JOURNAL OF DESIGN FOR RESILIENCE
IN ARCHITECTURE & PLANNING

Research Article
Online: www.drarch.org
Volume 2, Special Issue, (18-33), 2021
DOI: 10.47818/DRArch.2021.v2si033

Association between home layout connectivity and cognitive ability in community dwelling older adults: Implication for occupational therapy

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Abstract

Physical environment has long been recognized within occupational therapy as a key factor contributing to residents' functional abilities. However, the specific aspects of the physical environment that matter and the extent to which they do so remain less understood. This paper reports a quantitative study of the relationship between a characteristic of the physical home environment—the degree of interconnectedness of its rooms—and the cognitive ability of adults. Working with demographic, health, and home layout data collected from a sample of community-dwelling older adults in Atlanta, Georgia (N=72, Mage=69.5), we found that the cognitive functioning determined by the Montreal Cognitive Assessment (MoCA) score was significantly associated with the average connectivity and mean depth of the homes while controlling participants' age and education. Regression analysis suggested home connectivity independently explained a little more than 4% of the variance in the MoCA scores. The results further revealed that the relationship may be better modeled using non-linear models, and that the increase in the numbers of circulation rings as average room connectivity rises may be partly, but not entirely, responsible for its association with cognitive ability. The study points to directions for further work, including causal modeling, based on recommendations that could be developed for homes to support older adults' abilities to continue to reside in their own homes as they grow older.

Keywords: aging in place, cognitive functioning, home connectivity

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1. Introduction

The role of environment in its many forms, including the physical characteristics of space, is a central concept in occupational therapy research, theory development, and practice. Kielhofner in his Model of Human Occupation (Kielhofner et al., 2008) as well as Law in her Murriel Lecture (Law, 1991) discussed the role of space or physical built environment (BE) in facilitating optimal occupational performance. But can the effects of the environment be shown to be systematic enough for its role in occupational therapy to be practical and effective? And if such systematic effects are found, can they be associated with specific features of the environment?

This question has recent begun to receive some attention from researchers in public health, focusing particularly spatial layouts of residential neighborhoods. Over the last two decades, several studies reported significant associations between features of neighborhood BE with depression (Domènech-Abella et al., 2020; Pan et al., 2021), physical activity (Bonaccorsi et al., 2020; Cleland et al., 2019; Yu et al., 2021), obesity, hypertension, and diabetes (Chandrabose et al., 2019). Importantly, these are also established risk factors for dementia and/or Alzheimer's disease (AD) in older adults (Livingston et al., 2017; Roe et al., 2020). Recent research on BE and health is beginning to find empirical evidence for an association between the layout of BE characteristics and the cognitive health of older adult residents. For example, a 2015 study on neighborhood connectivity and integration demonstrated a significant relationship between physical neighborhood characteristics and continued cognitive performance (Watts et al., 2015). In 2019, Besser et al. showed that the association between BE and cognition could be moderated by apolipoprotein E (APOE) genotype, a genetic risk factor for AD, thereby establishing a gene-environment interaction (Besser et al., 2019). These studies proceed from the assumption that the layout of streets can create significant differences of affordances to neighborhood services and markets, walkable areas, and security between individual homes. The differential affordances can lead to differences in cognitive behaviors and explain the observed association between BE layout parameters and cognitive health. Decline in cognitive health is a key predictor of dementia and AD (Livingston et al., 2017).

It is possible to argue that the association between BE and cognition is not just due to overt behavioral consequences of differential opportunities of affordance but due to latent cognitive factors as well. For example, a recent survey of research on designing facilities for individuals suffering from dementia reports a few empirical studies exploring the idea that building configuration or layout may influence residents' orientation, wandering habits as well as social interactions (Day, 2002). There is however lack of explicit theory as a result of which intriguing empirical findings are left unexplained (Day, 2002: 380).

One basis for a possible theory is the fact that people do not rely merely on immediate perceptual information or affordances from the environment in order to negotiate it, but also construct and invoke cognitive maps of environments as part of their plans, strategies, and schemas for conducting everyday activities (Downs, 1973; Gati & Tversky, 1984; Tversky, 2003; Tversky & Hemenway, 1984). The cognitive map that we normally use to learn and navigate the layout of space is constructed by firing in the hippocampal place cells in response to signals from the sensory-motor cortex and visuo-spatial cortex (O'Keefe, 1978). Visuo-spatial memory is therefore especially implicated in this ability. Any loss of functionality in visuo-spatial memory will impact both the ability to form new cognitive maps and to navigate using existing maps. The evidence came from the observation of severe deterioration of wayfinding performance when the participants were distracted with tasks that interfered with visuo-spatial cognition (Hund, 2016). Some layouts, then, may be easy for older adults to map cognitively and to negotiate, but other layouts may be not.

The relationship between the cognitive complexity of layouts and behavior competency must exist at the level of the individual home as well. People construct cognitive maps of their homes as much as they do so at the neighborhood level. A person, theoretically, uses these maps to locate household and personal items, keep track of others in their homes, keep themselves oriented, and order their lives through the day. The cognitive maps of the layout of the home are particularly relevant in the case of older adults, who are likely to spend a considerable amount of their time in their own homes and performing various activities of daily living. Older adults whose cognitive abilities (memory and visuo-spatial cognition) suffer may find it difficult to construct cognitive maps of their environments, and thus their ability to engage in the occupational performances of their activities of daily living (ADLs).

If the layout induced cognitive challenges are not matched to their abilities, older adults tend to respond with maladapted behavior. For example, reducing the levels of their occupational activities, exhibiting learned helplessness, or showing negative affect. An idea that is well-entrenched in environmental studies of aging in the form of competence-environmental press model first developed by Nahemow and Lawton (1974).

