HHS Public Access
Author manuscript
Soc Sci Med. Author manuscript; available in PMC 2023 September 01.

Published in final edited form as:
Soc Sci Med. 2022 September ; 309: 115220. doi:10.1016/j.socscimed.2022.115220.

Cognability: An Ecological Theory of neighborhoods and cognitive aging

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Abstract

While a growing body of evidence points to potentially modifiable individual risk factors for dementia, the built and social environments in which people develop and navigate cognitive decline are largely overlooked. This paper proposes a new theoretical concept, Cognability, to conceptualize how supportive an area is to cognitive health among aging residents. Cognability incorporates a constellation of both positive and negative neighborhood features related to physical activity, social interaction and cognitive stimulation in later life. We analyzed data from the REasons for Geographic And Racial Differences in Stroke Study, a national sample of older Black and white adults in the United States (n=21,151; mean age at assessment=67; data collected 2006–2017). Generalized additive multilevel models examined how cognitive function varied by neighborhood features. Access to civic and social organizations, recreation centers, fast-food and coffee establishments, arts centers, museums, and highways were significantly associated with cognitive function. Race-, gender-, and education-specific models did not yield substantial improvements to the full-model. Our results suggest that the unequal distribution of amenities and hazards across neighborhoods may help account for considerable inequities observed in cognitive health among older adults. Cognability advances ecological theories of aging through an innovative "whole neighborhood" approach. It aims to identify which specific neighborhood

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The authors have no competing interests to declare.

features are most protective of cognitive health among aging adults to inform upstream public health initiatives, community interventions, and policy.

Keywords

built environment; urban amenities; aging in place; health behaviors; cognitive function; dementia risk; disparities

Introduction

Individuals, families, and communities in every city and town feel the impact of Alzheimer's Disease and Related Dementias (ADRD). Dementia is characterized by cognitive decline, including impairments in memory, attention, and executive function that progressively worsen and contribute to impaired activities of daily living, loss of independence, and mortality.[1,2] Alzheimer's disease is the most common type of dementia. Over six-million Americans and 46-million people globally are living with ADRD, and the number is rising given widespread population aging.[3,4] In the United States (US), the estimated cost of ADRD for 2021 is $355 billion. Further, over 11 million unpaid caregivers provide an estimated 15.3-billion hours of care valued at nearly $257-billion annually.[5] There is no cure for ADRD yet available, making prevention and risk reduction imperative.

A growing body of evidence points to potentially modifiable risk factors for ADRD. This includes diabetes, hypertension, head injury, smoking, air pollution, midlife obesity, lack of exercise, depression, excessive alcohol, social isolation, and low levels of education.[6,7] The *Lancet Commission*[6] estimated that together these modifiable risk factors account for about 40% of dementia cases worldwide which could theoretically be prevented or delayed.

Interventions are needed to tackle these risk factors. Proximal individual-level interventions can address risk factors such as diabetes, hypertension, obesity, and lack of exercise through educational, nutrition, and physical activity programs. Broader upstream societal actions are also needed to improve the contexts in which people age. For example, develop environments where opportunities for physical activity are accessible and safe, air pollution is minimized, and local 'third places' (e.g., coffee shops and senior centers) encourage regular social engagement and support.[6,8,9] Upstream neighborhood-level interventions to reduce ADRD risk can enhance efforts to modify individual lifestyles and behaviors through supportive surrounding built and social environments. They can address structural barriers, encourage widespread behavioral change, and promote public health. Given that the vast majority of people with dementia continue to live in their communities,[5] it is important to consider the role of neighborhood environments to prevent dementia or slow the progression of cognitive decline.

Neighborhoods and healthy aging

Neighborhood environments fundamentally shape health and wellbeing. They are linked to a multitude of ADRD risk factors including physical inactivity;[10,11] depression;[12] obesity, hypertension, and diabetes;[13] and social isolation.[14] Geographic variation in ADRD rates suggest that environmental risk factors may be important in the development of dementia.[8,15] However, the contexts in which people develop and navigate cognitive decline and impairments have been largely overlooked.[16–18] Aside from air pollution and other toxic environmental exposures,[15,19] research on the relationship between neighborhood environments and cognitive outcomes is relatively scarce.[20,21]

A growing body of evidence suggests that neighborhood built environments may be linked to cognitive decline, impairment, and ADRD risk. Greater land use mix,[22] urban density,[16] retail and service access,[23,24] public transit infrastructure,[25,26] walkability,[27] recreational sites,[24,26] and greenness and parks[21,24,28–30] have been associated with better cognitive outcomes among older adults. Social infrastructure associated with improved cognition among older adults includes senior centers, civic and social organizations, eateries,[31,32] community centers,[8] and museums and arts centers.[18] However, other studies have found contradictory evidence. For example, increased access to social and walking destinations (e.g., post offices, restaurants) was associated with worse cognition among Hispanic and Black older adults, while these associations were not observed in non-Hispanic white participants.[23]

Developing a clear understanding of how neighborhood environments are linked to cognitive aging is an especially salient task to understand population health disparities. Public and private amenities and hazards are not uniformly distributed across US geographies, but rather are heavily concentrated within particular neighborhoods, often along the lines of broader, historically informed systems of racism and classism.[18,33,34] If neighborhood conditions impact cognitive health, then their starkly unequal distribution across communities may help to account for considerable inequities observed in ADRD, cognitive function, and cognitive decline.[5] Further identifying if and how neighborhood environments contribute to cognitive aging—including efforts that center the potential uneven experiences of power and privilege to access neighborhood resources—may be critical to democratize cognitive health.

