

# Space syntax visibility graph analysis is not robust to changes in spatial and temporal resolution

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## Abstract

Space syntax is an influential framework for quantifying the relationship between environmental geometry and human behavior. Although many studies report high syntactic–behavioral correlations, previous pedestrian data were collected at low spatiotemporal resolutions, and data transformations and sampling strategies vary widely; here, we systematically test the robustness of space syntax’s predictive strength by examining how these factors impact correlations. We used virtual reality and motion tracking to correlate 30 syntactic measures with high resolution walking trajectories downsampled at 10 grid resolutions and subjected to various log transformations. Overall, correlations declined with increasing grid resolution and were sensitive to data transformations. Moreover, simulations revealed spuriously high correlations (e.g.  $R^2 = 1$ ) with sparsely sampled data (<23 locations). These results strongly suggest that syntactic–behavioral correlations are not robust to changes in spatiotemporal resolution, and that high correlations obtained in previous studies could be inflated due to transformations, data resolution, or sampling strategies.

## Keywords

Space syntax, virtual reality, spatial behavior, simulation, architecture

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## Introduction

Space syntax (Hillier, 1999a; Hillier and Hanson, 1984; Hillier et al., 1996) is a prominent framework for examining the relationship between human behavior and the geometry of the built environment. Syntactic measures are frequently used to quantify configurational properties of urban and architectural environments, and many measures have been shown to correlate with patterns of human movement and usage in a variety of settings, including museums (Batty, 2001; Turner and Penn, 2002), malls (Okamoto et al., 2013; Omer and Goldblatt, 2017), conference halls (Mashhadi et al., 2016), hospitals (Haq and Luo, 2012), and large-scale urban spaces (Turner, 2003). However, previous studies have examined relatively coarse pedestrian flow data collected at *low* spatial and temporal resolutions. As a result, the predictive strength of syntactic measures has not been systematically examined across a variety of spatial and temporal scales. If space syntax is to serve as a robust predictive framework, the strength of its correlations with pedestrian movement patterns should be robust to changes in the spatial and temporal resolution at which correlations are computed. To address this critical gap in the literature, the present study investigated the robustness of correlations between space syntax measures and *high* spatial and temporal resolution human walking data over a wide range of spatiotemporal resolutions.

### Overview of space syntax methods

This section provides an overview of space syntax methods and terminology with a focus on a subset of issues that are relevant to the present study (for more comprehensive introductions to space syntax concepts and terminology, see Bafna, 2003; Klarqvist, 1993).

**Visibility graph analysis (VGA).** In the present study, we focus on syntactic measures that can be computed from “visibility graphs” (Turner, 2003; Turner et al., 2001). A visibility graph is generated by superimposing a grid on a top-down view of a space (e.g. from a CAD drawing) using space syntax software. Syntactic measures (e.g. *isovist area*) can then be computed for each grid cell using topological methods for quantifying the proximity and inter-visibility of grid cells (Turner, 2003). The resulting analyses and visualizations are frequently used to examine configurational properties of spaces that may be relevant for predicting human behavior. *Integration*, a commonly cited visibility graph measure, is examined in detail in the present study. The integration value for a cell is obtained by computing the average depth (i.e. topological distance) of that cell to neighboring cells within a specified topological distance, effectively ranking cells “from the most integrated to the most segregated” (Klarqvist, 1993). A large number of other syntactic measures have been derived from visibility graphs, yet many of these measures have not been systematically investigated in a single study.

**Pedestrian data.** Previous studies have generally collected *low* spatiotemporal resolution pedestrian data, often manually. Typical methods employed in these studies include (Conroy, 2001): (1) *gate counts*, “the cumulative number of people passing over a specified ‘threshold’ within a given timeframe”; (2) *spot counts*, “the approximate location of all people present in any room or space at a given moment in time”; (3) *occupancy numbers*, “the total numbers of people present in a single space/room during specific time intervals throughout the day”; and (4) *movement traces*, most often obtained by researchers transcribing sketched approximations of paths taken as pedestrians walk through a space. The primary contribution of the present study is to examine correlations with continuous

high spatiotemporal resolution movement data. A key advantage of virtual reality systems leveraged in the present study is the ability to automate collection of high resolution movement trajectories using electronic motion tracking systems.

### *Criticisms of space syntax*

Space syntax remains the subject of lively debate. A number of thorough criticisms (Batty, 2001; Jguirim et al., 2014; Kostakos, 2010; Montello, 2007; Netto, 2016; Pafka et al., 2018; Peponis et al., 1997; Ratti, 2004a, 2004b; Turner et al., 2001), rebuttals (e.g. Hillier and Penn, 2004), and counter-rebuttals (e.g. Ratti, 2004a) to these criticisms have been advanced. Prior empirical studies investigating the relationship between space syntax measures and human movement report a range of correlation values ranging from weak (e.g. .142; Mora et al., 2014) to strong (e.g. .98; Penn et al., 1998). As a result, the predictive value of space syntax across a variety of spatial scales is in question, and a review of the literature reveals a number of important criticisms and limitations of prior research. The present study focuses on evaluating a subset of criticisms of space syntax with a focus on methodological limitations of previous empirical studies. In the following sections, we discuss each of these limitations in turn and describe our experimental approach.

