⁾			[22]*(+), {22} ⁽ⁿ⁾ , [27] ⁽ⁿ⁾	{[22]} ⁽ⁿ⁾	{[22]} ⁽ⁿ⁾ , [27] ⁽ⁿ⁾				
	Intersection density (n = 3)	[3] ⁽ⁿ⁾ , [4]*(-)		[18] ⁽ⁿ⁾	[3] ⁽ⁿ⁾ , [4] ⁽ⁿ⁾			[4] ⁽ⁿ⁾		[3] [#] , [4] ⁽ⁿ⁾		
	Infrastructure for walking and cycling (n = 2)	[12] ⁽ⁿ⁾ , {22} ⁽ⁿ⁾	[12] ⁽ⁿ⁾			[22] ⁽ⁿ⁾	[22] ⁽ⁿ⁾	[22] ⁽ⁿ⁾				[22] ⁽ⁿ⁾
	Road tidiness (n = 1)	{20} ⁽ⁿ⁾	{20} ⁽ⁿ⁾									
	Handicapped access (n = 1)	{20} ⁽ⁿ⁾	{20} ⁽ⁿ⁾									
Urban design (n = 4)	Aesthetics and pleasantness (n = 2)	{22}*(+)		{6} [#]		{22} ⁽ⁿ⁾		{22} ⁽ⁿ⁾		{22} ⁽ⁿ⁾		
	Streetscape/public space quality (n = 2)	[12] ⁽ⁿ⁾	[12]*(-)	{6} ⁽ⁿ⁾								
	Residential environment quality (n = 1)				[31] [#]							[31] ⁽ⁿ⁾
	Urban nature (n = 13)	[11] ⁽ⁿ⁾ , [36]*(+)	[13]*(-), [36]*(-)		[32]*(+), [33]*(+), [36]*(-), [37] [#]	[13] ⁽ⁿ⁾				[13]*(+)	[13] _{*(+)}	[1] [#] , [5]*(-), [23]*(-), [30] ⁽ⁿ⁾ , [32]*(+), [33] ⁽ⁿ⁾ , [34]*(-)

(continued on next page)

Table 4 (continued)

NBE domain	NBE Attribute	Cognition/dementia outcome	Overall cognitive function	Domain-specific cognitive function											Dementia
			GC (n = 18)	CCD (n = 9)	CV (n = 1)	CI (n = 6)	ME (n = 12)	SP (n = 1)	MSC (n = 1)	AC (n = 5)	PS (n = 6)	LVS (n = 8)	EF (n = 4)	Dementia (n = 11)	
Park availability at childhood (n = 2)				[9]*(-)											
Park availability at adolescent (n = 1)				[10] ^(a)											
Park availability at adulthood (n = 1)				[10]*(-)											
				[9]*(-)											

Note: Study references are present in Supplementary Table 3.

Abbreviations: GC = global cognition. CCD = cognitive change or decline. CV = cognitive vulnerability. CI = cognitive impairment. ME = memory. SP = sensation and perception. MSC = motor skills and construction. AC = attention and concentration. PS = processing speed. LVS = language and verbal skills. EF = executive function.

□ Objective measures; { } Subjective measures; [] Both subjective and objective measures.

*(+) Significant and positive relationship; *(-) Significant and negative relationship; (n) Insignificant relationship.

Mixed results. Reference 1 (Astell-Burt et al., 2020) has mixed results depending on the detection approach of dementia. In reference 3 (Besser et al., 2019), the positive relationship of destination density, intersection density, or land use mix with processing speed was only found among APOE e2 carriers. The positive relationship between land use mix and global cognition was only found among APOE e2 carriers. In reference 6 (Cassarino et al., 2020), the negative relationship between neighborhood pleasantness and cognitive failure was only found among those living in most and least urbanized areas. In reference 11 (Clarke et al., 2012), the positive association between institutional resources and global cognition was found among White but not among African American. In reference 14 (Estrella et al., 2020), neighborhood physical disorder was negatively associated with global cognition and memory among women but not among men. In reference 20 (Luo et al., 2019), basic infrastructure but not health care services was significantly associated with cognitive function at baseline/change over time. In reference 31 (Wu et al., 2017a), the direction of the association depends on living in urban versus rural areas. In reference 34 (Yuchi et al., 2020), distance to roads was negatively associated with incidence of non-Alzheimer's disease but not with the incidence of Alzheimer's disease. In reference 37 (Zhu et al., 2020), the negative relationship between greenness and cognitive impairment was only found among those non-e4 carriers.

cognitively impaired in rural areas (Wu et al., 2017a).