Concept of 'Cognability'

To advance this emerging area of research, our paper proposes a new theoretical concept, *Cognability*, to conceptualize how supportive an area is to cognitive health among aging residents. This research is inspired by walkability, which blends geography, urban planning, and public health to measure how friendly an area is to walking through built and social environmental features such as pedestrian street design, transit nodes, land use mix, parks, greenspace, and welcoming public spaces.[35,36] Senior-specific walkability audit tools evaluate neighborhood items especially pertinent to older adults, such as sidewalk cracks, curb cuts, intersection timing, and benches.[37,38]

Cognability conceptualizes how neighborhood contexts structure opportunities for and barriers to cognitive health in later life (Figure 1). It is grounded in an environmental gerontological approach, which aims to understand the relationship between aging people and their environments, and enhance wellbeing through optimized person-environment fit. Lawton and Nahemow[39] initially conceptualized wellbeing and behavior through the balance of personal competence and environmental press. This evolved into the Ecological

Theory of Aging,[40] which Cognability draws upon. We conceptualize neighborhood environments to include both physical/built characteristics (e.g., amenities and services, land use mix), as well as social contexts (e.g., social cohesion, norms, crime). These characteristics vary by structural factors, such as residential segregation by age, race, and wealth; as well as person-level characteristics such as biology, personality, and individual capital (Figure 1). Cognability advances ecological theories of aging by elucidating person-environment resources[41] specifically relevant to healthy cognitive aging.

The current neighborhood-cognition literature looks at a relatively narrow set of neighborhood features in isolation of one another. It does not capture the lived reality of older adults experiencing multiple environmental features simultaneously. Cognability addresses this by examining a constellation of neighborhood features simultaneously. In this paper, we focus on specific physical neighborhood characteristics as upstream influences on three primary health behaviors linked to improved cognitive aging: (1) physical activity, (2) social engagement, and (3) cognitive stimulation. We also include neighborhood 'disamenities'—hazards and barriers—which may prevent access or disincentivize use of neighborhood resources among aging residents.

Regular *physical activity* can benefit cognitive function and protect against cognitive decline. The neuro-protective pathways include neurogenesis and neuroplasticity; improved cardiovascular function and associated influence on the cerebrovascular system; reduced stress, anxiety, and inflammation; and improved insulin sensitivity.[42–45] Neighborhood resources and amenities that encourage regular exercise in later life include local parks, recreational amenities (e.g., gyms, golf courses, tennis courts), and nearby walkable destinations (e.g., shops, services, parks).[10,11,24,46–49]

Social engagement may boost cognitive health in later life through multiple pathways. Supportive social networks may prevent or minimize harmful responses to stressful events that are damaging to health,[50] including the brain directly through inflammatory pathways.[51] They can help motivate positive health behaviors such as regular exercise and non-smoking.[52] Socialization may also be a form of cognitive reserve to help older adults maintain day-to-day cognitive function.[53–55] Neighborhood places that can support socially-engaged aging in place (the ability to live in one's home and community safely, independently, and comfortably in later life)[56] include 'third places' to gather and interact such as coffee shops and fast-food eateries, senior centers, places of worship, civic and social organizations, bakeries, and grocery stores.[31,32,57–64]

Neighborhoods may also be neuroprotective by facilitating opportunities for *cognitive stimulation*. Navigating environments often involves complex and creative thinking with 'brain training' opportunities.[20,65] Local places can promote cognitively-stimulating activities such as reading, playing and listening to playing music, playing cards and games, solving puzzles, and continued learning.[53,66,67] These activities can enhance neuronal structure and brain function, strengthen processing skills (e.g., working memory, perceptual speed), and thereby protect against neurodegeneration and help compensate for cognitive decline.[68] In addition to boosting cognitive reserve,[69] the 'use it or lose it' hypothesis suggests that routine lack of stimulation in everyday life can lead to greater cognitive decline.[70] Sites that offer dedicated opportunities for cognitive stimulation include libraries, higher education campuses, museums, and performing and visual arts centers.[18,53,66]

In addition to cognitive health-promoting neighborhood infrastructure, there are also notable barriers and hazards. Neighborhood disamenities[33] may pose barriers to accessing and utilizing the above-mentioned community resources, and thereby increase risk for cognitive decline. Furthermore, exposure to stressful environmental features may affect neurogenesis,[71] which is integrally involved in memory function. Highways and polluting sites are physical barriers that can dissuade aging residents from engaging in physical, social, and cognitively-stimulating activities. They also represent pollution sources that pose risks for cognitive decline and ADRD along biological pathways.[6,29,72]

The challenge is to define which constellation of neighborhood environmental dimensions contribute most to healthy cognitive aging. Our paper tackles this challenge by testing multiple neighborhood features for associations with cognitive function and decline in a large aging cohort of Black and white Americans. We recognize that person-place relationships are complex and likely conditional on social factors that confer power and privilege.[18,20,23,73,74] Therefore, our analyses test for how Cognability may vary by age, gender, race, and education. Studying population variation can advance ecological theories of aging by disentangling specific components of person-environment fit,[41] and inform targeted public health and community interventions. Cognability is intended to help policymakers, service providers, community groups, older adults, and researchers advance age-friendly efforts (to develop environments that promote wellbeing, inclusion, and participation as people age),[75] help prevent cognitive decline, and facilitate healthy aging in place. We provide much-needed evidence organized through the novel concept of Cognability to inform upstream health promotion and reduce ADRD risk at the neighborhood scale.

Methods

REasons for Geographic And Racial Differences in Stroke (REGARDS) Study

The REGARDS study is an ongoing, national prospective cohort study. Investigators recruited community-dwelling adults aged ≥45 years from 2003–2007 by mail and telephone. The cohort includes 30,239 Black and white individuals with a mean baseline age of 64 years.[76] Telephone interviews collect demographics, behavioral and lifestyle information, and medical history. In 2006, investigators implemented a cognitive battery during follow-up. Residential addresses were geocoded to census tracts over the follow-up period. The University of Alabama at Birmingham Institutional Review Board annually reviews and approves ongoing study procedures, and all participants provided informed consent.

Measures

Cognitive Function.—The cognitive battery measures verbal learning, memory, and executive function biannually using Word List Learning (WLL), Word List Delayed Recall (WLD), Animal Fluency Test (AFT), and Letter Fluency Test (LF).[77] These cognitive measures were validated for Black and white individuals.[78] In addition, a 5-minute battery was administered beginning in 2009 with select Montreal Cognitive Assessment (MoCA)[79] items.

