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# Shared Paths to the Lab: A Sociospatial Network Analysis of Collaboration

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## Abstract

Spatial layouts can significantly influence the formation and outcomes of social relationships. Physical proximity is thus essential to understanding the elemental building blocks of social networks, dyads. Situating relationships in space is instrumental to formulating better models of collaboration and information sharing in organizations and more robust theories of networks and their effects. We propose, develop, and test a concept, the *functional zone*, which effectively captures Festinger et al.'s classic description of "functional distance" as it pertains to social interactions. We operationalize functional zone with measures of path and areal *zone overlap*. At two biomedical research buildings with different layouts (compact versus linear), regression analyses of collaboration rates show that increasing path overlap increases collaboration. More traditional distance measures influence collaboration only in the more linear building. The functional zone concept improves our ability to understand relationships and their attendant organizational outcomes.

## Keywords

physical proximity, social networks, scientific collaboration, functional distance, relationship formation

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## Introduction

Social relationships shape the activities of organizations, teams, and individuals in complicated ways (Burt, 2004; Hansen, 1999; W. W. Powell, Koput, & Smith-Doerr, 1996), but social scientists are only beginning to systematically explore how the arrangement of physical space influences workplace interactions and outcomes. People work and interact in the built environment (Grannis, 2011; Hua, Loftness, Heerwagen, & Powell, 2011). Research that disregards space or analytically divorces social phenomena from location is likely to result in impoverished theories, biased findings, and misspecified models (Kono, Palmer, Friedland, & Zafonte, 1998).

Many of the processes and outcomes that are the focus of organizational analysis depend upon social networks. The most elemental level of analysis for understanding networks based on information sharing, collaboration, or teamwork may be the dyad (Mizruchi & Marquis, 2006). Despite the importance of dyads, little work has explicitly examined spatial effects on dyad formation (Allen & Fustfeld, 1975; Sailer & Penn, 2009; Wineman, Kabo, & Davis, 2009). Spatial effects have not been robustly incorporated in such social science models because we have lacked spatial measures that are nuanced enough to operationalize key concepts. This article takes initial steps toward more fully integrating spatial and social explanations of collaborative relationships at work by developing a new measure of physical proximity that more effectively captures classic concepts of the effects of space on the likelihood of interaction (Festinger, Schachter, & Back, 1950). We demonstrate that our measure, zone overlap or the extent to which a pair of individuals share common physical spaces, explains rates of collaboration formation among interdisciplinary life scientists working in two research buildings on the campus of a large public research university. The explanatory power of this measure is distinct from the effects of more traditional distance variables including the metric measures of straight line and walking distances and the topological measure of turn distance.

Most contemporary efforts to understand spatial effects in organizational settings employ physical distance as a proxy for the subtle ways in which proximity enables or hinders interaction (Cowgill, Wolfers, & Zitzewitz, 2009; Liu, 2010; Sailer & McCulloh, 2012). While this body of research has incorporated spatial effects in organizational analyses, their measure of distance cannot generally capture the powerful but subtle relational and topological effects of space that we refer to as functional proximity. We draw on classic work examining spatial influences on interaction (Festinger et al., 1950) and pioneering efforts to capture the relational aspects of the built environment (Hillier & Hanson, 1984) to propose a new conceptualization of space, the functional zone, which captures individual spheres of operation in the workplace. From the functional zone concept we develop measures of zone overlap. Path and areal zone overlap*s* between individuals' capture key aspects of space that increase or decrease the likelihood of dyadic interaction. Zone overlap measures offer continuous, quantitative indices of proximity that are robust across spatial layouts and thus offer the possibility of application and generalization across multiple organizational settings.

Space is the platform on which face-to-face social interactions and the networks that result from them are enacted. Nevertheless, efforts to develop systematic sociospatial organizational research have languished since seminal, but largely descriptive analyses (Allen, 1977; Festinger et al., 1950). Festinger et al.'s (1950) study of interactions among residents in a new campus community for World War II veterans returning to university under the GI bill offer particularly valuable insights that have been too little developed. This study drew a distinction between two critical mechanisms through which space shapes interaction. The first is *physical distance* that captures the costs (in terms of time and effort) of interaction for a particular dyad. Here, the assumption is that greater distances between people make it more difficult to initiate and sustain face-to-face interactions.

The second mechanism, which was dubbed *functional distance*, focused more explicitly on the relational aspect of physical layouts by emphasizing, for instance, the ease and difficulty of movement among spaces. The implications of functional distance for social and organizational research have eluded careful consideration and measurement. This article operationalizes functional distance in terms of overlapping zones of activity and then compares those measures to metric and topological characterizations of physical distance.

We test the assertion that the arrangement of physical space exerts significant effects on collaboration and out starting point is the assumption that spatial effects are probabilistic and contingent rather than deterministic and universal (Sack, 1993). For example, someone whose workspace is located next door to a popular coffee bar, favorite break space, or even much visited restroom (Pfeffer, 1992) might forgo the increased opportunities for interaction offered by her location through the simple expedient of shutting a door or wearing large noise-canceling headphones. Proximity need not beget interaction. Likewise, the actual impact or importance of the costs imposed by physical distance may vary with the overall topology of the building where interactions occur. This suggests that the effects of physical distance will vary with building design, while functional distance will exert more consistent effects.