*Data transformations and correlation methods.* Supplemental Material Table 2 summarizes the results from a selection of previous studies (De Arruda Campos, 1997; Desyllas and Duxbury, 2001; Hillier et al., 1996; Mora et al., 2014; Okamoto et al., 2013; Penn et al., 1998; Turner, 2003; Turner and Penn, 1999). Taken together, these studies report a wide range of syntactic-behavioral correlations, yet many studies do not report whether data transformations were applied to pedestrian or configurational data, or do not report how correlations were computed. As a result, replicating previous studies has been hindered, casting doubt on whether high correlations may be a function of methodological decisions. In an unpublished space syntax software manual, Turner (2014) notes that taking the natural logarithm of observed pedestrian data is accepted practice when the data are not normally distributed, and that correlations of  $R^2 = .40$  between space syntax measures and log-transformed (ln) observed variables are “expected in space syntax theory,” though the reasons for this expectation are not made clear. In contrast, Penn et al. (1998) investigated correlations between configurational properties of street networks and flow rates (both pedestrian and vehicular) and used a data transformation not often used in other studies (taking the fourth root of flow rates). Sometimes, data transformations are also applied to syntactic measures themselves. For example, Turner (2003) averaged gate counts from a previous study and applied a log transformation to agent simulation data. While data transformations are sometimes justified, inconsistent application of transformations is an important limitation of previous work. Finally, some authors (e.g. Turner, 2003) report  $R^2$  as well as significance values for correlations, while others do not. The present study aimed to address these inconsistencies by systematically investigating the effects of various data transformations on correlations for many visibility graph measures computed for a single space.

*Spatiotemporal resolution of pedestrian and configurational data.* As Desyllas and Duxbury (2001) note, “one of the methodological issues when using VGA is the effect of changing the parameter of sampling grid resolution.” Yet the spatial and temporal resolutions at which human walking data have been collected, as well as the spatial resolution at which configurational data have been computed, have not been comprehensively and consistently

reported across studies. In general, pedestrian and configurational data have been examined at the level of meters and minutes rather than at the level of millimeters and milliseconds, limiting our understanding of space syntax's predictive capabilities at high spatiotemporal resolution. The present study is the first to examine correlations between space syntax measures and human walking data collected at high temporal ( $\sim 60$  Hertz) and spatial (0.75 millimeter,  $0.05^\circ$ ) resolution—on the order of milliseconds and millimeters—and to explore how correlations depend on spatial and temporal binning.

*Sampling strategies.* Past studies also vary widely in sampling methods used. For example, Turner and Penn (1999) calculated “mean isovist integration value[s] of nodes within a 1.5 m buffer of each gate location.” And as Silva (2013) notes, when studies are conducted in professional contexts, modeling of pedestrian and vehicular traffic patterns is frequently done on an intuitive basis, “following tradition, rather than a statistically sound methodology.” The present study addresses these limitations by clearly reporting how pedestrian and configurational data were collected, by more systematically evaluating the robustness of correlations across a variety of spatial scales and sampling resolutions, and by using a simulation approach to quantify the impact of sampling strategies.

*Characteristics of spaces examined.* The underlying mathematical formulations of space syntax theory embody an implicit hypothesis that human behavior is causally linked to the geometry of the environment. Previous research on the predictive strength of syntactic measures has primarily examined human movement patterns in rooms and urban spaces. If human movement patterns are constrained by the geometry of the environment, one would expect that movement patterns in narrow spaces (e.g. hallways or maze corridors, where movement is relatively constrained) should be highly predictable relative to movement patterns in more open spaces (e.g. interconnected rooms, where movement is relatively unconstrained). Testing the predictive capabilities of syntactic measures by asking participants to navigate restricted maze corridors provides a strong test of space syntax predictions in enclosed spaces.

### *The present study*

In sum, the present study contributes to the literature on space syntax by addressing three key criticisms and limitations of previous work. First, data collection methods are not always comprehensively reported, and details regarding data transformations applied to syntactic and pedestrian data are inconsistently reported; the present study addresses this limitation by (a) thoroughly documenting how the data were collected and transformed, and (b) assessing the impact of data transformations on correlations. We asked whether (Q1) correlations are sensitive to data transformations. Second, pedestrian data have generally been sampled at relatively *low* spatial and temporal resolutions, and prior studies have not systematically examined the impact of sampling grid resolution on syntactic-behavioral correlations; we address this by (a) sampling continuous walking trajectories at high spatial and temporal resolution using a motion tracking system, and (b) examining whether correlations vary as the spatial resolution of the sampling grid is increased. We asked whether (Q2) correlations depend on the spatial resolution of the sampling grid. Third, sampling strategies—in particular, the number of “gates”—used in previous studies vary widely; to address this, we examined how correlations change when an increasing number of randomly selected grid locations are used as the basis for computing correlations. We asked whether (Q3) a small sample of spatial locations would yield spuriously high correlations.

## Methods

The present study was conducted at the Virtual Environment Navigation Laboratory (VENLab) at Brown University.

### Participants

A total of 36 participants were included in the analysis (18M, 18F). The mean age of participants was 20.8 years ( $SD = 4.35$  years). Participants provided written informed consent to participate in the experiment in accordance with Brown University's Institutional Review Board requirements, and were paid (\$10/hour) for their participation.

### Apparatus

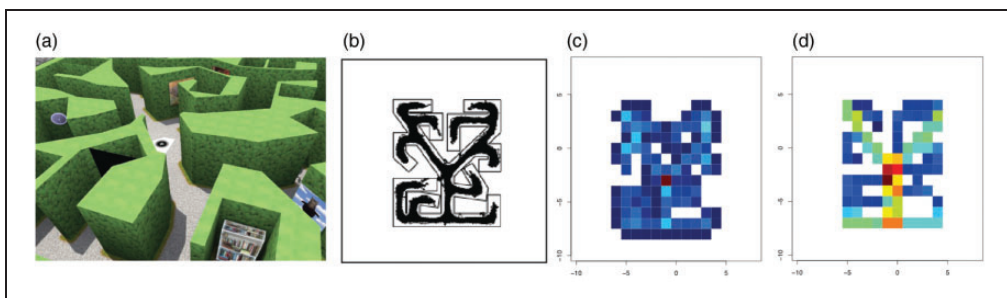
Participants walked freely within a  $10.5 \times 12.5$  meter area in the lab while a tracking system (InterSense IS-900, 1 millimeter linear and  $1^\circ$  angular RMS error, 60 Hertz sampling rate) recorded head position and orientation. Stereoscopic images of the virtual environment were presented via a head-mounted display (HMD, Rockwell-Collins SR80A,  $1280 \times 1024$  pixels,  $63^\circ$  H  $\times$   $53^\circ$  V field of view for each eye) calibrated to each participant's inter-ocular distance. Displays were generated on a Dell XPS 730X desktop computer (50 millisecond total latency).