We did not have a cognitive domain-specific hypothesis. To capture global cognitive function and use multiple sources of information from the REGARDS cognitive assessment, we created a factor score derived from a confirmatory factor analysis of all 5 cognitive tests (WLL, WLD, AFT, LFT, MoCA) across all assessments in the REGARDS follow-up period. The model fit the data well (Root Mean Square Error of Approximation=0.013; Comparative Fit Index=0.999). Further details on the factor analysis are previously published and available in the Appendix.[18,24,32] We output standardized factor scores for each participant at each assessment to use in analyses.

Neighborhood context.—We identified neighborhood characteristics likely related to physical activity, social interaction, and cognitive stimulation—including arts sites, civic and social organizations, coffee shops and fast-food restaurants, grocery stores, higher education campuses, libraries, museums, recreation centers, religious organizations, and senior centers. Establishment variables were derived from the National Establishment Time-Series (NETS) database, which provides annual detailed business records for private for-profit and nonprofit establishments, in addition to government agencies.[80,81] Establishments are categorized by the North American Industry Classification System (NAICS).[82] Three non-establishment contextual variables included highways (derived from the US Census Bureau's TIGER/Line shapefiles[83]), parks (Trust for Public Land's ParkServe[84]), and polluting sites (from the Environmental Protection Agency Toxics Release Inventory[85]). All measures are counts per 1,000 population in a census tract, and top-coded to the 99th-percentile to reduce the potentially outsized influence of exceptional, high-leverage points. If a participant moved within the study period (2006–2017), we updated their census tract measurements accordingly. Our neighborhood variables are described in Table 1.

Covariates

Covariates included individual and contextual-level features shown to be predictive of cognitive function. These measures included: *age at first cognitive assessment* (continuous; centered at 65 years), *sex/gender* (male; female), *race* (Black; white), *highest educational degree* (less than high school; high school; college or more); and *years of follow-up from first assessment* (continuous). Neighborhood-level covariates—derived from the 2008–2012 and 2013–2017 American Community Surveys[86]—included: *census tract population per square mile (i.e., "population density")* (continuous; log-transformed); *proportion of a tract's population living below the poverty line* (continuous); *proportion of a tract's residents who were Non-Hispanic Black* (continuous); and *proportion of housing units in a tract that were owner-occupied* (continuous).

Analytical Sample

REGARDS respondents who participated in at least one wave of data collection between 2006 and 2017 comprised our sample. Respondents varied in when they contributed their first cognitive test to the data, with approximately 80% supplying their first score sometime between 2006 and 2008. Most respondents were tested between 3 to 5 times over this interval. Years of follow-up after baseline ranged from 0 years (i.e., a participant who only contributed a baseline cognitive test to the sample) to 11.6 years. Given our previous urban-based qualitative fieldwork[18,24,31,32] and urban-focused neighborhood health effects literature[87,88] informing our hypotheses, we restricted the sample to individuals living in metropolitan areas, as defined by Rural-Urban Commuting Area Codes.[89] Our final analytic sample included 21,151 adults who contributed 73,228 observations.

Statistical Analysis

We fit Gaussian generalized additive multilevel models (GAMMs) to our sample to examine how cognitive function varied among REGARDS participants in response to the amenities and hazards distributed within their neighborhoods. In *Model 1,* we regressed respondents' cognitive scores on the neighborhood sites described above. To allow for nonlinear associations to potentially emerge from the data, we fit each focal neighborhood predictor as a smooth term, using thin-plate regression splines.[90] To allow for a degree of feature selection during the model fitting process, we specified each smooth term with an additional penalty, as described in Marra and Wood.[91] This additional smoothness penalty allowed for non- or weakly-informative features to be shrunk entirely towards zero. This conservative approach regularized our model and allowed only for the neighborhood features that were most strongly predictive of cognitive function to retain meaningful influence in the final fit.

To help account for features that might alternatively explain variation in cognitive function among participants, we also controlled for the covariates described above (e.g., age; race; neighborhood poverty) in Model 1. To account for non-independent observations—i.e., multiple respondents were clustered within the same geographies and each respondent contributed multiple test scores to the sample across time—we included person-specific intercepts; person-specific time slopes; census tract-specific intercepts; and county-specific intercepts as random parameters. Altogether, Model 1 allowed us to recover a parsimonious set of neighborhood features that were most strongly predictive of cognitive function among REGARDS participants.

To assess whether the set of neighborhood features that were most informative in predicting cognitive function differed among subpopulations within our sample, we fit several additional GAMMs to our data. In *Model 2*, we again regressed cognitive function scores on the penalized smooths of our focal neighborhood features, our full set of demographic and contextual covariates, and the random terms described above. We then specified factor-smooth interactions, which allowed for the association between each neighborhood feature and cognitive function to further vary by race. This model allowed us to assess whether the set of neighborhood conditions that were most strongly predictive of cognitive function were uniform across Black and white REGARDS participants, or if, instead, different contextual environments rendered different benefits across differently racialized sample populations. We repeated this exercise, fitting interactive models along other vectors of social power including gender (*Model 3)* and socioeconomic class, proxied here by educational attainment (*Model 4*).

To evaluate whether subpopulation-specific models offered a more accurate account of the association among neighborhood features and cognitive function, we used Akaike's Information Criterion (AIC).[90] In particular we compared the AIC of Model 1 (i.e., a model that forced the association between each neighborhood feature and cognitive function to be identical across all REGARDS participants) to the AICs of Models 2–4 (i.e., models that allowed for neighborhood determinants of cognitive function to vary by race, gender, and education, respectively). A lower AIC broadly indicates that a model has better predictive accuracy than an alternative specification.