## Collaboration and Space

Festinger et al. (1950) noted that brief passive or unscripted contacts constitute the foundation for formation of new relationships. A determinant of these chance encounters is what they referred to as required paths, such as the one that an individual must take from home to the bus stop.[1] Potential dyad members are more likely to initiate contact to the extent that their require paths cross or overlap. Yet, the absolute physical distance, say between homes, is a poor predictor of potential path overlap. Path overlap is better predicted by the relative positions of the multiple spaces in which people routinely navigate. In other words, if the overall configuration of a physical space and the distribution of commonly visited locations within it require individuals to encounter one another more often during the course of their daily activities, they will be more likely to interact, share information, and develop collaborative relationships.

The most notable contemporary method for configurational, system-level analysis of buildings is *space syntax*. Space syntax techniques highlight the relational nature of space by converting physical layouts into networks that represent proximities among rooms and passageways in relational terms (Hillier, 1996; Hillier & Hanson, 1984). Like social networks, spatial networks can be used at multiple levels of analysis, for example, buildings, campuses, and cities. At the level of buildings, spatial networks closely mirror their social counterparts as they allow for egocentric, dyadic, and overall network levels of analysis in a specific spatial system (see online appendix Table A1 at http://eab.sagepub.com/supplemental). This article seeks to expand our understanding of the sociospatial dynamics of collaboration networks at the dyadic level. However, it is precisely at the dyadic level of analysis that space syntax's contributions to the development of a sociospatial science start diminishing.

Dyadic topological distance measures derived from space syntax are more likely to be highly correlated with metric distance at the micro level of buildings as opposed to the more macro level of cities and regions. Thus, we independently compare our zone overlap measure with metric and topological physical distance measures with respect to explaining unplanned face-to-face encounters. That is, we test the proposition that zone overlap better captures the effects of space on collaboration dynamics than do physical distance measures.

## Measuring Functional Proximity

Following Festinger et al. (1950), efforts to examine the impact of space in organizational processes were rather coarse-grained. For reasons beyond

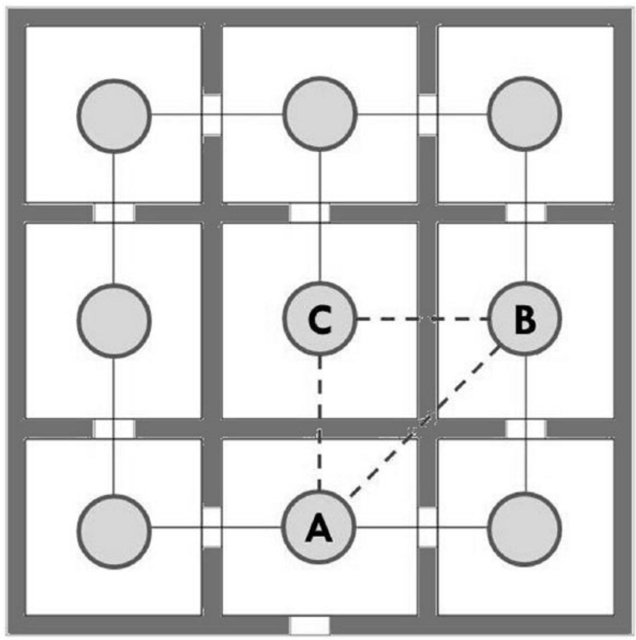



**Figure 1.** An illustration of straight line and walking distances between Individuals A, B, and C in a simple spatial layout.
*Note.* For simplicity, individuals are restricted to orthogonal movements. Walking movement paths are depicted using solid lines while the straight line paths are shown as hatched lines.

the scope of this study, practical conceptualization of functional distance or relational aspects of space has lagged the use of physical distance, even though functional distance is arguably better at capturing the latent interactions between actors in a specific spatial environment. The incorporation of space in these studies has been mostly limited to physical distance, especially the simpler straight line or "as the crow flies" distance even relative to the more nuanced measure of walking distance (Monge & Kirste, 1980). A simple example highlights differences in straight line versus walking distances in the analysis of physical spaces. In Figure 1, where each arc has a unit length, the actual or walking distance between individuals A and B is two units while the straight line distance is 1.414 units. The disparity between walking (five units) and straight line (one unit) distances is even greater for Individuals A and C.

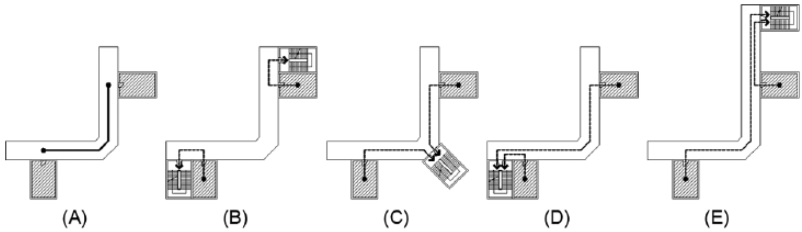



**Figure 2.** Further demonstration of the limitations of physical distance as a robust proxy for the finer-grained effects of spatial proximity.
*Note.* Holding the physical distance constant, changes in the relative locations of the individuals in the latent dyad lead to dramatic differences in the expected likelihood of encounters or interactions between them.