Characteristics of layouts and cognitive ability

One way to manage the mismatch between competence and press that comes with aging is to reduce the environmental press to match the lowered competence level. For example, layouts can be simplified, all areas of the home put on a single floor, and ways found to reduce visual clutter in the home. A useful study in this context is by Marquardt et al. (2011), who found that residents in institutional homes with lower convexity scored higher on scores for ADLs. Convexity was constructed as a measure on a ratio scale that combined the amount of fragmentation into convex spaces and the proportion of spaces assigned specific labels, in which low convexity could be interpreted as a setting that had fewer but proportionally more labeled spaces. They surmised that low convexity would make the layout as a whole easier to memorize and so facilitate participation in ADLs.

But another way is to create layouts that may offer just the right amount of challenge and act as an enabler for behavioral adaptations that may even improve mental health. After all, certain basic activities of living have to be conducted no matter what, and when compelled to do so in environments that are challenging, but not to the extent that they prevent the activities from being conducted, inhabitants of these environments may continue to engage in the necessary activity. Engaging in challenging mental activity would then lead to improvement in their cognitive ability, and the home layout may then be thought of as an active ingredient of therapeutic practice, playing a passive role but more actively helping their residents stave off cognitive decline that comes with age. Nahemow and Lawton (1974: 29-30) themselves suggested this line of thinking, demarcating “a zone of maximum performance potential” with slightly challenging environmental press, in which adaptation would take on positive effects (Figure 1).

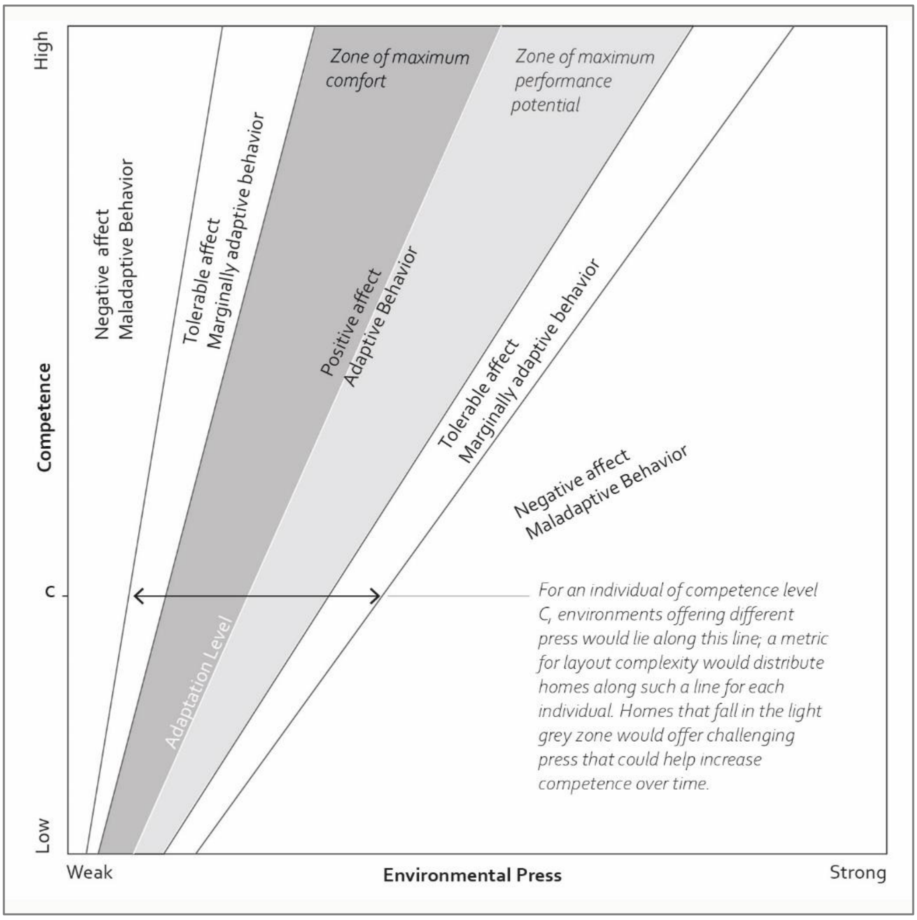

Figure 1 The press-competence model describing the types of adaptive behavior and affect individuals exhibit under varying conditions of environmental press and personal competence. Drawing after Nahemow and Lawton (1974).

There is a biological basis for this argument (termed “the enriched environments hypothesis” in neuroscience literature) that cognitively challenging environments can lead to improvement in cognitive function. However, the current evidence supporting it comes largely from animal models (Cao et al., 2017; Fischer, 2016; Leggio et al., 2005). If such an effect can be demonstrated in humans as well, it leads to the possibility of treating the home as a potential therapeutic aid or intervention tool. Early results are encouraging (Leggio et al., 2005), but reviews of this work routinely raise two kinds of questions that would need answering in order to devise effective treatments:

1) It is still not clear what exactly constitutes an enriched environment in the case of humans (Kühn et al., 2017);

2) there is lack of theory on the basis of which treatments may be standardized (Ball et al., 2019; Hertzog et al., 2008).

It is clear that the second of these questions depends on the knowledge required for the first. Once some key properties of an enriched environment are understood, experiments could be devised for developing the right level of complexity to create enriching environments and devising standards for treatment.