3.4.6. Urban nature

Six studies consistently demonstrated the cognitive advantages of living in a neighborhood with more greenspace measured by Normalized Difference Vegetation Index (NDVI) (Brown et al., 2018; de Keijzer et al., 2018; Paul et al., 2020; Yuchi et al., 2020; Zhu et al., 2019, 2020). Two life course studies indicated that early-life (childhood and adulthood) park availability was associated with better cognitive aging in later life (Cherrie et al., 2018, 2019). However, two studies reported that higher exposure to greenspace was related to higher odds of cognitive impairment or dementia (Wu et al., 2015a, 2017b); and another two found the relationships between green space/park exposure and cognition/dementia to be insignificant (Clarke et al., 2012; Wu et al., 2020). Astell-Burt et al. (2020) found that the direction of the association between green space and dementia incidence varied by the specific approaches used for dementia detection. In this study, dementia cases were detected using three different approaches: 1) anti-dementia medication; 2) hospitalization/death records; 3) combined measures of 1) and 2). The authors found that more exposure to green space was associated with higher incidence of dementia measured by anti-dementia medication but associated with lower incidence of dementia when the dementia cases were captured based on hospital/death records (Astell-Burt et al., 2020).

3.5. Mediators and effect modifiers of neighborhood built environment – cognition/dementia relationships

3.5.1. Mediators

Twelve studies examined the mediating effects of either individual-level or environmental-level factors. Individual-level health related factors were the most frequently examined mediators. Eight studies tested the mediating effect of physical activity (PA) or walking, but they reported mixed results. Two studies showed that self-reported PA partially mediated the positive association between the availability of institutional resources and cognition (Clarke et al., 2012); the negative association between neighborhood walkability and dementia (Guo et al., 2019); and the negative association between library accessibility and dementia (Guo et al., 2019). However, two other studies showed that self-reported PA did not mediate the negative association between greenness and cognitive change over time (de Keijzer et al., 2018), or between neighborhood physical disorder and cognitive function (Estrella et al., 2020). Self-reported walking time and the frequency of getting out partially attenuated the negative association between healthy food store availability and dementia incidence (Tani et al., 2019) but did not mediate the positive association between street connectivity and cognitive function (Watts et al., 2015). The mediation effects of transportation PA and leisure time activities were significant for both the association between land use mix and cognition, and the association between walkability and cognition (Ng et al., 2018). No attenuation effects of objectively measured light PA and moderate and vigorous PA (using accelerometers) were found in the negative association between street integration and cognitive impairment (Koohsari et al., 2019). Three studies examined the mediating effects of other health related factors. Health insurance and chronic conditions did not play a role in the association between community size and cognition (Saenz et al., 2018). Another study showed that the negative relationship between neighborhood physical disorder and cognitive performance was operated through anxiety symptoms but not through depressive symptoms (Sharifian et al., 2020). Tani et al. (2019) found that Nutritional/weight status, captured by Body Mass Index (BMI) or vegetable/fruit intake, did not mediate the negative association between food store availability and dementia (Tani et al., 2019).

Two studies examined the mediating effects of other individual-level factors. Specifically, Saenz et al. (2018) emphasized that the

detrimental effect of living in a rural community with small number of residents on cognitive function could be partially explained by low education. Clarke et al. (2015) reported that the individual social integration could not mediate the positive relationship between neighborhood resource availability and cognition (Clarke et al., 2015).

Three studies examined the mediating effects of environmental-level factors. Chen et al. (2017) demonstrated that the living closer to major roads increased dementia risk indirectly by exposing residents to air pollution. Lee and Waite (2018) found that neighborhood street disrepair negatively affected cognition indirectly by influencing residents' perception on neighborhood social environment. However, either air pollution or neighborhood social environment was not found to mediate the negative association between greenness and cognitive decline over time (de Keijzer et al., 2018).