We summarized model results by presenting both estimated model parameters and model-predicted cognitive function scores. We derived predictions by varying a neighborhood feature across its range, while holding all other predictors constant. Model predictions—and their corresponding 90% uncertainty intervals—were formed by taking draws from an approximation of the model posterior distribution. All analyses were performed in R.[92]

Results

Table 2 displays descriptive statistics for our analytical sample. Respondents (n=21,151) contributed 73,228 cognitive scores between 2006 and 2017. Study participants were clustered within 12,669 unique census tracts and 1,074 counties. The average cognitive function score, across the range of the observation period, was approximately 0.02 (SD=2.36). 40% of participants identified as Black; 56% identified as female; and 41% had attained at least a college degree. The average respondent was approximately 67 years old (SD=8.83) at the time of their first cognitive test. Respondents lived in a diverse array of neighborhood environments, with varying degrees of access to neighborhood resources (e.g., number of civic/social organizations per 1,000 population; mean=0.57; SD=0.63) and exposure to neighborhood hazards (e.g., highway density; mean=11.24, SD=14.48). As shown in Supplementary Tables 2 and 3, neighborhood features differed by socio-locational factors, such as race and education.

Table 3 presents parameter estimates for Model 1—a GAMM describing how cognitive function scores varied between sample participants according to the privileges and hazards distributed within their neighborhood environments. In this specification, several individual- and contextual-level covariates helped explain disparities in cognitive function scores observed among respondents. For instance, individuals who were younger at baseline demonstrated significantly higher cognitive function scores than their older counterparts (i.e., a 1-year increase in baseline age was associated with an estimated 0.09 decrease in cognitive function score); individuals who attained a college degree displayed higher scores than those who completed less than a high school degree (by an estimated 1.74 points); and respondents who lived in tracts with lower levels of concentrated poverty demonstrated elevated cognitive health relative to their peers.

In addition to describing between-person differences in cognitive function along several well-studied covariates, Model 1 uncovered a parsimonious set of neighborhood features that were strongly associated with disparities in cognitive function. Here, census tract-level access to recreation centers (*p-value*=0.03); civic and social organizations (*p-value*=<0.001);

fast-food and coffee establishments (*p-value*=0.002); arts organizations (*p-value*=0.025); museums (*p-value*=0.026); and highways (*p-value*=0.002) were estimated to be significant predictors—at a 0.05 level—of individuals' cognitive function scores. Note that Table 3 also shows that several neighborhood predictors were "shrunk" entirely out of the model. For instance–conditional on other covariates–neighborhood access to libraries, parks, and religious organizations offered no appreciable explanation of between-person disparities in cognitive function scores.

To gain a more precise understanding of *how* our focal neighborhood predictors were associated with cognitive function scores, we next simulated predictions from Model 1. In particular, we calculated model predicted cognitive function scores by varying each significant neighborhood feature across its range, while holding all other predictors constant. Figure 2 displays these predictions, along with 90% uncertainty intervals.

The first facet in Figure 2 summarizes how participants' cognitive function scores varied along neighborhood access to civic and social organizations. With all other covariates included in the model held equal, an individual who resided in a tract with no immediate access to civic or social organizations was estimated to have a cognitive function score of 0.264. Predicted cognitive function scores increased with access to civic and social organizations—such that individuals who resided in tracts with the highest observed density of such sites (i.e., 3.53 social organizations per 1,000 population) had predicted cognitive function scores of 0.486. This 0.22-point disparity in scores between individuals situated in environments with the least and most access to civic and social organizations is similar in magnitude to a 2-year difference in baseline age, as estimated by our model.

The second facet of Figure 2 demonstrates that neighborhood highway density was negatively associated with participants' cognitive function. Adults who lived in tracts with no exposure to highways experienced predicted cognitive function scores of approximately 0.338, while adults who resided in neighborhoods with the highest observed exposure to highways demonstrated predicted cognitive function scores of approximately 0.108. This 0.23 difference in predicted scores is, again, similar to a 2-year difference in baseline age.

While neighborhood civic/social organizations and highways shared the most pronounced associations with cognitive function, a handful of other neighborhood features also played detectable roles in structuring disparities among REGARDS participants. Individuals who resided in environments with elevated densities of coffee shops and fast-food establishments appeared to experience lower levels of cognitive function—such that adults who lived in tracts with 0 coffee shops or fast-food restaurants per 1,000 population displayed predicted cognitive function scores 0.15-points higher than adults who lived in tracts with 4 of such establishments per 1,000 residents. Neighborhood densities of art organizations, museums, and recreation centers appeared to play marginal, but significant, roles in predicting cognitive function too: individuals situated in environments that abounded with these amenities displayed estimated cognitive function scores approximately 0.10-points higher than adults who lived in environments that were largely devoid of these sites.

Though Model 1 offers insight into neighborhood drivers of cognitive function among older adults, it washes over critical issues of power—including structurally-imposed barriers that may cause sites to be less accessible, despite their spatial proximity, to particular communities. This includes economic accessibility, in which some sites (e.g., theaters, museums, gyms, golf courses) require a fee for entry or membership, as well as broader systems of racism that make engaging with certain public spaces fraught with physical and psychosocial risks, such as racially discriminatory interactions or the anticipation of such treatment.[93,94] To examine whether the same set of neighborhood conditions shown to be key drivers of cognitive function in Model 1 map across populations—or if instead broad systems of racism, sexism, and classism bear on these health-generative processes in ways that lead certain sites to be more or less salient in predicting cognitive health across populations—we next fit several interactive models that allow the influence of our focal predictors to vary by race (Model 2), gender (Model 3), and educational attainment (Model 4). For parsimony, we present the full set of parameters associated with each of these models in the Appendix. In the main text, we present the AIC of Model 1 compared to the AIC of each interactive model. These comparisons demonstrate whether allowing the full set of focal neighborhood predictors to vary by race, gender, or class improved the predictive accuracy of our original model fit (see Table 4).