### Displays

The virtual environment (Figure 1(a)) was a hedge maze containing a central "home" location, eight unique target objects located at the ends of maze hallways, and four paintings that provided local landmarks. The environment was created in 3DS Max (Autodesk) and presented to the participant using Vizard (WorldViz, Version 4.0).

### Procedure

Participants were brought to the center of a virtual hedge maze, instructed to learn the locations of the objects in maze while freely exploring for 10 minutes, and informed that they



**Figure 1.** Displays and data collection. (a) Birds-eye-view of the virtual hedge maze. (b) Raw aggregated walking data from all study participants comprising 1.5 million data points collected at 1.5 millimeters/ $0.10^\circ$  spatial resolution and 60 Hertz temporal resolution. (c) Low-resolution binned walking data (bin size = 1.0 meter). (d) Example of low-resolution space syntax data (connectivity; bin size = 1.0 meter) generated by depthmapX. With respect to (c) and (d), note that the simulation parameter  $N_{\text{GATES}}$  denotes the number of individual grid cells that have been randomly selected from among all of the available cells in the sampling grid to compute correlations; in the space syntax literature, this corresponds to the number of experimenters stationed to count pedestrian flows (i.e. obtain gate counts).

**Table 1.** Percentage of correlations ( $N = 410$ ) for which each potential data transformation yielded the highest computed  $R^2$  value.

Data transformation	$n$	%
W versus S	28	6.8
W > 0 versus S > 0	10	2.4
W versus S > 0	25	6.1
ln (W) > 0 versus S	97	23.7
ln (W + I) versus S > 0	35	8.5
ln (W + I) versus S	30	7.3
ln (W) > 0 versus S > 0	12	2.9
$\log_{10}$ (W) > 0 versus S	106	25.9
$\log_{10}$ (W + I) versus S > 0	30	7.3
$\log_{10}$ (W + I) versus S	27	6.6
$\log_{10}$ (W) > 0 versus S > 0	10	2.4

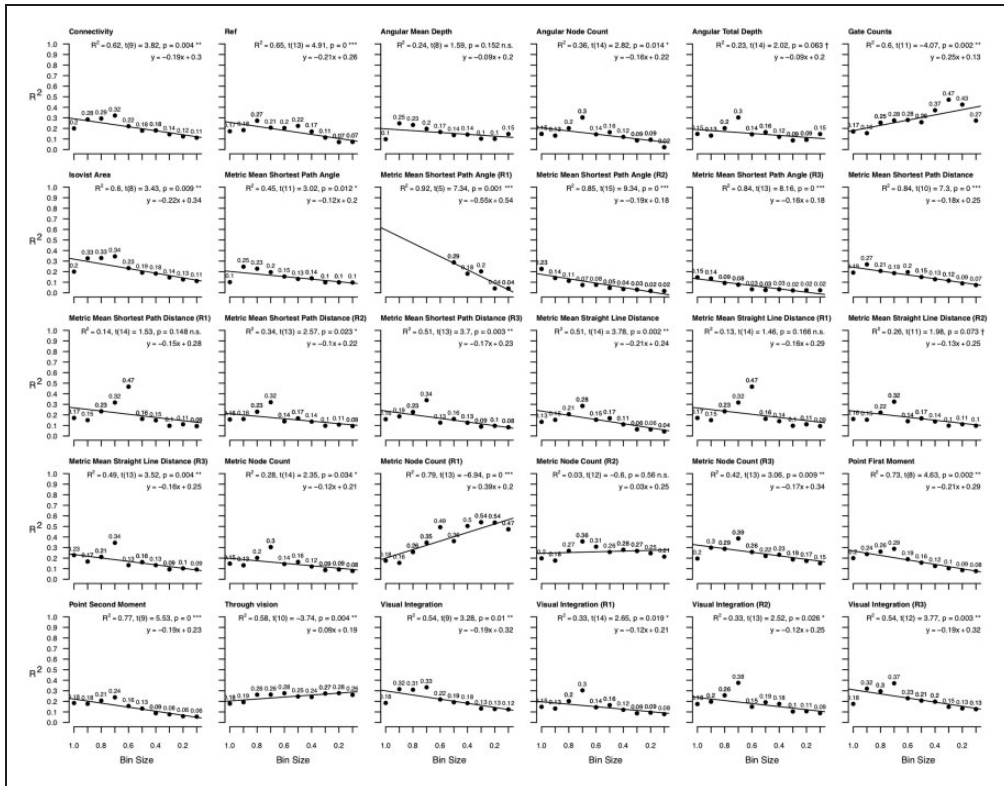
Note: W represents untransformed walking data, S represents untransformed syntactic measure, and parentheses indicate the order of operations applied to untransformed walking data prior to computing correlations ( $R^2$ ). Overall, percentages in the % column sum to > 100%: at some bin sizes, more than one data transformations produced equivalent maximal correlation values; this occurred for 110 cases, yielding a total of  $N = 410$  ( $300 + 110$ ) maximum correlations; in these cases, the counter ( $n$ ) was incremented for more than one data transformation.

would be tested on their knowledge of the object locations later in the experiment. When they walked up to an object, an audio file played telling them the name of that object (e.g. “bookcase”). If participants left the  $10.5 \times 12.5$  meter maze, virtual brick walls appeared to prevent collisions with the lab’s walls. Background noise (night sounds) was played over headphones, and a black cloth covered the HMD to block the view of the lab.