3.5.2. Effect modifiers

Eighteen studies explored the potential moderating effects of individual or environmental-level factors on the relationships between NBE and cognition/dementia among older adults. Eight studies examined the effect modification by individual-level sociodemographic characteristics including age, sex/gender, education, race/ethnicity, adulthood occupational social class, and living arrangement. The negative association between urban density (e.g. destination density, intersection density) and global cognition was strongest among non-white older adults (Besser et al., 2018). A higher density of institutional resources was related to better cognitive function among whites, but worse cognitive function among African Americans and Hispanics (Clarke et al., 2012). Higher social destination density was related to poorer cognition only among older adults with low education (Besser et al., 2018). Living closer to the major roads was associated with a higher risk of being cognitively impaired only among those with at least some college education (Wellenius et al., 2012). Cherrie et al. (2018, 2019) reported that the positive association between adulthood park availability and cognitive aging was strongest among women and those with the lowest occupational social class in adulthood. However, two studies found that the protective effects of greenness and cognitive functioning did not vary by sex (Paul et al., 2020; Tani et al., 2019). In terms of age, Zhu et al. (2020) found that the negative association between greenness and cognitive impairment was only found among older adults aged 65–79, but not among those aged 80 and above. Moreover, the detrimental effects of living closer to major roads on cognitive functioning was only observed among those aged 65–77, but not among those older than 77 (Wellenius et al., 2012). However, one study reported that age did not modify the negative relationship between greenness and dementia incidence (Paul et al., 2020). One study examining the modification effect of living arrangement reported that the protective effects of community resource availability (e.g. grocery stores, medical facilities) on older adults' cognition did not vary between those living alone and those living with others (Magaziner and Cadigan, 1989).

Four studies explored the moderating effects by individual-level health related factors including disability or functional limitations, lifestyle activity, PA, and chronic conditions. Zhu et al. (2019) found that the protective effect of greenness on cognitive function was found only for those older people who were physically inactive. Living in car-dependent (less walkable) neighborhoods was associated with higher risk of cognitive impairment among older adults with fewer lifestyle activities. For those with plenty of lifestyle activities, living in car-dependent neighborhoods did not lead to declined cognitive performance at an older age (Katayama et al., 2020). Cassarino et al. (2018) reported that the positive effect of population density on cognitive function was stronger among those with disabilities compared to those without any functional limitations. Paul et al. (2020) showed that chronic conditions (e.g. diabetes, hypertension, stroke, coronary heart disease) did not modify the negative association between green space exposure and dementia incidence in older adults (Paul et al., 2020).

All three studies that investigated the moderating effect of the

apolipoprotein E (APOE) genotype found significant results. Specifically, Cherrie et al. (2018) found that the positive effect of greater adulthood/childhood park availability on cognitive aging was strongest among APOE non-ε4 (ε4 is a generic risk factor for Alzheimer's disease) carriers. Similarly, Zhu et al. (2020) demonstrated that the negative relationship between greenness and the risk of cognitive impairment was only significant among APOE non-ε4 carriers. Besser et al. (2019) revealed that the positive effects of greater proportion of retail land and higher destination density on cognitive function was found only among APOE ε2 carriers.

The environmental-level factors examined in the reviewed studies included neighborhood/country income, road traffic accident density, and development intensity of the living areas. Wu et al. (2020) reported that the protective effects of living close to lifestyle amenities (e.g. café, movie theatres) and health care services (e.g. pharmacy) against dementia were found only among older adults in middle- and low-income countries (Wu et al., 2020). Cherrie et al. (2019) found that the positive association between adulthood park availability and cognitive aging was strongest among those living in areas with low traffic accident density (Cherrie et al., 2019). Brown et al. (2018) and Paul et al. (2020) investigated neighborhood income but did not find it to modify the positive association between green space exposure and dementia incidence among older adults.

Five studies examined the effect modification by the level of development intensity. The negative association between perceived neighborhood pleasantness and cognitive vulnerability was stronger among older adults living in the most rural (countryside) and most urbanized (inner city) areas compared to those living in areas with an intermediate level of urban development (e.g. village, town, city suburbs) (Cassarino et al., 2020). The association between residential proximity to roads and dementia incidence was stronger among Canadian urban residents living in major cities (Chen et al., 2017). Also, Wu et al. (2017a) demonstrated that living in an area with poor residential environment quality was related to about twice higher odds of cognitive impairment among urban residents, compared to the rural residents. Wu et al. (2017) revealed that a higher exposure to natural environments was associated with a lower risk of cognitive impairment among older adults living in highly urbanized areas, but the relationship was unclear among those living in less urbanized areas. The negative association between land use mix and cognitive impairment did not differ by urban versus rural settings (Wu et al., 2017b). Furthermore, Zhu et al. (2019) reported that there was no urban-rural difference in the positive relationship between greenness exposure and cognition.