Walking distances between the primary spaces (e.g., offices) that individuals occupy offer more salient conceptions of distance than do straight line measures. Nevertheless, point-to-point walking distances still miss aspects of space that shape the likelihood of passive contacts in the course of normal daily activity. Consider Figure 2, which presents several scenarios where building features might alter the likelihood that the occupants of two offices will encounter one another. Panel A shows the walking distance from door to door for the two offices. In subsequent panels, the walking distance between offices remains constant, but the placement of stairwells alters the likelihood that occupants will encounter one another.[2] Panel B represents a configuration where stairwells at the ends of each corridor would lead office occupants to enter and depart by different paths, lowering the chance that they encounter one another. Given the elbow-shaped bend in the hallway it is possible that occupants might rarely even see one another. Panel C, in contrast, places a single stairwell equidistant from the two offices. Office occupants are likely to encounter each other at the stairwell, but soon part ways as they head to their separate spaces. Panel D suggests an even greater likelihood of passive contacts. Here occupants may meet at the stairwell and sometimes walk together briefly as their paths overlap. In addition, one person's path to the stairwell will lead them by the other's office door. In this configuration, then, the possibility of passive contact does not depend entirely on coordinated comings and goings via the stairwell. Finally, consider Panel E, which seems to us to offer the greatest possibility for passive contact. Panel E features a shared stairwell, a passed door, and a longer walking path overlap than in Panel D. In these alternative layouts, the walking distance between offices remains constant but their occupants' functional zones vary dramatically in ways that introduce greater or lesser possibilities for unplanned, face-to-face encounters in the course of daily interaction. Walking distance is a richer conception of physical distance than straight line distance, but is limited in its ability to capture how these more subtle effects of spatial layout affect functional distance.

Festinger et al. (1950) defined functional distance in terms of the "positional relationships and features of design" that make it more or less likely that two individuals will have unscripted encounters or interactions (pp. 34-36).[3] This implies that the distance refers to topological relationships between spatial elements. To highlight this relational meaning, we substitute *proximity* for *distance.* Not only is proximity understood to be the antonym of distance (Merriam-Webster, 2003) but it also encompasses the broader dimensions of adjacency and contiguity. Therefore, from this point on, we will refer to *functional proximity* whenever we mean to invoke the *functional distance* of Festinger et al. In accordance with previous usage of the term *functional proximity*, our concept shares the connotation of accessibility between actors engendering interactions between people (Moodysson & Jonsson, 2007; Pierce, Byrne, & Aguinis, 1996; G. N. Powell & Foley, 1998). However, our construct is analytically more precise and quantifiable, lending itself to application in empirical and comparative studies. We recognize that the romantic relationships in the Mainiero, Pierce et al., and Powell and Foley studies are driven by different rationales than the research collaborations in our study. However, these studies explicitly apply the functional proximity concept while research on the phenomena we are interested in—workplace and scientific collaborations—does not (Heerwagen, Kampschroer, Powell, & Loftness, 2004; Toker & Gray, 2008).

To say that two individuals are proximate is to infer a degree of closeness between them on the basis of contiguity in a specific dimension. Individuals in the workplace have more or less established spheres of operation. An individual might always take the same elevator or stairway to their office, use one restroom over another, or prefer to take breaks in a specific area. We define the individual's sphere of operation as the functional zone. It is an aggregate function of the spaces that are the sites of task performance or personal movement in the workplace.

For the biomedical research buildings analyzed in this study, we emphasize four types of spaces: individuals' workspaces (offices, labs), public or shared spaces (restrooms), circulation spaces (elevators, stairways), and connectors (hallways). Of course one could draw up a different typology of spaces for these focal buildings, and it is likely that in buildings supporting

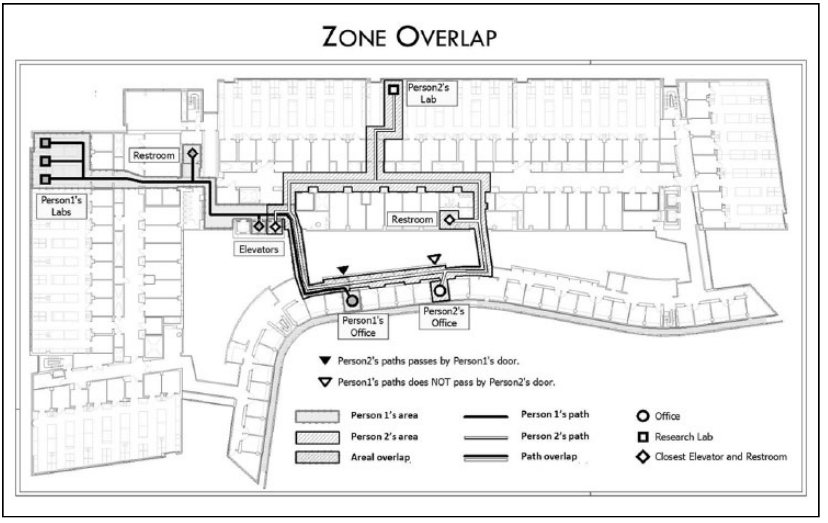



**Figure 3.** An illustration of the two measures of zone overlap (areal and path) using the BLD1 building.
*Note.* Also shown is the related concept of "door passing." The shared spaces that bound each person's functional zone in the example cited hereinbefore are the elevators and the restrooms.

other kinds of work, such as engineering production or software research, employees' functional zones will consist of sets of spaces that differ from the four types outlined above. In other words, our typology is not necessarily exhaustive or general enough to apply in its entirety across different building types or usages. Using the four types of spaces, we consider each individual's functional zone to be bound by their individual workspaces, most proximate restrooms, and the closest elevators, and threaded together by the connector spaces. For simplicity, we also assume the individuals take the shortest path available. Our definition of the individual's functional zone is therefore quantifiable and provides metrics that allow for the capture of spatial use patterns at the individual level.