### Data analysis

Here, we present an overview of the analytical approaches used to examine each of our primary research questions (for additional detail on each approach, see Supplemental Material: Methods). Both syntactic measures and human walking data were binned at 10 discrete spatial scales in .01 meter increments to produce grids where the edge lengths of the cells ranged from 0.01 to 1.00 meter. Walking data were aggregated across all participants, yielding 1.5 million positional data points (x, y, time); raw walking data values (W) were obtained by counting the number of points in each grid cell, and raw syntactic measure (S) values were computed for corresponding grid cells using depthmapX (Version 0.5b; Varoudis, 2015b). To examine whether correlations are sensitive to data transformations (Q1), we applied 11 different data transformations (see Table 1) to all 30 syntactic measures across 10 different spatial resolutions (bin sizes), and compared the performance of each transformation. To examine whether correlations decline with increasing spatial resolution (Q2), we used a regression analysis and plotted  $R^2$  values against bin size (see Figures 2 and 3). To examine whether spurious correlations would be obtained when few relatively few sampling locations ( $N_{\text{GATES}}$ ) within the overall sampling grid are used to compute correlations (Q3), we used a simulation approach in which an increasing number of randomly positioned sampling locations ( $N_{\text{GATES}}$ ) were used to compute correlations for each measure and bin size using the most frequently effective data transformation ( $\log_{10}(W) > 0$  versus S) (see Figure 4, and Supplemental Material Figure 7).





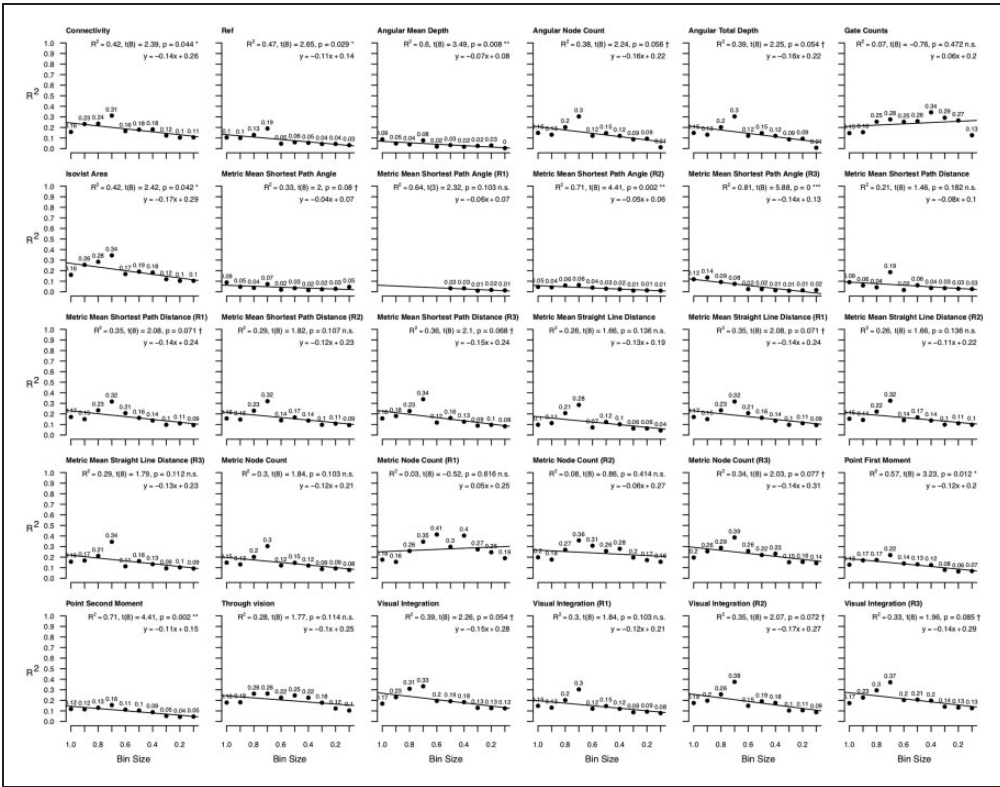
**Figure 2.** Correlation ( $R^2$ ) versus spatial resolution (best data transformation at each bin size). In order to facilitate interpretation with respect to predictions concerning spatial resolution, bin sizes are plotted in reverse order (i.e. in order of increasing spatial resolution) from left to right. Significance tests and regression equations ( $y = mx + b$ ) reported beneath facet titles (syntactic measures) indicate statistical results of linear regression. Significance levels are indicated as follows: \* $p < .05$ ; \*\* $p < .01$ ; \*\*\* $p < .001$ , †marginal ( $.05 < p < .1$ ), and results that failed to reach significance are also indicated (n.s.). Metric Mean Shortest Path Angle (R1) could not be computed for bin sizes ranging from 0.6 to 1.0 meters.

## Results

Here, we present results with respect to our three primary research questions. Hillier (1999a) notes that “in most studies the best performing spatial variable is Radius-3 Integration” (denoted *Visual Integration (R3)* in the present study). In contrast, in the present study, we found that *Metric Node Count (R1)* was the best performing spatial variable. Therefore, for simplicity of presentation, aggregated results are presented for all 30 syntactic measures (see Table 1 and Figures 2 and 3), while more detailed results are presented for two key measures: *Visual Integration (R3)* and *Metric Node Count (R1)* (see Supplemental Material Figures 5 and 6).