4. Discussions

Our review summarized the methods and findings of empirical studies that examined the association of NBE with cognitive function and dementia risk among community-dwelling older adults. These studies identified six domains of NBE characteristics that have been linked with older adults' cognitive function or dementia outcomes. Among those, the land use domain was most frequently studied ($n = 15$ studies) but some individual variables examined in these studies (e.g. presence of cross walks, presence of discontinued sidewalks, recreational environment) failed to show any significant relationships with the cognition/dementia outcomes. The urban nature domain was considered in 13 studies, and all but two studies showed significant links with the outcome. Especially, green/park area was the most frequently studied variable across all domains, and nine out of 11 studies that examined this variable showed at least one significant link with the cognition/dementia outcomes. Also, seven of these studies specifically addressed the dementia outcome, and the results generally suggested protective roles of green/park spaces on dementia (3 negative, 1 positive, 1 mixed and 2 insignificant associations). The transportation infrastructure domain followed with 11 studies, but the majority of the individual variables considered in these studies were insignificant

except access to public transit, residential distance to roads, and street network measures (e.g. street integration, street connectivity, intersection density). The remaining three domains of urbanity/rurality, neighborhood physical disorder, and urban design were considered in five or fewer studies with limited empirical support, but the community size variable showed a consistently significant and mostly positive association with cognitive performance. The mediating effects of both individual and environmental-level factors were not confirmatory with the mixed results. Most studies that explored the modification effects of both individual and environmental-level factors found significant relationships, with evidence supporting the moderating effects of NBE-cognition/dementia association by individual demographics, health status, health behaviors, APOE genotype, neighborhood walkability, and an area's level of development intensity. Direct comparisons across studies are not possible due to significant differences in research design, measurement instruments, sample sizes, and the definition of neighborhoods.

This review also revealed several aspects where the existing empirical evidence is weak. Below are the gaps identified in the methodological and substantive knowledge in this body of literature.

4.1. Methodological limitations of reviewed studies

4.1.1. Lack of standardized built environment measures

Inconsistent findings about the roles of the same BE attribute on cognition/dementia may partially be due to the lack of clarity in the definition or standardized measurement instruments for the BE attributes. This issue is also reported in another review (Besser et al., 2017). The same BE attribute was defined and measured differently across studies. For instance, access to public transit was measured by the perceived distance from home to the most frequently used bus stops in one study (Luo et al., 2019), while it was measured by the number of public transportation networks in another study (Bastos et al., 2015).

4.1.2. Limited consideration of long-term built environmental changes/interventions

Most studies used a single time point to assess NBE due to limited data availability. Only two studies considered long-term NBE exposures and found that childhood and adulthood park availability was related to better cognitive aging at an older age (Cherrie et al., 2018, 2019). The significant findings supported the life course theory in that cumulative benefits or risk factors in the early and middle-stage might affect health in later life (Jacob et al., 2017). However, in those two studies, the mean age was 13 and 33 years for childhood and adulthood, respectively. Future studies should consider broader age stages (e.g. toddlerhood, early-childhood, late-childhood, adolescence, early-adulthood, middle-adulthood) to examine the long-term effects of NBE exposure on cognitive function and to identify appropriate time points to measure and assess its impact on health across different age stages.

4.1.3. Lack of assessment on specific urban design features

Most of the examined BE features in the reviewed studies, such as the public park, access to public transit, and land use mix, are among the common features considered important for healthy aging in general. Although an increasing number of studies are using disaggregated measures instead of composite measures to capture the roles of individual BE characteristics, a knowledge gap still remains about the specific urban design elements that may impact the cognitive health and dementia of older adults. A small body of literature outside the scope of this review including the non-peer-reviewed documents proposed potential design solutions to make the outdoor environments dementia-friendly. The key design aspects they considered included distinctive architectural features, sufficient street amenities (e.g. shaded seating, lighting), clear hierarchy of places, wide and plain pavements, simple and explicit signs, and clearly-marked crosswalks (Fleming and Bennett, 2017; Mitchell et al., 2003; Mitchell, 2012). These urban design features

are attractive targets for interventions as they are generally more feasible and sustainable than other large-scale environmental or program-based interventions. Future studies need to identify valid and consistent ways to measure the roles of specific design features and to establish more solid pathways between urban design elements and cognitive health in older adults.