Consider Figure 3, which represents the work paths of two hypothetical investigators who share a floor in the BLD1 building. The path outlined by a heavy black line traverses the shortest walking routes connecting Person 1's assigned office, lab space, the nearest elevator and the nearest relevant restroom. The path depicted by the double gray lines does the same for Person 2. While the offices assigned to these investigators (identified by circles) are very close together in physical and functional terms, their spheres of operation do not overlap to a great degree. Their overlap is represented by the path that includes both the black and double gray lines. These particular work paths overlap primarily because of a shared elevator, suggesting that these researchers are most likely to bump into one another when they enter or leave the building rather than during the course of their daily work or as they move back and forth between their offices and laboratory spaces. In this article, we focus our attention simply on the extent to which paths overlap or not. Future work attending to the different roles of public and shared spaces (such as restrooms, break rooms, conference rooms, or scientific instruments) might offer even stronger insights into collaborative dynamics.

An individual's functional zone defines his or her sphere of potential interactions with others in a spatial system. It does not measure the impact of actions to constrain others' access to space. Functional zone should not be confused with territory as defined in the territoriality literature (Sack, 1986, 1993; Sykes, 1977). Human territoriality represents a strategic intent to control or influence people and social interactions. For example, in the home parents might use a territorial strategy by limiting children's access to a particular room. Similarly, zoning prescribes what activities are allowed within certain areas of a city (Sack, 1986). The crux of territoriality as a strategy is the intent to control differential access to material and human resources (HR) including social interactions. We use "zone" rather than "territory" to avoid confounding the impact of control over space with the probabilistic effects of simply being present in space.

Functional zone is an individual-level measure that facilitates the development of dyadic and potentially group-level spatial measures that are not replications of physical distance. The dyadic measure we propose is the zone overlap between individuals, which could be *path* or *areal* overlaps. *Path* measures of overlap correspond to the paths in individuals' functional zones while *areal* measures are contingent on the total size of the spaces in their functional zones. Whether path or areal, measures of zone overlap allow for dyadic and higher-level analyses. This relational conception of proximity enables novel analyses of the dynamics and outcomes of interactions in sociospatial contexts.

## Hypotheses

Our central claim is that space matters for the dynamics and outcomes of workplace interactions because proximity increases the likelihood of unplanned face-to-face contact while decreasing the costs of planned meetings. Physical distance by itself is a poor proxy for the role of space in social

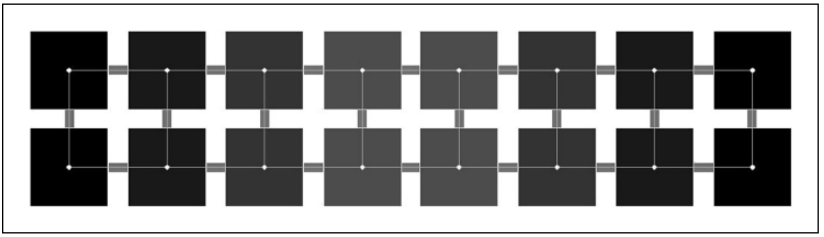


**Figure 4.** A more linear 16-space layout with the links between the spaces shown as light-gray lines.
*Note.* From the darkest to lightest, the spaces are coded according to their mean distance. The four values of mean distance are 4.267, 3.467, 2.933, and 2.667.

interactions and relations. Space also acts through adjacencies and contiguities, that is, functional proximity.

Physical distance affects the likelihood of interaction, but measures of physical distance are sensitive to topology or configuration effects. For example, consider Figures 4 and 5 which show two different 16-space layouts, the former linear and rectilinear and the latter square and compact, and where each space is a 4-unit square and the centroid-to-centroid distance is one unit in length. Calculation of the mean distance values shows that the spaces in Figure 4 ($M = 3.333$, $SD = 0.611$) are generally at greater distances from each other than are the spaces in Figure 5 ($M = 2.667$, $SD = 0.377$). This suggests that the physical distance between spaces is affected by the overall layout of the building or spatial system. Thus,

*Hypothesis 1a (H1a)*: The greater the walking distance between two people the lower the potential for knowledge transfer between them and the lower their dyadic research collaboration index; this effect is more significant for linear layouts relative to more compact layouts.

*Hypothesis 1b (H1b)*: The greater the turn distance between two people the lower the potential for knowledge transfer between them and the lower their dyadic research collaboration index; this effect is more significant for linear layouts relative to more compact layouts.

While functional proximity (zone overlap) is dependent to some degree on the physical distance between individuals, it emphasizes the relative locations and walking paths of individuals in a potential or actualized dyad. To paraphrase Festinger et al. (1950), interaction in dyads may depend more on the frequency or magnitude of the intersections of common paths than on the physical distance between primary spaces. Therefore,