Table 4 demonstrates that allowing the *full set* of neighborhood-drivers of cognitive function to vary by race, gender, or education did not yield substantial improvements to our prior model specification. Model 2, for instance—which allowed for distinct associations to emerge across Black and white sample populations—had an AIC of 287,172.7, while our original model—which constrained associations to be uniform across racialized populations—had an AIC of 287,161.7. This 11-point increase in AIC scores suggests that allowing the association between cognitive function and *each* neighborhood feature to vary across racialized groups did not provide a compelling enough improvement in predictive accuracy to justify the additional model complexity. The AICs of our gender- and education-specific models led to similar conclusions. The core neighborhood features identified in Model 1 appear to predict cognitive function similarly across subpopulations—though, as we discuss in the Appendix, more theoretically motivated, targeted investigations into population heterogeneity may yield more critical insights into the matter.

Discussion

This paper introduces Cognability to conceptualize how supportive a neighborhood is to cognitive health among older residents through access to amenities that encourage physically active, socially engaged, and cognitively stimulated aging in place. Studies examining the role of neighborhood environments in cognitive aging have increased recently, but evidence is extremely limited—particularly in sociodemographic diversity and geographic scope. We frame Cognability through evidence from a large national cohort and critically consider potential differences by gender, race, and education. Unlike previous studies, which investigate cognitive outcomes through a relatively narrow set of neighborhood features in isolation of one another, we examined a constellation of both positive and negative contextual variables simultaneously through the novel concept of Cognability.

Our findings extend the scholarship on neighborhoods and cognitive health by emphasizing a "whole neighborhood" environment. Since 2015, researchers have moved beyond the consideration of individual risk factors for cognitive decline to examine the importance of neighborhood context. Early studies relied on composition measures of neighborhood context (including neighborhood socioeconomic disadvantage, or a socioeconomic deprivation index),[95–97] which prompted detailed inquiry on the actual amenities that link economically advantaged neighborhoods with higher cognitive function. However, this literature remains largely exploratory, and there is a critical need to identify which combination of neighborhood built and social features may mitigate cognitive decline using large nation-wide samples of older adults.[16] Our work highlights the importance of considering a suite of neighborhood resources, including civic and social organizations, museums, recreation centers, and the absence of highways, to understand the fabric of neighborhoods that older adults encounter in day-to-day life. Much like walkability has evolved from the examination of connected streets in isolation from other neighborhood features, Cognability pushes this growing area of scholarship to consider the impact of multiple features simultaneously for cognitive wellbeing.

Our results suggest that the unequal distribution of amenities and hazards across neighborhood environments may be implicated in the cognitive health of older adults. Neighborhood access to civic/social organizations and exposure to highways contributed most to predicting the stark geographic disparities in cognitive function observed among our sample participants. This validates and extends existing studies finding associations between local social infrastructure (e.g., senior centers, community centers, volunteer organizations) and better cognitive health outcomes.[8,32] Highways are toxic pollution exposures that have been linked to increased risk for cognitive decline,[6,72] though we conceptualize highways more along psychosocial pathways as barriers to leisure walking and access to neighborhood amenities. Previous literature indicates that high-traffic roads and highways pose perceived barriers to walking and reduce access to everyday destinations through greater distances, obstacles to activity-friendly routes, and hazardous street design. Lack of sidewalks, inadequate pedestrian crossings, and wide lanes with high-speed limits that encourage fast driving can discourage walking and access to everyday destinations, particularly among older adults and underserved communities.[98–100] Between-person disparities in cognitive function scores were also explained to a lesser extent by census tract densities of coffee shops and fast-food establishments (negatively associated); as well as art organizations, museums, and recreation centers (positively associated). These findings largely validate previous studies finding positive associations between cognitive aging outcomes and local arts/cultural sites, recreational amenities, and overall greater densities of service and retail destinations.[16,18,22–24] Our results differed from a previous study finding positive associations between coffee shops and fast-food establishments and cognitive function, which (as discussed below) may be due to differences in measurement or analytical approaches. While these contextual factors contributed far less to explaining disparities in cognitive function scores than other markers of social inequality—such as educational attainment and the broad, relational system that it proxies—their significant, measurable associations with cognitive function aligns with the notion that the neighborhood environment contributes to shaping cognitive aging.

Cognability aligns with Lawton's equation in the Ecological Theory of Aging that behavior is a function of a person and their environment.[39] It critically considers a constellation of neighborhood features, both positive and negative, which can encourage or hinder cognitive health behaviors among aging individuals. Civic and social organizations, and to a lesser degree arts organizations, museums, and recreation centers, may promote cognitive health through a blend of physical activity (e.g., active transit to these destinations, organized walking clubs), social engagement and support networks, and creative and complex activities. The neuro-protective pathways of these health behaviors include neurogenesis and neuroplasticity; improved cardiovascular function and associated influence on the cerebrovascular system; reduced stress, anxiety, and inflammation; routine stimulation and 'use' of the brain; strengthened processing skills and perceptual speed; and overall enhanced brain function that can contribute to cognitive reserve.[42–45,50,51,53–55,68–71] Highways pose barriers to these protective cognitive health behaviors, and also represent biological risk sources of pollution.[6,29,72]

While our results demonstrate a significant association between neighborhood amenities and cognitive function, we urge readers to interpret our findings as descriptive and a springboard for future research. In this regard, there are a number of limitations to note. For example, we were unable to determine REGARDS participants' utilization of neighborhood amenities. Greater access to local establishments does not necessarily mean that participants frequented these establishments. Furthermore, we used one spatial measure (number of sites per 1,000 people living in a census tract) which is just one indicator of access. Additional geographic dimensions, such as distance to the nearest amenity, quality, and affordability, may yield different results. Indeed, a previous paper among REGARDS participants utilizing a kernel density method[31] to define participant neighborhoods found a positive association between access to coffee shops and fast-food eateries and cognitive function, in contrast to the negative association demonstrated here. This could be attributed to differences in measurement (e.g., perhaps eateries very close to home facilitate more cognitively-healthy activities than living in an area with multiple establishments) or analytical approaches (e.g., this paper sought associations conditional on having access to other amenities, as opposed to prior work which modeled this relation without considering access to alternative sites of activity and socialization). We restricted the analysis to urban and suburban-dwelling older adults. Future work should investigate geospatial measurement and community resources specifically relevant to Cognability in rural communities. The neighborhood categories are broad and may generalize distinct activities and participation centered in each site, such as coffee shops versus fast-food restaurants; or art galleries and science and technology museums both captured under the same NAICS code. Furthermore, our list is of neighborhood features not exhaustive; future efforts should consider additional services, amenities, and hazards as potential components of Cognability.