### Q1: Are correlations sensitive to data transformations?

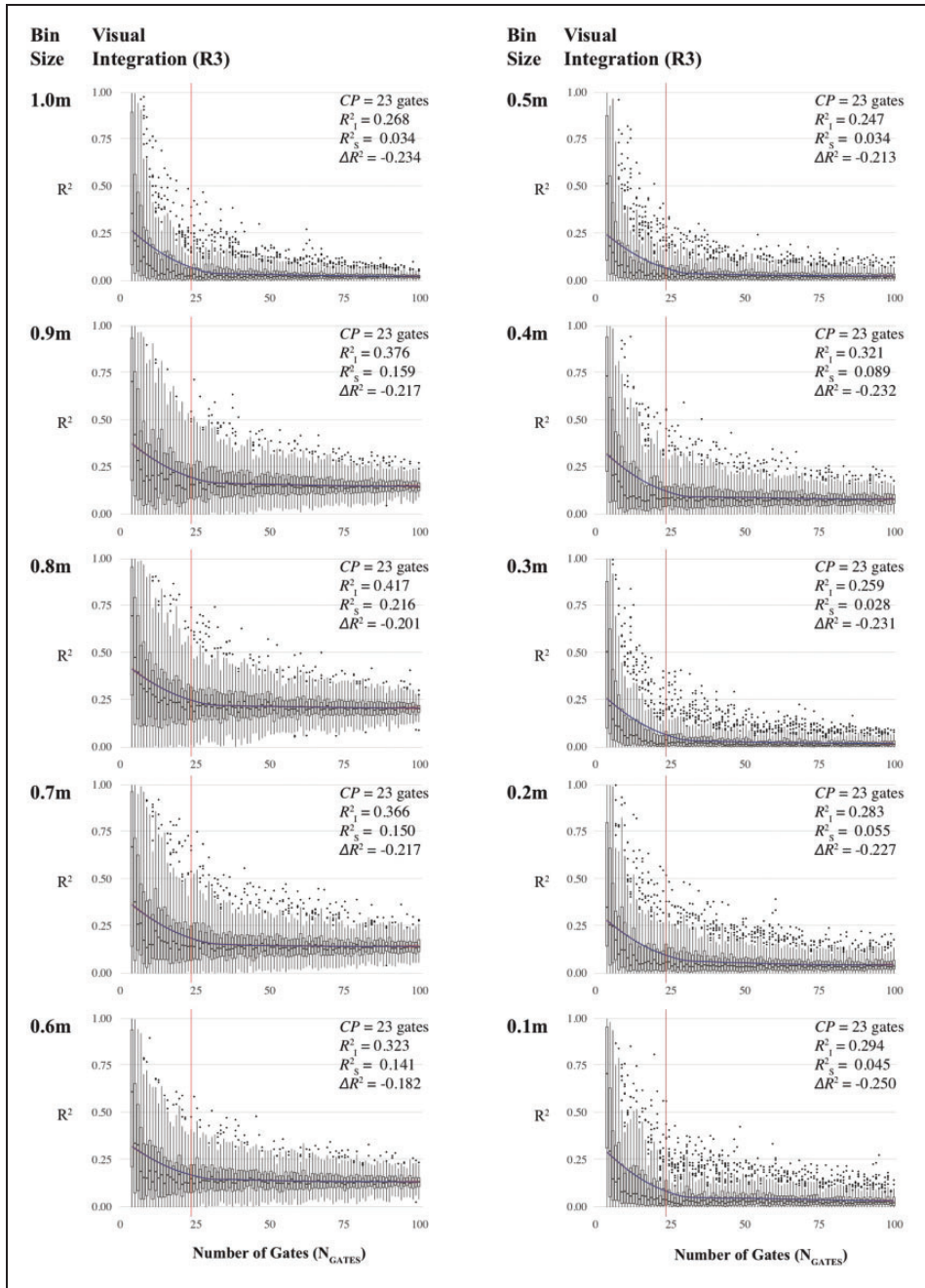
**Determining the best overall data transformation.** To identify the most effective overall data transformation, syntactic-behavioral correlations were computed for 30 syntactic measures across 10 sampling grid resolutions (see “Methods” section). For each of the 300 resulting measure-bin size pairs, a series of 11 data transformations (see Table 1) were applied to the data,



**Figure 3.** Correlation ( $R^2$ ) versus spatial resolution for best overall ( $\log_{10}(W) > 0$  versus  $S$ ) data transformation. In order to facilitate interpretation with respect to predictions concerning spatial resolution, bin sizes are plotted in reverse order (i.e. in order of increasing spatial resolution) from left to right. Significance tests and equations ( $y = mx + b$ ) reported beneath facet titles (syntactic measures) indicate statistical results of linear regression. Significance levels are indicated as follows: \* $p < .05$ ; \*\* $p < .01$ ; \*\*\* $p < .001$ , †marginal ( $.05 < p < .1$ ), and results that failed to reach significance are also indicated (n.s.). Note: The Metric Mean Shortest Path Angle (R1) calculation in depthmapX could not be computed for bin sizes ranging from 0.6 to 1.0 meter.

yielding 3300 ( $300 \times 11$ ) correlation ( $R^2$ ) values. The transformation(s) yielding the highest  $R^2$  value(s) for each measure–bin size pair were then tabulated (Table 1,  $n$  column) and converted to percentages for each data transformation (Table 1, % column). A summary of this analysis is presented in Table 1. The  $\log_{10}(W) > 0$  versus  $S$  transformation produced the highest correlation for 25.9% of the cases examined, followed by  $\ln(W) > 0$  versus  $S$  (23.7% of cases examined). The percent score indicates that these two transformations tended to yield the highest correlation values. In comparison, leaving data untransformed ( $W$  versus  $S$ ) yielded the highest correlation values in only 6.8% of cases examined. In sum, we found that (Q1) syntactic–behavioral correlations were sensitive to data transformations; in particular using logarithmically ( $\log_{10}$  and  $\ln$ ) transformed walking data and untransformed syntactic values yielded the highest syntactic–behavioral correlations. Therefore, to ensure that subsequent analyses were charitable toward space syntax measures (without resorting to algorithmically cherry-picking the best data transformation for each specific case, as in the previous analysis) we present  $\log_{10}(W) > 0$  versus  $S$  in several of the analyses and figures that follow.