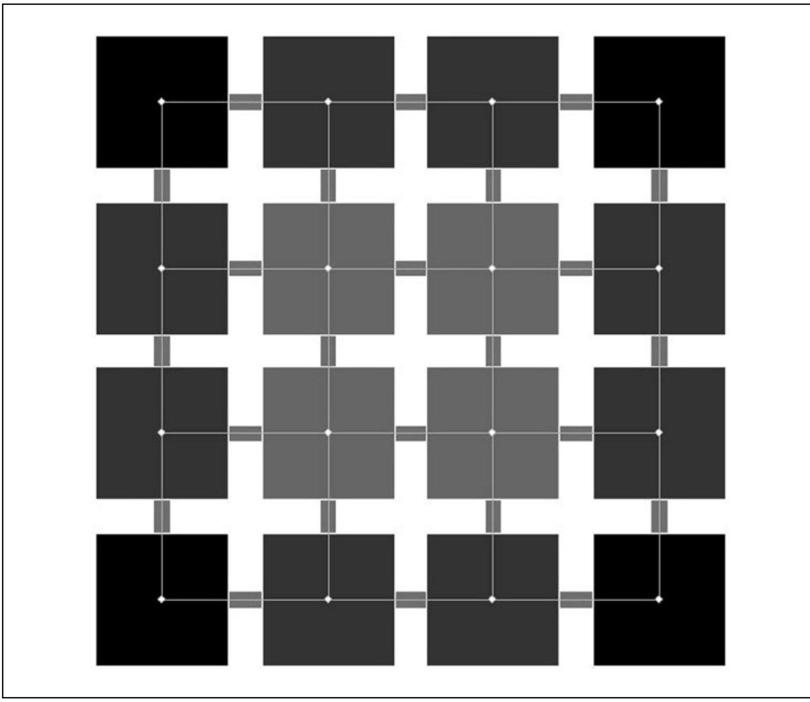


**Figure 5.** A more compact 16-space layout with the connections between the spaces shown as light-gray lines.
*Note.* The spaces are coded from the darkest to lightest to correspond with the three levels of mean distance (values are 3.200, 2.667, and 2.133).

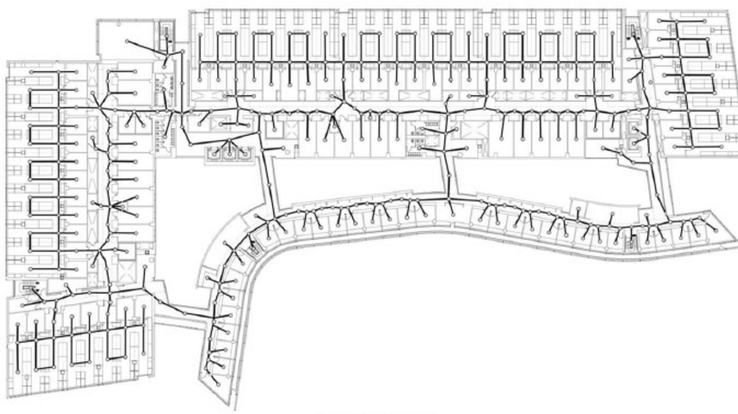
*Hypothesis 2 (H2)*: The greater the zone overlap between two individuals the higher the potential for knowledge transfer between them and the higher their dyadic research collaboration index; this effect is robust to building layouts.

## Method

### *Participants and Research Sites*

We test our hypotheses using data from a sample of researchers working at a large public university medical school in the United States during the period 2006-2010. We analyze data for researchers resident as of the end of 2006 in BLD1 (*n* = 166) and BLD2 (*n* = 94), both are biomedical research

BLD1



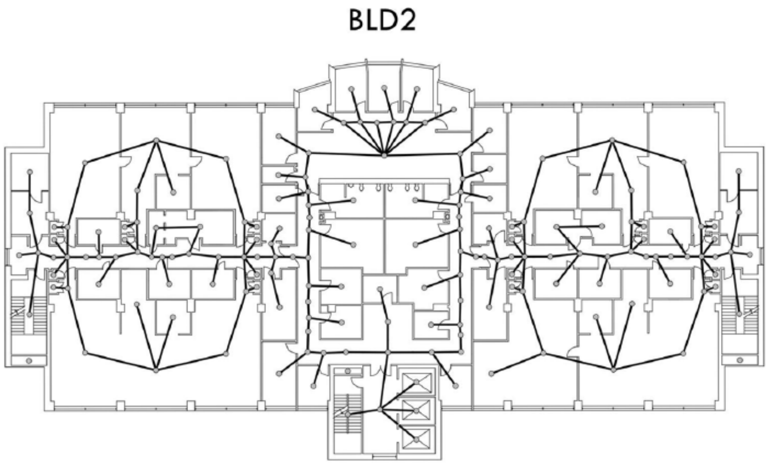
[Non-zero values only]

| Variable | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| Path overlap | 6220 | 326.97 | 219.33 | 3.8 | 1044.5 |
| Walking distance between labs | 44572 | 325.40 | 112.63 | 10.3 | 646.0 |

Path overlap & walking distance correlation = -0.563 ($p$ = 0.000)

**Figure 6.** Path overlap and physical walking distance at BLD1 are computed from one space to another.
*Note.* The image shows the spatial network graph of one of the BLD1 floors and identifies the connections between the spaces (black lines) where spaces are connected if there is a way to physically get from one to the next.

buildings which were opened or initially occupied in 2006 and 1997, respectively. Figures 6 and 7 show that the two buildings have different layouts; one is more linear while the other is more compact. BLD1 has an internal atrium that separates labs and offices. The single largest contiguous part of BLD1 (the northern wing) is 428′ long by 86′ wide, giving a length-to-width ratio close to 5. In contrast, BLD2 has a compact central service core instead of an internal atrium and is 223′ long by 117′ wide giving a ratio roughly equal to 2. BLD1 is therefore more linear in its topology and longer in terms of actual physical dimensions. There was less information available on interior arrangements in BLD2, and this likely affected the granularity of the resulting spatial network relative to the one in BLD1. The two populations were similar in terms of status and other demographic factors. Their main difference was that one of the populations moved at the




[Non-zero values only]

| Variable | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| Path overlap | 2833 | 294.72 | 162.90 | 11.2 | 793.3 |
| Walking distance between labs | 11435 | 224.50 | 68.66 | 9.7 | 354.0 |

Path overlap & walking distance correlation= -0.548 ($p$ = 0.000)

**Figure 7.** Path overlap and physical walking distance at BLD2 as computed using the spatial network graph.
*Note.* The connections between adjacent and accessible spaces are shown (black lines).

beginning of the study period while the other did not. Prior to its opening in 2006, BLD1's researchers were spread out over several buildings at the medical campus.