Metrics for environmental complexity

Our study is intended to address the first question. More specifically, the question that motivates our research is whether the complexity of layout can play a role in creating environmental enrichment and, if so, what properties of layout could capture this enrichment. Space syntax offers several indices to capture various characteristics of layouts derived from different kinds of discretization schemes (Bafna, 2003; Hillier, 1984; Peponis, 1997; Turner et al., 2001)[1] .The one that we favor in this case is a type of partitioning scheme known as the “boundary map”, a very early analytical strategy (Hillier, 1984) that has gone out of favor in recent work (but see Bafna, 2001). It is created simply by dividing the entire space of the home into discrete spaces (rooms) using two rules: 1) there should exist a clear, sharp, and unambiguous transition between two spaces, 2) the rooms so formed should have a distinct identity, established either through a label or through specific elements of furnishing. Doorways (with or without doors) are typical of such transitions, but there are other instances where a sharp threshold demarcates one room off from another—a nook or alcove, off a larger room, or a change of ceiling height between two spaces. The standard procedure, which we follow, is to treat the partitioned space as a graph in which nodes and sometimes edges can be assigned numeric indices that depend upon their positions within the graph.

In adopting the boundary map, we drop the typical requirement that the rooms formed by partitioning be convex spaces. Defining both consistent (that is, unique) and efficient convex partitions has been shown to be a problem without a solution in all cases (Peponis, 1997), and if efficiency is sacrificed in order to ensure consistency, the resulting scheme produces spaces that do not have a straightforward interpretation in terms of categories of rooms through which residents conceive of their homes.

This procedure generates a partition that has several features to recommend it:

1. It creates graphs that can be interpreted in a straightforward manner: edges as sharp transitions, either as doorways, or as thresholds, between distinct rooms, nodes as rooms that can be described in terms of categories that form a part of residents’ conceptions of their homes.
2. The graphs, therefore, have a *realist* character; they represent not something accidentally created in the process of shaping a building, as often happens in the case of convex mapping schemes, but an organization that can conform closely to the residents’ cognitive maps of the spatial organization of their homes.
3. Most importantly, this approach gives us a way to create indices that are easily computed, with measurement errors easily checked and corrected.

The metric that we think would capture the cognitive complexity of the layout most efficiently is the average room connectivity. Computed as the average number of links associated with each node in the boundary graph of the home, roughly as the number of doors per room in the house, it can be taken directly as a measure of the degree of interconnectedness of the rooms of the layout. If more doors are opened in the rooms of a house without increasing the number of rooms, then it follows that the extra doors will create internal circuits or rings, that is, alternate pathways between rooms. A house with a greater number of internal doors per room would offer greater variety for movement trajectories or movement options within it and encourage a more active lifestyle. It would, however, require a greater cognitive effort in the organization and execution of activities of daily living—in the selection of routes through the home by comparing expected effort, for instance, or in keeping track of other members of the household as they move around, or even in making mental maps of the house. On the other hand, this effort cannot become prohibitively great if the house is to maintain a sense of livability. Average room connectivity is therefore a good measure of layout complexity: it is simple to compute; it can be directly associated with design guidelines; and, within the range of normal houses, it is likely to vary from a value that is associated

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[1] Space syntax is an analytical approach to the description of built space that seeks to capture the sociologically relevant aspects of the space of buildings and settlements. Those readers who are unfamiliar with space syntax will be able to find an accessible introduction in Bafna (2003); those seeking a more in-depth explanation of its theoretical ideas that motivated it should consult Hillier and Hanson (1984). Peponis and Wineman (2002) review the different questions in environment and behavior studies to which space syntax had contributed, and so give a fairly comprehensive sense of its successes and challenges.

with very little cognitive effort, to one that is associated with just enough challenge to lead to positive adaptations of the kind proposed by Nahemow and Lawton (1974).

2. Methods

Design and participants

This study is a cross-sectional design. Data were collected in three successive phases over 3 years. Seventy-one adults living within the greater Atlanta GA area participated in the study. These participants were recruited via convenience sampling, consisting of fliers, and word-of-mouth. Inclusion criteria were: (1) having an of age 60 or older, (2) living in their own home, (3) having no known cognitive impairments, and (4) having the desire to stay in their own home. Exclusion criteria included current orthopedic or neurological issues that prevented independent living. Any participants who lacked adequate vision or were non-ambulatory were also excluded from this study.

Variables

Demographic Variables: Age, gender, education, and income of all participants were collected. As a comparison, the same measures of US population estimates were also collected from U.S. Census Bureau data.

Variable characterizing cognitive ability: The Montreal Cognitive Assessment (MoCA) is an assessment that can be used to screen for cognitive impairment as well as to assess cognitive ability and track cognitive changes over time (Koski et al., 2009). The MoCA has excellent internal consistency (alpha = 0.83), excellent test-retest reliability (r = 0.92), and excellent concurrent validity (r = 0.87) (Nasreddine et al., 2005). At a cutoff score of 26, the MoCA has a very high sensitivity of detecting mild cognitive impairment (90%) and Alzheimer’s disease (100%), with a somewhat lower specificity of 87% (Nasreddine et al., 2005). Lower than expected scores on MoCA may therefore indicate reduced cognitive ability but not cognitive impairment as such.

Variables characterizing home layouts: Space syntactical metrics were used directly to create variables characterizing different aspects of home layouts. Home layouts were recorded by observers trained to draw maps of homes on-site and to record measurements of room-sizes. These hand-drawn maps were then translated into diagrams in a generic CAD-format (.dxf) that recorded individual rooms as polygons connected by centerlines that represented doors between them. Depthmap version 10.14.00b (Copyright: University College London, Alasdair Turner, Eva Friedrich, 2010-11), was used to compute syntactical metrics.

Syntactical metrics are graph measures that are computed either for each node (that is, for each room in the house), or for the entire house. Our study took the entire house as a unit of measurement, and metrics that are computed at room level were aggregated and averaged to produce house-level metrics. The main variable of interest, as described in the previous section, was average room connectivity—this is computed simply as the mean number of links per node that occur in the graph of the home. Two other syntactical metrics also featured as explanatory variables in some of our models, but only as possible co-variates in our explorations to achieve proper specifications of our models. One of these was the number of nodes (the number of rooms obtained after partitioning the layout of the house), and the other, the average mean depth of all the nodes (the mean of all shortest paths between all non-identical pairs of nodes of the graph representing a house).