4.1.4. Limited consideration of multidimensional green space measures

Green space, an important NBE feature for promoting healthy aging (Ekkel and de Vries, 2017), has been found to be protective against cognitive impairment/dementia among older adults in many previous studies. Most studies used either aggregated measures, typically NDVI, or a percentage of green space within a neighborhood to quantify the area or density of green space. However, no studies considered specific amenities within parks (e.g. toilets, tennis court, benches, and lighting) or park usage (e.g. frequency of using parks, time spent in parks), which could potentially impact the cognitive health of older adults. In addition, according to Wang and Tassinary (2019), the morphology of green spaces within a neighborhood (e.g. uniform vs. complex shape, fragmented vs. integrated form, level of connectedness between each other) was associated with the risk of mortality, and the effect was stronger for the neighborhoods with higher percentage of older adults. This finding suggested that the overall area/ratio of green space alone might not fully capture the significant variance in health outcomes, and future research should consider the morphology and quality of green space to better assess their roles in impacting the cognitive health of older adults.

4.1.5. Limited assessment on domain-specific cognitive function

Most studies utilized standardized cognitive tests which were valid and reliable. MMSE and its adapted versions were the most commonly used cognitive test instruments. However, this cognitive test tool has been shown to have a low sensitivity in detecting mild cognitive impairments in older adults living in communities (Pinto et al., 2019). Furthermore, most studies assessed overall cognition by constructing a composite score based on the results of a single test or multiple cognitive tests. Less than one third of the studies assessed domain-specific cognitive function. Based on the previous findings, a specific built environment feature might only be pertinent to certain cognitive domains. For instance, neighborhood social destination densities were related to processing speed but not with other cognitive domains including memory, construction, attention and language (Besser et al., 2018, 2019; Ng et al., 2018). A reasonable explanation is that processing speed can benefit from higher levels of PA and walking (Frederiksen et al., 2015) which are related to the destination density of the neighborhood (McCormack et al., 2008). Future studies are encouraged to consider the specific and multiple domains of cognitive function, to help elucidate the underlying mechanism through which NBE influences older adults' cognitive function.

4.1.6. Limited exploration of mediating and moderating effects

Eight of the twelve studies that examined mediators focused on PA or walking outcome, of which seven studies used subjective measures by participants' self-reports and only one study used objective measures (accelerometer measure of PA). The mediating effects of subjectively measured PA or walking were found to be significant in some studies (Clarke et al., 2012; Guo et al., 2019; Ng et al., 2018; Tani et al., 2019). However, this measurement approach often accompanies recall bias as respondents may not remember their previous physical activities accurately, which may limit the ability to detect accurate associations with cognitive function. It is recommended that future studies employ objective measures to capture the levels of PA more accurately and confirm its mediating role in the BE-cognition relationships. Additionally, none of the examined mediators of the association between neighborhood greenness and cognitive decline, including self-report PA, perceived neighborhood social environment and air pollution, were significant (de Keijzer et al., 2018). Therefore, more studies are

encouraged to further explore the underlying mechanism of the longitudinal association between greenness and cognitive decline. Furthermore, anxiety was found to mediate the association between neighborhood physical disorder and cognition (Sharifian et al., 2020). This finding suggests that psychological distress which explains the associations of NBE with cognitive trajectories at an older age might be an important mediator requiring further investigation. Depressive symptoms, a known psychological risk factor for cognitive impairment/dementia in later life (Byers and Yaffe, 2012), was found to be influenced by the poor quality of NBE (Barnett et al., 2018), warranting further exploration of its role as a potential mediator in future studies.

Individual-level factors (sociodemographic characteristics, health behaviors, and health status) were more explored as effect modifiers compared to environmental-level factors (e.g. neighborhood income). Most findings of the effect modification by individual-level factors supported the cumulative disadvantage theory (Wheaton and Clarke, 2003) in that the effects of the same neighborhood environment feature might be stronger among those more vulnerable such as women and those with disabilities or a lower socioeconomic status. The exploration on the age-specific relationships between NBE and cognition/dementia is limited, which is one of the gaps that future research can contribute to. Furthermore, the evidence on the effect modification by environmental-level factors was insufficient to draw any meaningful syntheses. Therefore, more studies are needed to explore the potential environmental-level moderators (e.g. area of residence, neighborhood socioeconomic status) that might modify the NBE-cognition relationship.