**Figure 4.** Simulations: Visual Integration (R3). *x*-axes ( $N_{\text{GATES}}$ ): number of randomly sampled gate locations; 100 replications were simulated for each value of  $N_{\text{GATES}}$ . *y*-axes:  $R^2$  values between the 100 simulations and the walking data. The mean and range are displayed for each value of  $N_{\text{GATES}}$ . *Boxplot whiskers*: min/max of  $1.5 \times$  interquartile range. *Black dots*: outliers. *Trend lines*: best fit line for LPR fit. *CP* (red vertical line): first estimated change point value in LPR fitted  $R^2$  values.  $R^2_i$ : initial  $R^2$  value of LPR fit line (at  $N_{\text{GATES}} = 3$ ).  $R^2_s$ : stabilized  $R^2$  value, estimated by obtaining the mean of all LPR fitted  $R^2$  from  $N_{\text{GATES}} = \text{CP}$  gates to  $N_{\text{GATES}} = 100$ .  $\Delta R^2 = R^2_i - R^2_s$ . For each value of  $N_{\text{GATES}}$ , 100 simulation runs were performed. *Boxplot hinges*: 25th and 75th percentiles.

## Q2: Do correlations depend on the spatial resolution of the sampling grid?

*Part 1: Best data transformation for each measure–bin size pair.* For this analysis, we used whichever data transformation yielded the highest correlation in order to obtain maximal  $R^2$  values for each measure–bin pair. For each syntactic measure, a simple linear regression was calculated to predict syntactic–behavioral correlation strength ( $R^2$ ) as a function of spatial resolution (bin size). We asked whether (Q2) correlations would decline as the spatial resolution of the sampling grid is increased, corresponding to negative regression lines. Results appear in Figure 2.

Significant regression equations were found ( $p < .05$ ) for 24 of the 30 (80%) syntactic measures. Regression lines had significant negative slopes for 22 of the 30 (73%) syntactic measures ( $p < .05$ ), significant positive slopes for 2 of the 30 (6.7%) syntactic measures (Metric Node Count, Gate Counts), and marginally significant negative slopes ( $.05 < p < .1$ ) for two measures (Angular Total Depth; Metric Mean Straight Line Distance ( $R^2$ )). Regression equations for the remaining four measures (13.3%) did not reach significance. The syntactic measure that yielded the highest computed correlation ( $R^2 = .54$ ; 0.2 and 0.3 meter bin sizes) was Metric Node Count (R1); the slope of the regression line was significantly positive ( $p < .05$ ); equivalent correlation values ( $R^2 = .54$ ) were obtained using both the  $\ln(W+1)$  versus  $S > 0$  and  $\log_{10}(W+1)$  versus  $S > 0$  data transformations. Several measures exhibited an apparently nonlinear trend with peaks at intermediate bin sizes (e.g. Metric Mean Shortest Path Distance (R1), Figures 2 and 3).

In sum, (Q2) correlations declined as spatial resolution was increased: regression equations for a majority (22/30 or 73%) of syntactic measures revealed a significant ( $p < .05$ ) negative relationship between syntactic–behavioral correlation strength and spatial resolution (bin size), and a significant positive relationship was found for only a small percentage (2/30 or 6.7%) of the syntactic measures.

*Part 2: Correlation ( $R^2$ ) versus spatial resolution for the best overall transformation ( $\log_{10}(W) > 0$ ).* In this analysis, the best-performing  $\log_{10}(W) > 0$  versus  $S$  data transformation was used. For each syntactic measure, a simple linear regression was calculated to predict correlation strength ( $R^2$ ) based on spatial resolution (bin size). Results appear in Figure 3.

Significant negative regression equations were found ( $p < .05$ ) for 8 of the 30 (26.7%) syntactic measures, and (Q2) correlations declined approximately linearly for these measures. The syntactic measure that yielded the highest computed correlation ( $R^2 = .41$  at 0.6 meter bin size) was Metric Node Count (R1); this is the only measure that exhibited a positive regression equation ( $p < .05$ ) with a positive relationship between correlation strength and spatial resolution. Marginally significant ( $.05 < p < .1$ ) regression equations were found for 10 of the 30 (33.3%) syntactic measures, and (Q2) associated regression line slopes exhibited a negative trend, indicating that correlation strength declined approximately linearly for these measures. Regression equations for the remaining 12 of 30 (40%) measures did not reach significance. In sum, (Q2) correlations declined as spatial resolution was increased.

## Q3: Does a small sample of spatial locations yield spuriously high correlations?

To examine our third research question, we used a simulation approach to examine the relationship between correlation strength and the number of randomly located gate locations ( $N_{\text{GATES}}$ ) at which pedestrian data are sampled. Specifically, we ran 100 replications for each of 100 randomly located gates and 10 bin sizes (resolution). The key result we will examine here is the change in the correlation as the spatial resolution increased. Prior to

running these simulations, syntactic data and walking data were computed for each bin size using the  $\log_{10}(W) > 0$  versus  $S$  transformation; this transformation yielded the highest percentage of maximal correlations in the foregoing analysis (see Table 1). Boxplots were used to summarize simulation results for the two syntactic measures examined in the previous section: Visual Integration (R3) (Figure 4) and Metric Node Count (R1) (Supplemental Material Figure 7).