Analytical approach:

Our general analytical approach was to test different models for explaining variations in MoCA scores, with a particular focus on average room connectivity as a predictor. We began by examining each of the variables of interest for potential problems or to identify distinctive or unusual values. MoCA scores were compared to published normative data to see if our sample had any unusual characteristics. Of the explanatory variables, both demographic variables and the syntactical indices were also compared to available public data in order in order to get a sense of the representativeness of our sample. Correlations between explanatory variables were examined to give us some information about how to set up multiple regression models that we would eventually use. After this preliminary work, we constructed a series of simple regressions to check how each of our proposed predictors performed individually and then finally constructed several multiple regression models testing different assumptions about both nature of the relationship between the outcome and explanatory variables—whether it was best taken to be linear or non-linear—and whether the specific characteristics of the outcome variable called for particular types of modeling approaches. Throughout our approach focused on exploration of data and discovery rather than on proving or disproving specific hypotheses.

The analyses and data-transformations were performed using a number of libraries available for the R programming language, using Rstudio as the IDE (R Core Team [2020]. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria).The results reported here used the base library of R as well as libraries *ARM* [Andrew Gelman and Yu-Sung Su, 2020, *Data Analysis Using Regression and Multilevel/Hierarchical Models*, (R package version 1.11-2)], *CAR* [John Fox and Sanford Weisberg, 2019, *An R Companion to Applied Regression, Third Edition* (Thousand Oaks CA: Sage)], *Betareg* [Achim Zeileis, Francisco Cribari-Neto, et al. 2021, Betareg: Beta Regression (R package version 3.1-4)], and *Splines2* [Wang W, Yan J, 2021, Splines2: Regression Spline Functions and Classes (R package version 0.4.5)]. Graphics were all produced using the base R package.

3. Results

Preliminaries

Our sample included data from 71 individuals, of which 26 were men and 45 women. All were, by sampling design, older adults ranging in age from 60 to 92 years, distributed around a mean of 69.5 years (with a standard deviation of 8.8 years). As Table 1 shows, the level of education in our sample was relatively high. Only 2 individuals reported education level without a high school diploma, and 38 individuals (53%) reported having obtained a bachelor's degree or higher. In comparison, 54% of adults older than 65, residing in Atlanta, have a bachelor's degree (U.S. Census Bureau, 2019b). The income distribution in our sample (Table 1), with a median income category of ($50,000 to $74,000) also conformed quite closely to that of the city of Atlanta population (median income = 65,385; U.S. Census Bureau, 2019a).

Table 1 Characteristics of the study sample, compared with national demographic characteristics (US Census Bureau, 2019a and 2019b)

		Sample Data			**Population Estimates (US)**	
		N (%)	**Mean (SD)**	**Range**	**%**	**Mean**
Age			69.5 (8.8)	60-92		NA
Gender	Male	26 (37%)			46%	
	Female	45 (63%)			54%	
Education	No High School	2 (2%)			12.43%	
	High School	31 (43%)			48.39%	
	College Degree	38 (53%)			39.17%	

Income	Less than $20,000	7 (9%)			12 %
	$20,000 to $34,999	10 (14%)			11.3 %
	$35,000 to $49,999	11 (16%)			9.8 %
	$50,000 to $74,999	12 (17%)			15.4 %
	$75,000 to $99,999	6 (9%)			11 %
	Over $100,000	25 (35%)			29.1 %
Av. Room Connectivity			1.99 (1.7)	1.61-2.36	NA
Av. Mean Depth			3.10 (0.71)	1.87-4.82	NA
MoCA30 Score			25.27 (3.46)	15-30	26 (2.3)

The MoCA scores of our sample had a mean of 25.3, with a standard deviation of 3.5 points. Thirty-three individuals (46%) scored below the standard cut-off value of 26 that is used to identify individuals with possible cognitive impairment. In a study to gather normative data, Rosetti et al. (Rossetti et al., 2011) obtained a much lower mean value of 23.4 (sd = 4.0) from a sample of 2356 individuals. However, the sample included individuals between 18 and 85 years, who were not screened for any diagnosed cognitive impairment. Another normative study (Borland et al. 2017) with a more comparable sample of 758 adults with an age range (65-85 years) to our sample, which also excluded any individual with severe cognitive impairment, had a mean score of 26 (sd = 2.3), with 37.3% reporting scores below 26, reports data that conform quite well with our sample. Our sample, in short, did not exhibit any unusual characteristics with respect to the MoCA scores.

The average connectivity scores of the homes of the individuals in our sample ranged from 1.61 to 2.36. The range appears very small but is actually well within expected limits. It can be interpreted somewhat roughly as the average number of doorways per room of the house. Given contemporary privacy norms, most rooms in a typical single-family house will have one doorway, a few may have two, and very few other spaces, such as hallways, corridors, or lobbies have more than three doorways opening into them. The number of spaces (all distinct and separable spaces in the home that can accommodate at least one person conducting some daily activity) in these homes ranged from 6 to 27, showing that there was a fairly good degree of variation in the size of the homes in our sample.