Perhaps the greatest limitation centers on the fact that neighborhood attainment is not a completely stochastic process, but rather one that is deeply entangled with other systems of health and inequity. Reverse causation where individuals with better cognitive health might be more readily able to select into neighborhood environments layered with amenities and fewer hazards is a salient consideration. Similarly, the lack of pre- and post-treatment confounding variables measured in REGARDS—e.g., personal wealth, which likely plays a role in predicting both access to generative neighborhood environments and cognitive function—makes omitted variable bias a concern. Other neighborhood-level factors (e.g., proximity to surrounding tracts with high-levels of access to amenities) further muddy precise identification of effects.

Despite these limitations, our study demonstrates an intimate overlap among neighborhood environments and cognitive health in the US.[1] To better clarify *how* this overlap between neighborhoods and cognitive health arose, future research should explore the above considerations in more detail. Data that contain a broad collection of confounders—measured across the entire life course—and data that allow researchers to observe, and thus disentangle, the long-run, interconnected processes by which individuals came to their current residence and their level of cognitive function would allow for more precise statements on why we observe significant intersections between cognitive health and neighborhood features. We provide a within-person analysis in the Appendix to begin to address individual cognitive trajectories over time, but additional data are needed to make substantial progress here.

In addition to uncovering a parsimonious set of contextual predictors of disparities in cognitive function through the theoretical model of Cognability, our study examined whether the neighborhood environments that were most supportive of cognitive health were uniform across populations in the US. We investigated if, through systematic patterns of power and privilege, different contextual environments yielded distinct benefits across racialized, gendered, and classed individuals. Although our data did not support allowing the *entire* set of neighborhood conditions to vary across these social groups, we caution against the interpretation that our findings offer no insight into the intersection among neighborhood environments, cognitive health, and social power. The distributions of neighborhood amenities found to be predictive of cognitive function are intimately tied to social dimensions, particularly race and class. A robust sociological literature, for instance, demonstrates that white communities are, and have historically been, the recipients of perpetual privileges and investments—including many of the neighborhood amenities investigated here. By the same token, communities of color—particularly Black communities—are systematically saddled with disinvestment and harms by both public (e.g., government highway construction) and private actors (e.g., polluting sites).[101,102] If the associations uncovered here imply any degree of causality, then this unequal, racialized distribution of amenities and hazards may contribute to broader racial disparities in population health, even if the strength of the relationship between each neighborhood condition and cognitive health is largely uniform across populations.

Conclusion

Given the immense and unequal burden of ADRD in the US and worldwide, it is critical to better understand how neighborhoods may benefit cognition and help buffer against

[1]In some cases, these alternative accounts of our findings themselves offer unique, nuanced insights into the production of population health disparities. If, for instance, access to health-generative neighborhoods is gated by cognitive health, as implied by a reverse causality interpretation, then one could implicate disparities in cognitive function in the production of other spatialized health inequities.

cognitive decline. Cognability motivates future research and highlights the need to address neighborhood inequities, unequal resource distribution, and community disinvestment framed by structural inequalities. In the US context, unequal built and social environments may contribute to the disproportionate risk among older Black Americans to have ADRD.[5] In order to holistically address poor cognitive health outcomes, particularly among marginalized and underserved communities, we need to address systematic disinvestment and prioritize action to produce more equitable access to health-promoting neighborhood amenities.

Cognability aims to identify which specific neighborhood features are most protective of cognitive health among diverse aging adults and socio-geographic contexts. This informs public health initiatives, community interventions, and policy that encourage later-life cognitive health. These efforts may complement and enhance biomedical and individual lifestyle approaches to reduce risk for cognitive decline and ADRD. For example, Cognability could inform and advance community development guidelines, such as tax incentives to build Cognability infrastructure in residential and commercial building projects. Grant-funded programs could encourage and enable cognitively-healthy aging in place, such as support for civic and social organizations that serve diverse older adults; subsidized rates to attend galleries, theaters, museums, and exercise programs; and book clubs and coffee groups hosted in libraries, coffee shops, and other third places. The goal is to enable individuals, healthcare providers, community groups, public health officials, and policymakers to knowledgably assess local environments and pursue changes that ameliorate community barriers and create more equitable opportunities to promote healthy aging in place.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This research project is supported by cooperative agreement U01 NS041588 co-funded by the National Institute of Neurological Disorders and Stroke (NINDS) and the National Institute on Aging (NIA), National Institutes of Health (NIH), Department of Health and Human Service. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NINDS or the NIA. Representatives of the NINDS were involved in the review of the manuscript but were not directly involved in the collection, management, analysis or interpretation of the data. The authors thank the other investigators, the staff, and the participants of the REGARDS study for their valuable contributions. A full list of participating REGARDS investigators and institutions can be found at: https://www.uab.edu/soph/regardsstudy/. Additional funding for this project was provided by NIH/NIA grant 1RF1AG057540-01 (Clarke), the Michigan Institute for Clinical & Health Research Postdoctoral Translational Scholar Program UL1 TR002240-02 (Finlay), and NIH/NIA Ruth L. Kirschstein National Research Service Award Individual Postdoctoral Fellowship F32 AG064815-01 (Finlay).