4.2. Conceptual limitations of reviewed studies

4.2.1. Lack of integration of relevant theories

More than half ($n = 22$; 59.5 %) of the included studies did not provide any discussions on relevant theories. Some studies briefly mentioned theories in the background and/or introduction sections. Only a few studies used theories to derive research questions and/or guide the variable selection and measurement approaches. Commonly cited theories or conceptual models included person-environment fit model (Lawton and Nahemow, 1973), cognitive reserve model (M Tucker and Stern, 2011), attention restoration theory (Ohly et al., 2016), and life course models (Jacob et al., 2017). A study by Luo et al. (2019) is a good example of utilizing theories to inform the research hypotheses from the beginning and interpret the findings relating to the theories later in the discussion section. Future studies may benefit from using relevant theories to guide the research formulation, execution, and interpretation.

4.2.2. Lack of appropriate definition of neighborhood for older adults

For studies dealing with neighborhood impacts on health outcomes, defining the concept of a neighborhood and delineating its spatial boundary are the prerequisites. There is an emerging trend of defining a neighborhood using spatial boundaries using a street-network based buffer area around each participant's home location with radii ranging from 250 m to 1600 m. Slightly over half of the reviewed studies utilized this approach to create the neighborhood boundary. According to a previous review article, compared to the administrative boundaries, small-scale and individualized buffers can more accurately capture the immediate activity space for older adults given their reduced mobility capacity (Yen et al., 2009). However, study results can differ depending on the definition and size of the neighborhood, and the conceptual definition and the optimal size/shape of the neighborhood for older adults are still largely unknown. Cerin et al. (2017) suggested defining neighborhoods based on older adults' mobility capacity and readiness to walk. With the increasing availability of smartphones and wearable sensors that include a GPS technology, researchers can use a data-driven approach to define the neighborhood based on the actual locations being used or exposed to by older adults. However, the spatial extent of a

neighborhood that may impact cognitive health are likely to be different from and possibly larger than the neighborhood that is defined based on the behavioral/mobility capacity. The dynamic nature of neighborhoods as they are perceived and experienced suggests the need for further work, to guide the development of an operationalizable definition of a neighborhood for the purpose of studying its impacts on older adults' cognitive health.

4.3. Limitations of this systematic review

This review has three major limitations. First, the large variability of the environmental exposure measures limited the ability to quantify the effect size and evaluate the strength of the evidence. However, the gathered evidence at least provided some guidance on what the major concerns are around this topic, calling for more higher-quality research studies to investigate the underlying mechanism of the associations between NBE and cognition/dementia. Second, this review was restricted to peer-reviewed observational and quantitative studies written in English. Publication bias resulted from peer-reviewed articles alone may result in overestimation of the neighborhood effects. Third, the criteria utilized to evaluate the quality of each study was not validated although adapted from existing/published instruments. However, it provided a way to systematically evaluate the methodological strength of the study design, sample, measures, and statistical analysis.

5. Conclusion

This review provided a comprehensive assessment of the current evidence about the relationships between NBE and older adults' cognitive function and dementia. The promising findings for the associations between NBE and cognition/dementia suggest the significance of and need for more attention in this area. Several domains of NBE were shown to impact the cognitive health of older adults, including urbanity/rurality, land use, neighborhood physical disorder, transportation infrastructure, urban design, and urban nature. The reviewed studies showed significant associations of neighborhood size, destination density, land use mix, physical disorders, walkability, and green space exposure with cognition/dementia. Future research needs to consider standardized and long-term NBE measures; develop an appropriate definition of a neighborhood for older adults; examine the roles of specific urban design features, morphology/quality of green spaces, and domain-specific cognitive function; further explore the mediating and moderating effects; and integrate relevant theories into the study design and result interpretation. The findings of this review can also provide insights for policy makers and planning practitioners in the development of community-level environmental intervention strategies to promote cognitive health, lower the risk of dementia among older adults, and support healthy aging in place.

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Appendix A. Supplementary data

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