Models

A simple OLS regression of MoCA scores on the average connectivity of the individuals' homes showed that the connectivity was able to explain 5% of their variation (p = 0.039; df = 1 & 69). The corresponding coefficient was 5.09 MoCA score units, with a standard error of 2.42. MoCA scores have been found to be quite susceptible to age and education in most normative studies; there is more equivocal evidence about the role of gender in determining them. We checked with this with a series of simple OLS regressions, with each of these variables taken as independent regressors. Age was found to predict about 23% of the variation in MoCA scores ($p = 1.17 \times 10^{-5}$; df = 1 & 69). Education (taken as an ordinal variable with three levels) was found to predict 9% of the variation (p = 0.004, df = 1 & 69). It is conventional to treat education as a categorical variable, but our sample data showed a consistent and linear increase in the MoCA scores between all three categories taken in order, thus supporting the case for treating it as a single regressor on an ordinal scale. Gender accounted for just about 1% of the variation in scores without reaching significance (p = 0.83, df = 1 & 69). Income level was also found to be a potential predictor of MoCA scores, explaining nearly 12% of the variation (p = 0.002, df = 1 & 69), but income level is correlated with education in our sample (as it should be), and when the model was adjusted for age and education, the effect of income disappeared (coefficient = 0.29, s.e. = 0.21, p = 0.17).

Learning from these exploratory models, we decided to adjust for both age and education, but not for gender or income, in modeling MoCA scores by average connectivity. An OLS regression model (see Figure 2) with three predictors—age, education, and average connectivity—produced $R^2 = 0.34$, ($p = 7.28 \times 10^{-7}$, df = 3 & 67). All three predictors reached the set significance level of 0.5 (see Appendix 1a for details of the model). The estimation of the coefficient associated with average connectivity reduced slightly (4.61, in comparison with 5.09 from the regression with average connectivity as the sole regressor), but it came with a gain in efficiency (s.e. = 2.08, in comparison to 2.42 in the simple OLS regression). A comparison model of the MoCA scores with only age and education level as predictors, produced an $R^2 = 0.31$ ($p = 1.53 \times 10^{-6}$, df = 2 and 68). This means that average connectivity was able to account for an additional 3% of the overall variation in the MoCA scores.

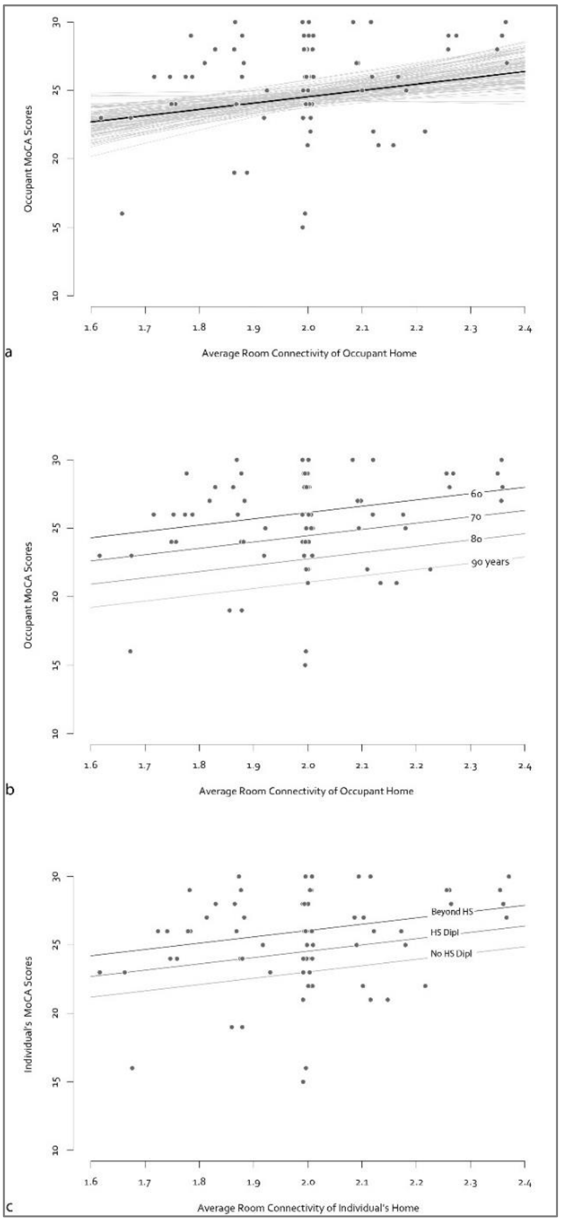

Figure 2 Estimated MoCA scores expected from given the average room connectivity values of their homes, plotted over actual values. The estimates are derived from the multiple linear regression model reported in Table 2. **2a** shows the line of best fit for 65 years old individuals educated up to high school; grey lines, representing other possible fits that might explain the given data, indicate the uncertainty of the estimates. **2b** shows estimated best fit lines for selected ages for a high school educated individual, and **2c** shows estimated best fit lines for each of the three levels of educational categories for a median aged individuals from the study sample. Note that in all diagrams, observed values are jittered along the x-axis to reveal overlapped datapoints, and so may not match each other precisely.

Basic diagnostic plots (Figure 3) of the regression model with age, education and average connectivity as predictors did not reveal any serious concerns. As the plots show, very slight heteroscedasticity as well as a slight departure from normality (hinting towards a negative skewness) in the residuals at the extreme range. Both these points reflect the truncated character of the MoCA scale at the upper end—the fact that MoCA scores of our sample cluster near the top, but cannot go past the highest score of 30. The observations are not a severe threat to the validity of the model for our data, but we discuss one possible way to address them in the section below for the more general case. There are no points with unusually high leverage.