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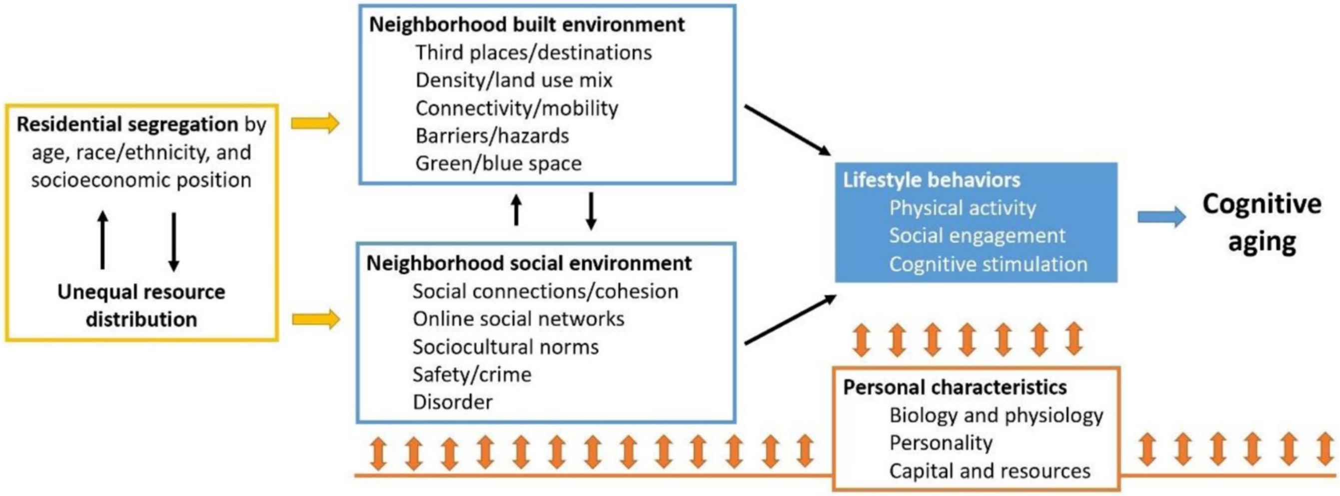

Figure 1.
Simplified model of Cognability.

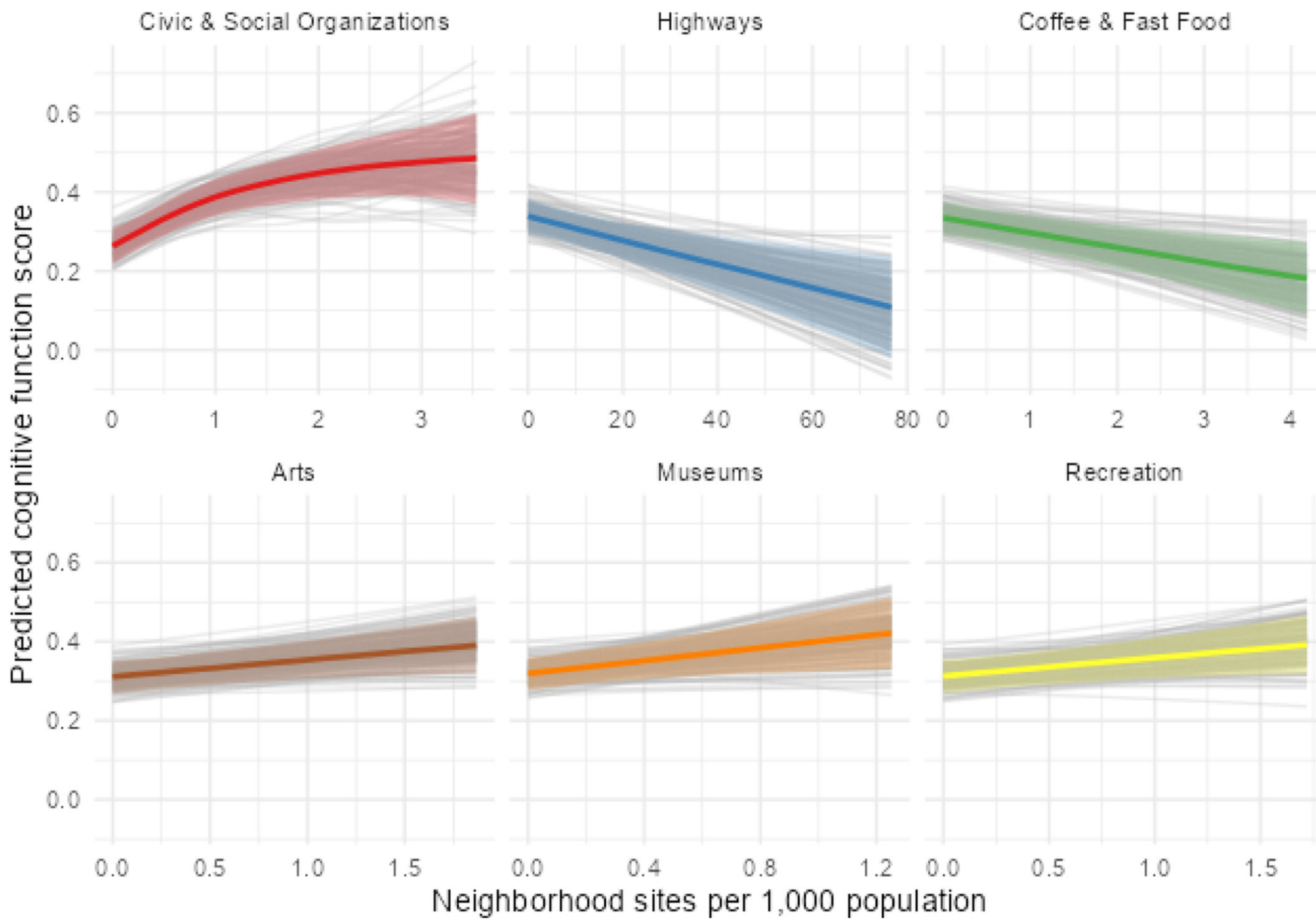

Figure 2.

Model-predicted cognitive function scores across the range of each significant neighborhood feature. *Note:* Predicted values are constructed by sampling from the posterior distribution of Model 1. 90% uncertainty intervals are marked as ribbons. 200 draws from the model posterior are plotted to further summarize uncertainty.