*Visual Integration (R3).* At all 10 spatial resolutions examined, correlations between Visual Integration (R3) and walking data decreased ( $\Delta R^2$ ;  $M = -.22$ ,  $SD = .019$ ) as  $N_{\text{GATES}}$  increased. The first value of  $N_{\text{GATES}}$  (Figure 4, x-axis) at which a significant change (Ross, 2015) in local polynomial regression (LPR) fitted  $R^2$  values (Figure 4, y-axis, blue best fit line) was detected was  $N_{\text{GATES}} = 23$ .

This value was consistent across all 10 of the spatial resolutions examined. Beyond 23 gates, correlations tended to stabilize ( $R^2_{\text{S}}$ ) at a low but relatively constant value (*mean*  $R^2_{\text{S}} = .095$ ;  $SD = .067$ ). With respect to Q3, when fewer than 23 gates were used to compute correlations, perfect positive correlations ( $R^2 = 1$ ) between Visual Integration (R3) and walking data were sometimes obtained; this result strongly suggests that using a small number of sampling grid locations can inflate correlations.

*Comparisons to random noise.* To assess whether this measure correlated with walking data above chance levels, random noise was substituted for syntactic data, and correlated with walking data. Initial correlations ( $R^2_{\text{I}}$ ) between syntactic data and walking data (*mean*  $R^2_{\text{I}} = .32$ ,  $SD = .06$ ) were 28% higher than correlations between random noise and walking data (*mean*  $R^2_{\text{I}} = .25$ ,  $SD = .02$ ),  $t(10) = 3.58$ ,  $p < .01$ . Stabilized correlations ( $R^2_{\text{S}}$ ; beyond  $N_{\text{GATES}} = 23$ ) with walking data were also higher for syntactic data ( $M = .095$ ,  $SD = .067$ ) than random noise data ( $M = .022$ ,  $SD = .01$ ),  $t(9) = 3.47$ ,  $p < .01$ . Thus, syntactic measures performed better than chance. However, with respect to Q3, perfect positive correlations ( $R^2 = 1$ ) between random noise and walking data were sometimes obtained when fewer than 23 gates were used, strongly suggesting that using a small number of sampling grid locations can inflate correlations.

## Discussion

In this section, we examine our results in relation to each of our three research questions and compare our findings to the results of previous studies.

**Q1: Correlations are sensitive to data transformations.** We examined the relationship between (a) syntactic-behavioral correlation strength and (b) the underlying spatial resolution of both syntactic and pedestrian data. At each of the 10 spatial resolutions examined, we found that correlations were highly sensitive to data transformations (see Table 1). The  $\log_{10}(W) > 0$  versus  $S$  data transformation yielded the highest correlation for a majority (25.5%) of measures examined, followed by the  $\ln(W) > 0$  versus  $S$  transformation (23.4%). The results strongly suggest that logarithmic ( $\log_{10}$  or  $\ln$ ) transforming of positional data (to correct for departures from normality) and excluding zero values from the calculation yields the highest correlations between syntactic measures and continuous walking trajectories. Because data transformations are rarely reported in prior research, we strongly recommend that researchers check the distribution of their pedestrian data and clearly report whether the data were transformed.

**Q2: Correlations decline as spatial resolution is increased.** The results of the present study strongly suggest that correlations between syntactic measures and continuous walking

trajectories are not robust to changes in scale. We found that when the most effective data transformation is used, the relationship between correlation strength and spatial resolution is significantly negative for a majority (24/30 or 80%) of syntactic measures ( $p < .05$ ). Only 1 of the 30 (.03%) measures, Metric Node Count (R1), revealed a significant positive relationship between correlation strength and spatial resolution ( $p < .05$ ). Thus, for the vast majority of the syntactic measures examined, correlation strength declined with increasing spatial resolution.

**Q3: A small sample of spatial locations can result in spuriously high correlations.** When fewer than 23 locations ( $N_{\text{GATES}}$ ) in the virtual environment used in the present study were used to sample syntactic and pedestrian data, the probability of obtaining spuriously high correlations increased dramatically. For each of the measures examined using the simulation approach, using fewer than 23 gates to compute correlations sometimes yielded outlying perfect positive correlations ( $R^2 = 1$ ) between random noise and walking data. However, it is important to note that stabilized  $R^2$  values remained higher than chance (i.e. performed better than correlations between random noise and walking data) when more than 23 gates were used, suggesting that space syntax measures can at least partially account for the variance in pedestrian movement patterns. Studies that use a small number of locations in space but show high correlations should be regarded as spurious because correlations between random noise and walking data exhibited the same behavior.

### *Relationship to previous research*

Previous observational studies of people walking in real urban and architectural environments have found correlations between space syntax and walking data ranging from weak (e.g. .142; Mora et al., 2014) to strong (e.g. .98; Penn et al., 1998). Hillier (1999b) claims that “in most studies the best performing spatial variable is radius-3 integration.” In comparison to previous studies, the present study used a controlled laboratory experiment and virtual reality to examine syntactic-behavioral correlations, and found that Visual Integration (R3) reached a maximum correlation of  $R^2 = .30$  (0.7 meter bin size, see both Figures 2 and 3). In the present study, the highest computed correlation with continuous walking data was found for Metric Node Count (R1) ( $R^2 = .54$  at 0.6 meter, see Figure 2;  $R^2 = .41$  at 0.6 meter, see Figure 3) using the  $\log_{10}(W) > 0$  versus  $S$  data transformation; other measures were generally inconsistent with this pattern of results. Results for Metric Node Count (R1) are all the more curious given that most previous research has generally focused on Visual Integration.