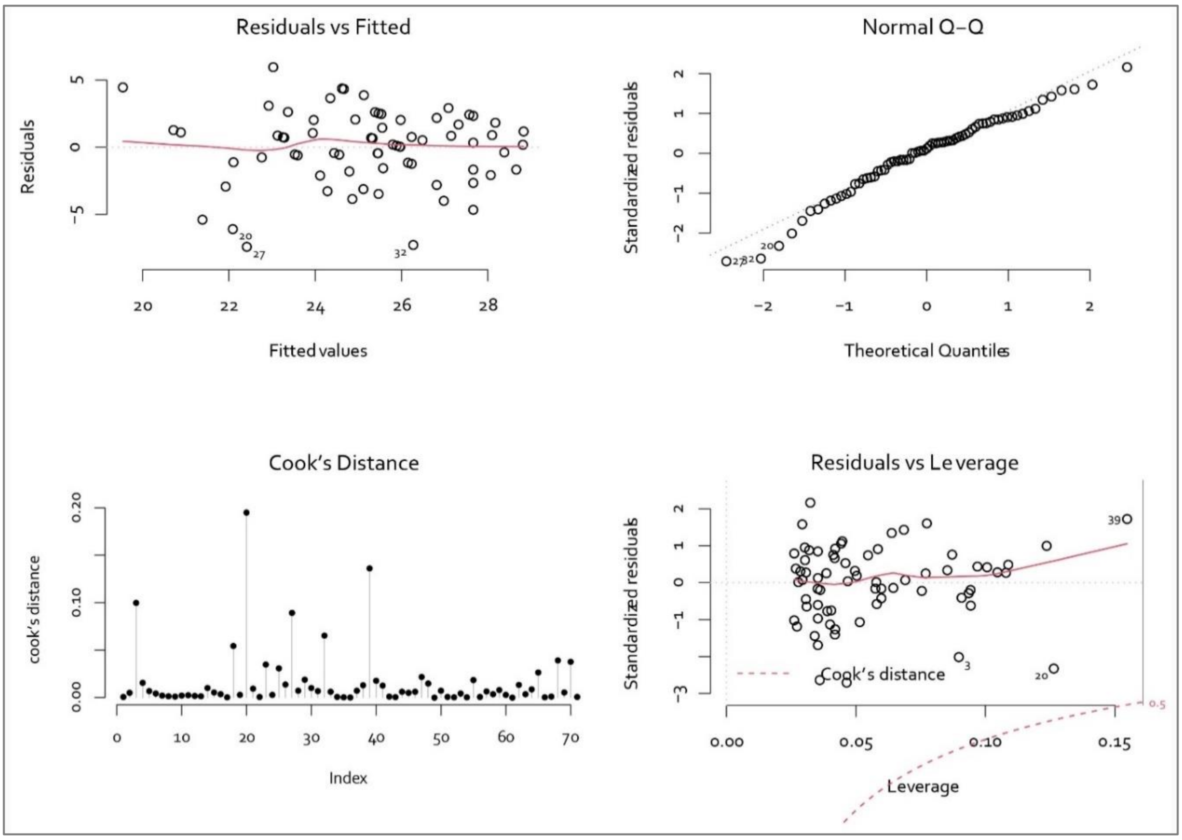

Figure 3 Diagnostic plots for the model presented in Appendix, Table 2.

Cognitive ability as a non-linear function of connectivity

It is reasonable to question whether the assumption that the relationship between the outcome variable and our main predictor can be expressed as a simple linear function. MoCA scores are constrained to lie between 0 and 30, and a large majority of healthy adults are expected to score near the higher end. In fact, the actual distribution of the scores that we modeled is only moderately skewed (skewness = -0.85); the residuals from our model still retain some skewness (-0.51), as our diagnostic plots (Figure 3) show. A somewhat related worry is the possible presence of heteroscedasticity as a result of the truncation of scores. To ameliorate this worry, we also tested a beta-regression model, rescaling MoCA scores as fractions of the maximum values, and modeling it as a beta distributed variable that ranges between 0 and 1 (Appendix 1b). The AIC value of –149.6 of the beta regression model is much lower as compared to AIC of –131.0 for an ordinary linear regression model of MoCA scores on the same scale, so it does offer improved efficiency. But within the range of connectivity values normally obtained in residences, the parameter estimates themselves close enough to the linear model to make the simpler linear model acceptable (Figure 4a; Appendix 1b).