## *Spatial Mapping*

The first step in the mapping of individuals in space is to ascertain office and lab assignments. We do this by appeal to university administrative data for regular—that is, nontemporary—faculty for the time period 2006-2010. This data set includes HR information on job code, department, gender, education; applications to institutional review boards (IRBs); submitted animal research protocols; successful and unsuccessful grant applications to external sponsors; and space utilization and location information (including offices and labs). To create spatial networks, we use ArcGIS and AutoCAD files for the

Medical School campus in addition to finer-grained layouts for the BLD1 and the BLD2 buildings. We link the space location data to work addresses from the HR data set to build a comprehensive picture of researchers' spatial location.

We convert electronic BLD1 and BLD2 layouts into spatial networks, decomposing the floor plan into smaller spaces as follows. First, primary assigned spaces such as offices and labs, and public and circulation spaces such as break rooms, restrooms, elevators, and stairways are treated as discrete elements. In some cases, large primary spaces are broken up into two or more subspaces so that distances between centroids accurately reflect actual walking distances. Second, connector spaces such as hallways are decomposed to identify paths between scientists' primary spaces. To achieve this goal, the connector spaces immediately adjoining the doors to primary spaces (labs and offices) are demarcated as *thresholds*. Then, connector spaces between thresholds are subdivided into smaller spaces so that the distances between the centroids of the resulting spatial element reflect actual walking distances, conditional on the arcs or edges connecting these centroids not crossing walls or other physical barriers. For typical connector spaces such as hallways, the numbers of subspaces or spatial elements between thresholds has no impact on the calculation of path and areal measures of zone overlap. That is, decomposing the hallway into many smaller subspaces versus one long space does not change the area or path overlap. The totality of the spatial elements or subspaces constitutes a spatial network where the nodes are connected on the basis of accessibility and adjacency (see Figures 6 and 7).

## *Calculating Zone Overlap*

After generating this spatial network, we map the individuals in our study, define individuals' functional zones, and calculate the zone overlaps between individuals. There are three major steps in the calculation of the zone overlap of a dyad. First, the floor plan is decomposed into spatial nodes. The distance between two nodes is computed using their centroids as a reference, provided the nodes satisfy the dual requirements of adjacency or contiguity and direct physical accessibility from one node to the other.

Second, individuals' functional zones are defined. In this study, zones are bounded by the following nodes: their workspaces (offices and labs), nearest public spaces (restrooms), closest circulation spaces (elevators and stairways), and all connector spaces that link them. Each person's zone is stored as a set of nodes with unique numerical identifiers. Third, the zone overlap between any pair of individuals is derived from the intersection of the sets of

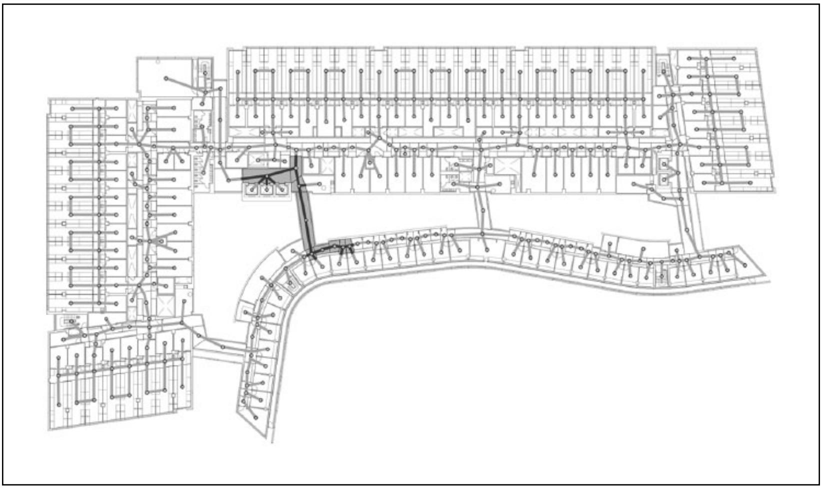


**Figure 8.** The zone overlap between the two individuals referenced in Figure 3 was computed by obtaining the intersection set of their functional zones (areal overlaps), and by summing the lengths of the paths in the intersection set (path overlap).
*Note.* The spaces in the intersection set are shaded in gray in the figure, while the path in shown in black.

nodes in their respective functional zones. For example, if A's functional zone is the set of nodes [1, 3, 5, 34, 36, 45, 68, 73, 98] and B's functional zone is the set [1, 3, 5 11, 16, 25, 34, 36], then the zone overlap between them is the set [1, 3, 5, 34, 36]. We can then obtain measures of areal overlap or the sum of the area of the nodes in the intersection set, and path overlap or the sum of the total length of edges (node-to-node links) in the intersection (Figure 8).

## *Dependent Variable*

*Collaboration index.* For any given year from 2006 to 2010, we create a composite index of research collaboration for each dyad in the study. This index measures the extent to which a dyad generated administrative evidence of early-stage collaboration. For each year, the index equals the sum of the following: applications to IRBs, animal research protocols, and grant applications to external sponsors. Because most potential dyads in the study never consummate a collaboration, the collaboration index is overdispersed and has a left-skewed distribution.