Desyllas and Duxbury (2001) compared the predictive capabilities of axial maps and VGA by sampling pedestrian flow data ( $N_{\text{GATES}} = 84$ ) in a busy urban area (St Giles Circus, London) at a rate of 5 minutes/hour on two non-consecutive days (Saturday and Tuesday). They computed syntactic-behavioral correlations for several axial map measures, and one local VGA measure (the natural log of Mean Visibility at 3 and 5 meter grid resolutions). Overall, they found that VGA significantly outperformed axial map analysis (best VGA correlation:  $R^2 = .625$ ; best axial map correlation:  $R^2 = .429$ ), and that the correlation between  $\ln$  Mean Visibility and  $\ln$  Mean Pedestrian Movement Data increased from  $R^2 = .456$  to  $.625$  as spatial resolution was increased from 5 to 3 meters. The present study differs from Desyllas and Duxbury’s study in several important ways. First, while they examined several axial map measures and only one VGA measure, we systematically examined a wide variety of VGA measures. Second, they examined only two spatial resolutions (5 and 3 meters), and these were considerably lower than those used in the present study (1.0–0.1 meter). Our results revealed an opposite pattern of results for a majority (80%) of syntactic measures, and only one measure (Metric Node Count (R1)) exhibited

an outlying pattern consistent with Desyllas and Duxbury's (2001) results. Because the present study more systematically examined a wider range of spatial resolutions, these results strongly suggest that correlations for most syntactic measures will be *strongest* when computed at *low* spatial resolution and will *decline* at *high* spatial resolution. In addition, we evaluated a relatively large number of syntactic measures, providing baseline data for future examinations of whether syntactic measures might be grouped into classes that exhibit similar behavior across spatial scales.

### *Limitations of the present study*

In order to provide a strong test of syntactic predictions in enclosed spaces, we chose to examine correlations between syntactic measures and continuous, naturalistic walking trajectories in hallways (a virtual hedge maze), where locomotion is relatively constrained. Future studies should examine correlations between syntactic measures and continuous walking trajectories in a variety of large open spaces (e.g. buildings consisting of variably sized rooms linked by hallways and rings of circulation), using GIS methods (Lee and Seo, 2013; Liu et al., 2015), and leveraging tracking data from mobile phones and smart cities to examine the robustness of space syntax to changes in spatiotemporal resolution across a wider variety of navigational modes, contexts (both real and virtual), and spatial structures. Based on the present results, we expect that correlations will be even lower in open spaces because locomotion is relatively less constrained in open spaces than in restricted corridors. Although our goal-directed task is one that humans routinely perform in everyday life, it is unknown whether the cognitive demands of goal-directed navigation match those of the more undirected tasks from previous work. Thus, future work should also examine correlations when pedestrian data are drawn from a variety of tasks, in addition to the goal-directed exploration task used in the present study. In addition, because few comparisons of walking paths in real and virtual environments have been reported, future work should directly compare environments with matched configurations.

Past research has clearly demonstrated that space syntax measures *correlate* with human movement. Although strong correlations have led some researchers to conclude that spatial geometry *causes* particular behavior patterns, we recommend caution in drawing causal conclusions from correlational data. Future studies should more rigorously explore whether the features of environmental geometry that are encoded in space syntax measures play a demonstrably *causal* role in shaping human behavior and spatial knowledge. To this end, future studies should examine the robustness of syntactic predictions to parametric manipulations of environmental geometry. For example, we found that syntactic-behavioral correlations tended to stabilize when at least 23 gates were used to sample pedestrian data—a number that roughly corresponds to the number of maze segments between junctions and corners. This suggests a tentative hypothesis: that strong syntactic-behavioral correlations in enclosed spaces will be found when the number of gates corresponds to the number of path segments. Our use of randomly positioned gates underscores that spuriously high correlations can be obtained even when the gate positions are not placed in principled locations (e.g. corresponding to major path segments or junctions), which casts doubt on the hypothesis that strong syntactic-behavioral correlations in enclosed spaces will be found when the number of gates corresponds to the number of path segments.

Finally, past research suggests that a variety of contextual factors including the presence of salient objects (e.g. paintings, Tzortzi, 2009), landmarks (Appleyard, 1970; Montello and Pick, 1993), people (Appleyard, 1970; Dalton et al., 2011; Emo et al., 2012; Peponis et al., 1990), shops (Hillier et al., 1993), and traffic (Emo et al., 2012) can serve as attractors that



impact pedestrian movement patterns. In contrast to prior observational studies—which have been constrained by the configuration of existing spaces—the use of controlled laboratory experiments in conjunction with virtual reality offers researchers the ability to systematically test the relationship between contextual factors, configurational properties, and human movement patterns.

## Conclusions

The goal of the present study was to systematically examine how syntactic–behavioral correlations are impacted by data transformations, data resolution, and sampling strategies. The present study contributes to the space syntax literature by clarifying the impact of data transformations, comparing the performance of syntactic measures to a baseline of random noise, and more closely examining the robustness of correlations to changes in spatiotemporal scale. In sum, we found that syntactic–behavioral correlations (Q1) are sensitive to data transformations, (Q2) decline as the spatial resolution of VGA sampling grids is increased, and (Q3) can reach spurious levels when computed for only a subset of sampling locations in a visibility graph. We also found that correlations tend to stabilize when at least 23 sampling locations are used in the calculation, for our environmental configuration. Our results also provide useful baseline data for assessing the performance of syntactic measures across a wide variety of spatial and temporal scales. Finally, our findings strongly suggest that space syntax correlations are not robust to changes in spatial or temporal scale, and that high correlations obtained in previous space syntax studies may be spuriously high due to previously unexamined effects of data transformations, data resolution, or sampling strategies. Therefore, we recommend that researchers employing space syntax methods thoroughly report—and carefully consider—how each of these factors impact syntactic–behavioral correlations.

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## Supplemental material

Supplementary material for this article is available online.



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