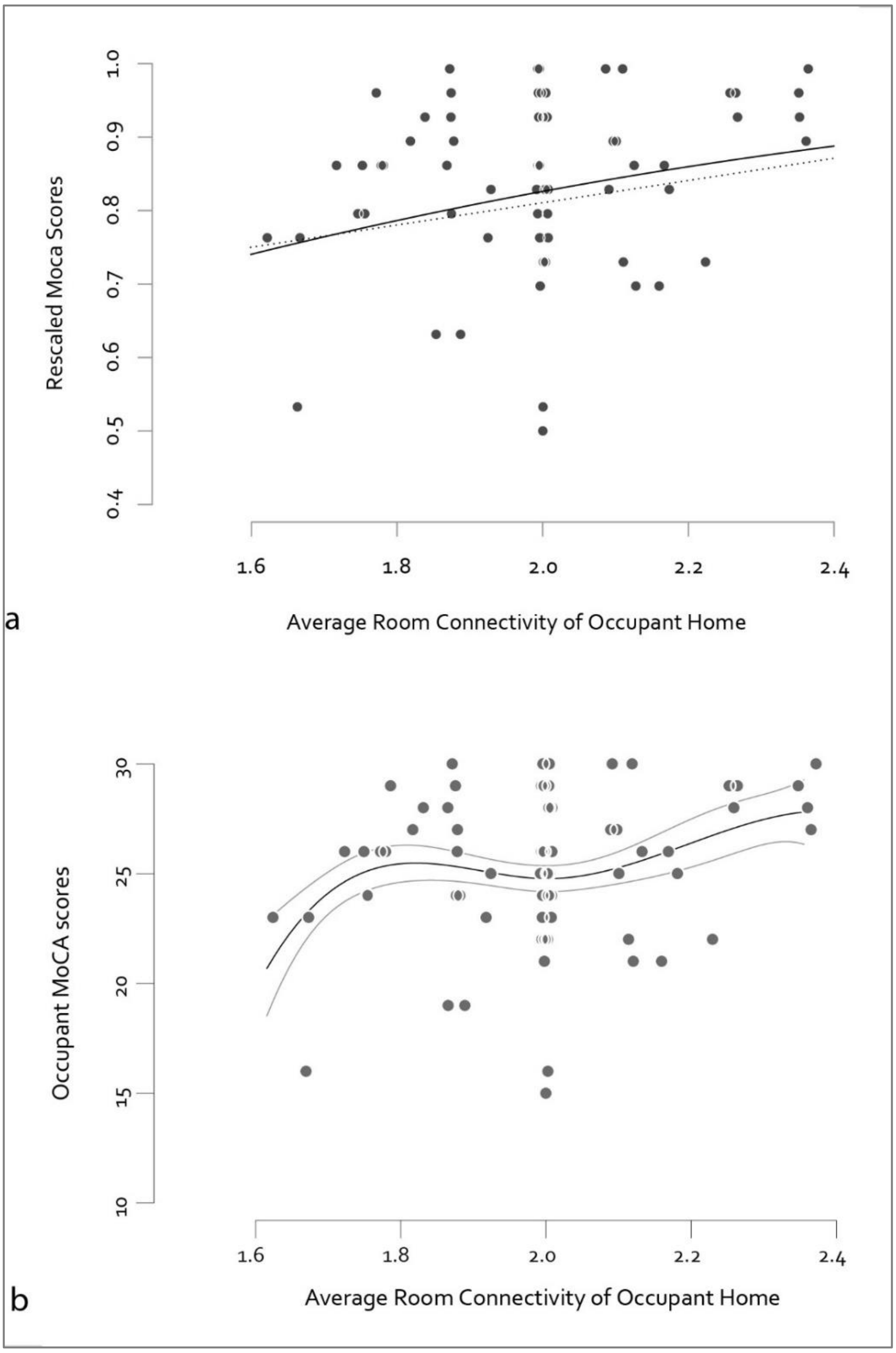

Figure 4 Models exploring non-linear associations between MoCA scores and Average room connectivity **4a** compares two fit curves; the dotted curve is the best fit line obtained for 70 years old individuals educated up to high school from a generalized linear model with gaussian distribution and identity link (in essence, an ordinary least squares multiple regression model); the solid curve is the best fit line from a beta regression model for individuals with the same characteristics (details in Appendix, Table 3); MoCA scores for both fits were rescaled to lie between 0 and 1. **4b** shows the pattern of association between MoCA scores of individuals and the average connectivity of their homes revealed by spline regression. The modeled curve shown here is a constructed using a b-spline basis (polynomials of degree = 3; df = 4), showing variation in MoCA scores predicted by average connectivity for a median aged individuals from the study sample with a high school education.

But there are other more substantive reasons to consider possibilities of non-linear relationship between connectivity and MoCA scores. Looking more closely at the scattergram in Figure 3, we can that a straight line may not best capture the change in MoCA scores as connectivity changes. In particular, there seems to be a less clear indication of a consistent positive association between the two for homes with average room connectivity below 2. This could be just a characteristic of our sample, but there are reasonable theoretical grounds to believe that the pattern is general. From Euler's well-known theorem for polygons, we know that connectivity values greater than 2 can only arise if there are rings in the graphs, that is, if more than one paths exist between some pairs of nodes (Bafna et al., 2019). Below this threshold of 2, the drop in connectivity values is entirely a function of the number of rooms in the home; above this threshold, the connectivity depends upon a combination of the number of rooms and the number of circuits. We tested the hypothesis of non-linear relationship by modeling MoCA scores on our three predictors using a b-spline of 3 degrees for the relationship with average room connectivity, with 4 degrees of freedom. The estimated model produces an R^2 value of 0.36 (F = 7.46, Df = 6 and 64, $p = 4.3 \times 10^{-6}$), explaining 2% more of the variation, as compared to the model with a linear relationship (Figure 4b). To see if this increase in the explained proportion of variance is entirely due to average connectivity, we first modeled the MoCA scores with age and education as predictors, and then modeled the residuals from this fit, using only average connectivity as a predictor; the R2 value obtained was 0.06, which was 0.02 more than the proportion of variance explained by average connectivity alone in the OLS model. There are clear indications, therefore, that the relationship that exists between average connectivity and MoCA scores is not linear; however, a much larger sample and a stronger theory are required for exploring this relationship further.

4. Discussion

We must caution any enthusiastic readers against the inference that our findings offer empirical proof that layout can influence cognitive ability. Studies of this kind, based on observational data collected from the field, are only designed to test the extent to which the data are consistent with some hypothesized stochastic model that describes the posited relationship between predictor and outcome variables. The limited sample size of our study, which reflects the considerable resource costs needed to collect layout data on homes, also calls for caution in inference. But matters are somewhat ameliorated by the fact that our sample seems to be fairly representative of the US population in its demographic character (Table 1), giving us some confidence in the estimates generated from it.

Keeping these limitations in mind, we can make three reasonable inferences from the findings. The first, is that our data are consistent with the assumption that the relationship between features of home layout and their elderly residents' cognitive ability has a systematic component. Second, assuming that our sample data are representative, we can form at least a provisional judgment about the size of the associative effect we ought to expect. In our data, the average amount of difference in scores predicted over a standard deviation of interconnectivity found in houses—about one unit on the MoCA scale—was of the same order as that predicted by a decade of difference in ages. But the non-deterministic component—the between-subjects variance about the expected difference—is still relatively high; average room connectivity accounts for 4% of the variation in cognitive ability that is not accounted for by other factors. Third, our data clearly indicate that increase in cognitive ability is closely associated with increased occurrence of rings in traversal routes around the home, but that the increase of rings alone cannot account for the predicted difference in cognitive ability; it is possible that along with the increase in rings there is also an increase in perceived complexity of the home as the degree of interconnectivity increases, since larger homes with more rings also increase the difficulty of forming hierarchical conceptions of layouts.