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Table 1.

Neighborhood contextual variables.

Neighborhood feature	Description
Arts sites	Live production and arts performance establishments featuring actors, singers, dancers and other performing artists (NAICS 7111).
Civic and social organizations	Establishments primarily engaged in promoting civic and social interests. Examples include social clubs, veterans' membership organizations, alumni associations, granges, sororities/fraternities (NAICS 8134).
Coffee shops and fast-food restaurants	Limited-service restaurants (NAICS 722513) where patrons select items and pay before eating, such as fast-food restaurants, takeout sandwich shops, and limited-service pizza parlors; as well as snack and non-alcoholic beverage establishments (NAICS 722515) with on-premise brewing and baking that serve items such as coffee, bagels, doughnuts, and ice cream.
Grocery stores	Grocery stores and supermarkets (NAICS 445110) as well as specialty food stores (NAICS 4452).
Higher education campuses	Higher education institutions including colleges, universities, and professional schools (NAICS 611310).
Highways	The number of highway stretches, derived through primary and secondary road segments (divided interstate highways, US highways, state highways, county highways).
Libraries	Public libraries and archives (NAICS 519120) that maintain document collections (e.g., books, journals, newspapers) for informational, research, educational, and recreational needs.
Museums	Establishments that preserve and exhibit objects of historical, cultural, or educational value (NAICS 7121). This includes art galleries and museums, planetariums, science and technology museums.
Parks	Open public parks in cities, towns, and communities.
Polluting sites	Polluting sites within a census tract plus half-mile buffer. Facilities are typically larger and involved in manufacturing, metal mining, electric power generation, chemical manufacturing, and hazardous waste treatment.
Recreation centers	Fitness and recreational sports facilities (NAICS 713940) for exercise, physical conditioning, and recreational sports (e.g., gyms, aerobic dance centers, ice- or roller-skating rinks, physical fitness centers, racquetball or tennis club facilities, swimming or wave pools); in addition to golf courses (NAICS 713910).
Religious organizations	Establishments primarily engaged in administering, operating, or promoting religious activities, such as churches, temples, and monasteries (NAICS 813110).
Senior centers	Services for older adults and persons with disabilities (NAICS 624120) including adult day care centers, senior citizen activity centers, and non-residential social assistance programs that provide care, support, and socialization.

Note: Neighborhoods are operationalized as census tracts. NAICS=North American Industry Classification System.

Table 2.

Sample descriptive statistics.

Variable	Mean/proportion	Std. deviation
Cognitive function score	0.02	2.36
Black	0.40	-
Female	0.56	-
Education: less than a high school degree	0.09	-
Education: high school degree	0.51	-
Education: college degree	0.41	-
Age (at baseline test, in years)	67.0	8.83
Years from baseline test	3.45	3.18
Tract: proportion of housing owner occupied	0.63	0.21
Tract: proportion of residents earning below poverty line	0.19	0.13
Tract: proportion of non-Hispanic Black residents	0.42	0.35
Tract: population density	4,291.93	9,052.73
Tract: recreation center density	0.25	0.35
Tract: civic/social organization density	0.57	0.63
Tract: religious organization density	2.73	2.00
Tract: fast-food and coffee density	0.63	0.77
Tract: senior services density	0.11	0.19
Tract: educational organization density	0.08	0.21
Tract: arts organization density	0.29	0.38
Tract: museum density	0.09	0.21
Tract: library density	0.08	0.17
Tract: polluting site density	0.07	0.20
Tract: park density	0.49	0.59
Tract: highway density	11.24	14.48
Tract: grocery store density	0.97	0.82

Note: Density measures are counts per 1,000 population in a census tract, and top-coded to the 99th-percentile.

Table 3.

Model 1: Gaussian multilevel generalized additive model of cognitive function score.

Parametric terms:			
parameter	**estimate**	**std. error**	**t-value**
Intercept	0.315	0.125	2.52
Age at baseline	−0.094	0.001	−76.66
Years from baseline test	−0.075	0.002	−34.05
White	0.962	0.031	31.33
Male	−0.344	0.023	−15.24
Education: college degree (ref.)	-	-	-
Education: high school degree	−0.900	0.024	−37.08
Education: no formal degree	−1.743	0.041	−42.16
Tract, proportion owner occupied housing	0.192	0.074	2.60
Tract, proportion Black	−0.152	0.049	−3.09
Tract, proportion below poverty line	−0.340	0.112	−3.04
Population density (logged)	0.035	0.012	3.04
Random terms:			
parameter		**std. deviation**	
Person-specific intercepts		1.263	
Person-specific time slopes		0.127	
Tract-specific intercepts		0.229	
County-specific intercepts		0.165	
Smooth terms:			
parameter	**EDF**	**p-value**	
Tract, recreation center density	0.795	0.031	
Tract, social organization density	2.240	<0.001	
Tract, religious organization density	0.000	1.000	
Tract, fast-food and coffee density	0.913	0.002	
Tract, senior services density	0.000	1.000	
Tract, educational organization density	0.623	0.103	
Tract, arts organization density	0.813	0.025	
Tract, museum density	0.800	0.026	
Tract, library density	0.000	1.000	
Tract, polluting site density	0.000	1.000	
Tract, parks density	0.000	1.000	
Tract, highway density	0.933	0.002	
Tract, grocery store density	0.025	0.311	

Note: *EDF* denotes “effective degrees of freedom” and summarizes the number of parameters associated with each smooth term. *Ref.* indicates “reference category.”

Table 4:

AIC comparison of multiple candidate models of cognitive function score. The column titled $AIC_{Model\ X} - AIC_{Model\ 1}$ summarizes the change in AIC between each model and Model 1.

Model	AIC	$AIC_{Model\ X} - AIC_{Model\ 1}$
Model 1 (*uniform*)	287161.7	-
Model 2 (*race-specific*)	287172.7	11.0
Model 3 (*gender-specific*)	287192.9	31.2
Model 4 *(education-specific*)	287165.1	3.4