## Independent Variables

*Path overlap.* We use path overlap (measured in feet) in our regression estimates given hereafter. For these buildings, areal and path overlap are highly correlated ($r$ = .986). Because the interpretation of path overlap is somewhat more intuitive, we use it in our analysis. The correlations between measures of physical distance and path overlap are negative and low, suggesting that they capture complementary aspects of space (see online appendix Tables A2 and A3 at http://eab.sagepub.com/supplemental). In Table 1 the variables used in the regression models and analysis are listed.

*Physical distance.* We calculate three measures of physical distance: the first two are metric, walking distance ("walking") and straight line distance in feet. The third is topological, "turn." For each measure, the distance between individuals is calculated as the distance between the centroids of their primary workspaces (lab or office) using Dijkstra's algorithm (Dijkstra, 1959). For individuals who had labs and offices, we designate their primary space as the lab. Walking distance is the actual distance between these centroids, taking into account walls and other barriers as well as the presence of a physical connection between spaces. Straight line distance is the distance between centroids of spaces without consideration of barriers and physical accessibility or connections between these spaces. Turn distance is the minimum number of turns to get from one space to another. Walking and turn distances are highly correlated ($r$ = .911).

## Control Variables

*Collaborativeness.* We consider a collaboration to exist whenever two people appear together on an IRB application, animal research protocol, or grant proposal to external sponsors. To control for personal differences in the propensity to collaborate, we create a dyad-level count variable, "collaborativeness," equal to the sum of all collaborations that each member of the dyad had with all other researchers in their building (including the other half of the dyad).

*Same department.* Previous research has shown that affiliation, such as being in the same department, encourages and reflects homophily and, subsequently, higher levels of interaction (Agneessens & Wittek, 2012; Kossinets & Watts, 2006; Wineman et al., 2009). We created and included a binary variable equal to one if the two people in a dyad were in the same department at any point in that particular year, and zero otherwise.

**Table 1.** Key Variables and Concepts.

| Variable or concept | Definition |
|---|---|
| Collaboration index | Yearly combination of applications to institutional review boards, animal research protocols, and grant applications to external sponsors |
| Path overlap | The length of the overlap in feet of the paths in the functional zones of the two people in the dyad |
| Walking distance | The actual distance in feet between the offices and/or labs of the two people in the dyad |
| Turn distance | The number of turns between the offices and/or labs of the dyad members |
| Straight line distance | The straight line distance in feet between the offices and/or labs of the two people in the dyad |
| Collaborativeness | The sum of the number of collaborations both people in the dyad have with all other people in their respective building samples including the dyad itself |
| Same department | Coded as 1 if the two people in a dyad were in the same department that year |
| Jobcode | The variable captures whether both people in the dyad had academic or tenured/tenure-track positions (Coded 0), whether one person only or half of the dyad had an academic position (Coded 1), or whether both people in the dyad did not have academic positions (Coded 2) |
| Year | The variable has a value for each of the five years in the period 2006-2010 |
| Functional zone | An individual's sphere of operation that is an aggregate function of the spaces that are the sites of task performance or personal movement in the workplace. In this study, there are four main types of spaces: individuals' workspaces (offices, labs), public or shared spaces (restrooms), circulation spaces (elevators, stairways), and connectors (hallways). |
| Areal overlap | The total area or size of the overlapping spaces—for example, in square feet–of two individuals' functional zones. |

*Jobcode.* For academic settings, the primary distinction in faculty or research appointments is between those who are tenure-track or tenured and those who are in other types of positions. To account for the impact of differences in job types on collaborations in a potential dyad, we code each individual's position as "academic," (if tenured or tenure track) and "other" otherwise. At the dyadic level, we create a three-level categorical measure equal to zero if both dyad members had "academic" positions, one if exactly one dyad member had an academic position, and two if both dyad members had "other" positions.

*Year.* We use year dummy variables for each year during the period from 2006 to 2010.

## Statistical Analysis and Model Specification

The class of Poisson regression models is best suited for count dependent variables such as our index of research collaboration. However, one of the assumptions of Poisson regression is that the mean and variance are equal. Because the dependent variable is overdispersed (the variance is greater than the mean, online appendix Tables A2 and A3 at http://eab.sagepub.com/supplemental), a more appropriate model is the negative binomial regression. Even so, a major reason for the overdispersion is the large number of zero counts for the dependent variable. The zero counts reflect that many potential dyads never form. A model that corrects for overdispersion and accounts for the large number of zero counts is the zero-inflated negative binomial regression (Karazsia & van Dulmen, 2008; Long & Freese, 2006). The zero-inflated negative binomial regression has two equations: a logit model to predict whether or not research collaboration occurs and a negative binomial model to predict value of the research collaboration index, given the existence of a collaboration (Long & Freese, 2006).

The logit equation takes the following form:

$$\log\left(p/1-p\right)=\beta_0+\beta_1\mathrm{STR}+\beta_2\mathrm{DEP}+\hat{e}, \tag{1}$$

where $p$ = the probability of a research collaboration occurring, STR = straight line distance between dyad members, DEP = whether dyad members are in the same department, and $\hat{e}$ = error term.

Straight line distance captures the costs or frictions of interaction between the members of a dyad in their most basic form while being in the same department proxies homophily effects as well as knowledge proximity.