If the results of study hold in further study, and if the substantive size of effects is judged to be therapeutically useful, our study offers support for a different approach into designing domestic environments for the elderly. Rather than designing home environments to only to reduce the environmental press, the design of environments may be utilized as a way to actively promote their health. As we had discussed in the introduction, the idea of devising a day-to-day living environment that offers the right level of cognitive challenges that lead to improved cognitive ability, or forestalls cognitive decline that comes with age, has been in the air since the 1970s. A key stumbling-block has been the lack of ability to define what features of the environment can offer the right kind of enrichment for humans. Our findings lead towards the idea that the interconnected of layouts may be a basic feature of enriched environments.

Naturally, more work is needed to confirm these findings, to ensure that the associations they capture are consistent, and to establish reliable effect sizes, so that practical decisions about health outcomes may be made. The thrust of such work, if it develops, ought to be towards developing and clarifying the underlying theory rather than just seeking to establish more precise empirical associations with increasingly complex models.

Funding

This work was supported by Georgia State University's Byrdine F. Lewis College of Nursing & Health Professions Intramural Grant Program.

Acknowledgement

We would like to acknowledge our participants for their time and contribution. The following graduate students assisted in data collections as a part of their Master's group project: Audrey Reiner, Benjamin Allen, Marianna Thomas, Kaitlyn Barker, Katherine Moss, and Nicole Sweeny.

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Resume

Dr. Bafna studies the principles that shape the built environment and govern its relationship with social, cultural, and imaginative life. He has published empirical studies on the impact of space on human behavior, cognition, social organization, and health, as well as critical studies of architectural works that explore topics in representation, aesthetics, and interpretation. As a member of the school of architecture faculty at Georgia Tech, he teaches courses in architectural theory, analysis and interpretation, and research methods. He is currently serving as the director of the PhD program in Architecture in the College of Design. Current projects include a book titled Imaginative Reasoning in the Shaping of Buildings.

Dr. Maitra is a Professor and the Chair and Professor of the Department of Occupational Therapy (OT) at Georgia State University, Atlanta, GA. He is an occupational therapist and a cognitive neuroscientist. Currently, he is working to understand the relationship between space cognition and the occupation of living in community-living older adults. He publishes in peer-reviewed national and international journals and regularly presents in national and international forums. Dr. Maitra received research support from federal agencies like the National Science Foundation (NSF) and the National Parkinson Foundation besides intramural fundings. He is a Fellow of the American Occupational Therapy Association, and he served as a Board of Trustees of the American Occupational Therapy Foundation for several years.

Dr. Lim is a pediatric occupational therapist at Let's Talk Therapy, Duluth, Georgia. She is also a lead clinical instructor and supervises fieldwork students from Occupational Therapy programs. Her clinical expertise is in strengths-based approach to autism and behavior and provides family-centered practice. Dr. Lim is a member of American Occupational Therapy Association.

Mansi is an architect and urban designer with 11 years of experience spanning practice, research, and teaching in India, the US, and Europe. She was mentored by Balkrishna Doshi – the 2018 Pritzker Laureate at his design laboratory in Ahmedabad, India from 2010-2014. Her research interests lie in understanding architecture's interaction with multiple disciplines such as psychology, linguistics, and anthropology. As a *visiting research scholar at Georgia Institute of Technology, she has been a part of several projects exploring the relationship between human behavior and the environment. She is currently a participant in a joint project between the architecture and psychology schools at Georgia Tech investigating the role of physical environments in post-pandemic work settings.*

Yi-An Chen is an Assistant Professor in the Department of Occupational Therapy at Georgia State University (GSU). Chen's research interests mainly focus on upper extremity rehabilitation for people with neurological disorders (e.g., stroke and Parkinson's disease). She has been collaborating with experts and researchers from Georgia Tech and Emory University on several different projects, with the common goal to provide patient-centered training or design to allow better independent life of patients. Chen had her clinical training and earned a Master's degree in Occupational Therapy. She further pursued her Ph.D. in Biokinesiology at the University of Southern California, concentrating on neurorehabilitation. She completed her postdoc training at GSU Physical Therapy Department, focusing on telerehabilitation in stroke.

Appendix

Table 2 Summary details for ordinary least squares multiple regression model of MoCA with Age, Education (categorical) and Average Room Connectivity of Home as co-predictors

Call:
lm(formula = Moca30 ~ Age + Educ2_ord + Hs_connect, data = all_data)

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	24.09	4.97	4.85	0.00
Age	-0.17	0.04	-4.13	0.00
Educ2_ord	1.51	0.66	2.30	0.02
Hs Connect	4.61	2.08	2.21	0.03

Residual standard error: 2.8 on 67 degrees of freedom
Multiple R-squared: 0.37, Adjusted R-squared: 0.34
F-statistic: 13 on 3 and 67 DF, p-value: 7.3e-07

Table 3 Summary details of Beta Regression model of MoCA (rescaled) with Age, Education (categorical) and Average Room Connectivity of Home as co-predictors; the model for the estimation of means was specified with a logit link function; an intercept-only model with an identity link was specified for the estimation of the precision parameter

Call:
betareg(formula = Moca_beta_scl ~ Age + Educ2_ord + Hs_connect, data = all_data)

Coefficients (mean model with logit link):

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	1.38	1.17	1.18	0.24
Age	-0.04	0.01	-4.55	0.00
Educ2_ord	0.32	0.15	2.10	0.04
Hs_connect	1.27	0.51	2.52	0.01

Phi coefficients (precision model with identity link):

	Estimate	Std. Error	z value	Pr(>|z|)
(phi)	13.52	2.28	5.92	0.00

Log-likelihood: 80 on 5 Df
Pseudo R-squared: 0.35
Number of iterations: 19 (BFGS) + 2 (Fisher scoring)