The log of the research collaboration index is predicted with a linear combination of the predictor variables (Long & Freese, 2006). The negative binomial equation to be estimated is

$$\log\left(\text{INDEX}\right) = \beta_0 + \beta_1\text{PATH} + \beta_2\text{DIST} + \beta_3\text{COLL} + \beta_4\text{DEP} + \beta_5\text{JOB} + B_6\text{YEAR} + \hat{e}, \quad (2)$$

where INDEX = the expected counts of the research collaboration index in a dyad; PATH = path overlap between dyad members; DIST = physical distance between dyad members, walking or turn; COLL = total collaborativeness of the dyad members; DEP = whether dyad members are in the same department; JOB = job code of the dyad members; YEAR = yearly fixed effects; and ê = error term.

We create two different zero-inflated negative binomial regression models corresponding to each of the buildings to account for differences in spatial layout. The first model estimates collaboration of researchers who had moved to BLD1 by the end of 2006. The second only examines researchers resident in BLD2 as of the end of 2006. In other words, even though we run models for the period 2006-2010, there are no new individuals in the two samples post-2006 (Table 2). However, there is attrition so the sample gets progressively smaller over time as people either leave the university or relocate to other buildings within the university. There were 4,371 BLD2 dyads in 2006, but only 2,485 by 2010. Similarly, there were 13,695 BLD1 dyads in 2006 and 8,128 dyads by 2010.

In summary, our regression models focus on inter-dyad variations while controlling for year-to-year variations (such as changes in NIH funding levels) that will affect all dyads in the sample. In these models a significant and positive effect of zone overlap, for instance, would suggest that collaborators with more shared pathways will have more collaborations than collaborators with less functional overlap. We compare the effectiveness of our path overlap measure as a predictor of the dyadic collaboration index relative to walking and turn measures of physical distance for two samples of biomedical researchers during the period from 2006 to 2010. The two samples work in different buildings, and the differences in the layout between these two spaces allow us to speak to the measure's robustness across building designs. This point is important because we believe that physical distance is susceptible to layout effects, and that any measure of functional proximity or dyadic spatial effects should be robust to layout effects to facilitate comparisons of different buildings.

## Results

Results of the regression models are shown in Table 3; Models 1 to 5 are for BLD1 and Models 6 to 10 are for BLD2. The models were constructed as

**Table 2.** Yearly Incidences of Dyads and Researchers.

| | BLD1 | | BLD2 | |
|---|---|---|---|---|
| Year | Dyads | Researchers | Dyads | Researchers |
| 2001 | 3,916 | 89 | 2,145 | 66 |
| 2002 | 4,950 | 100 | 2,926 | 77 |
| 2003 | 6,670 | 116 | 3,741 | 87 |
| 2004 | 10,011 | 142 | 3,916 | 89 |
| 2005 | 12,090 | 156 | 4,371 | 94 |
| **2006** | **13,695** | **166** | **4,371** | **94** |
| 2007 | 11,026 | 149 | 3,486 | 84 |
| 2008 | 9,180 | 136 | 3,160 | 80 |
| 2009 | 8,646 | 132 | 2,701 | 74 |
| 2010 | 8,128 | 128 | 2,485 | 71 |

Note: The bold values correspond to the year when BLD1 sample moved into the building for the first time.

follows. First, a set of models was run with each of the three independent variables plus the control variables, that is, path overlap and controls (Models 1 and 6), walking distance and controls (Models 2 and 7), and turn distance and controls (Models 3 and 8). Second, for each building, two sets of models were run for combinations of path overlap, either of the two physical distance variables, and controls. These were path overlap, walking distance, and controls (Models 4 and 9), and path overlap, turn distance, and controls (Models 5 and 10). Recall that walking and turn distances were nearly perfectly correlated and therefore were not included in the same models. Our analysis and interpretation of the results will concentrate on the full models (4 and 5 for BLD1, and 9 and 10 for BLD2).

Across the two buildings, path overlap is significantly and positively correlated with the collaboration index even controlling for the physical distance between dyad members, thus confirming H2. In BLD1, a 100-foot increase in path overlap in a dyad is associated with a 14.6% increase in the expected counts of the research collaboration index when controlling for walking distance, and a 15.9% increase if controlling for turn distance (Models 4 and 5). Path overlap has an even larger effect in BLD2: a 100-foot increase in path overlap correlates with 19.4% and 29.2% increases in expected counts of the research collaboration index when controlling for walking and turn distances, respectively (Models 9 and 10). In other words, across the two buildings, a 100-foot increase in path overlap relates to significantly higher outputs of IRB applications, animal research protocols, and grant applications to external sponsors.[4]

**Table 3.** Effects of Path Overlap, and Walking and Turn Distances on the Dyadic Collaboration Index at BLD1 and BLD2.

| | BLD1 | | | | | BLD2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DV = collaboration index variables | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| Path overlap | 0.0021*** | | | 0.0014*** | 0.0015*** | 0.0025*** | | | 0.0018*** | 0.0026*** |
| | (0.0003) | | | (0.0004) | (0.0004) | (0.0004) | | | (0.0005) | (0.0004) |
| Walking distance | | −0.0065*** | | −0.0044** | | | −0.0062*** | | −0.0026 | |
| | | (0.0013) | | (0.0015) | | | (0.0018) | | (0.0018) | |
| Turn distance | | | −0.0593*** | | −0.0368*** | | | −0.0402*** | | 0.0013 |
| | | | (0.0096) | | (0.0110) | | | (0.0095) | | (0.0128) |
| Collaborativeness | 0.0189*** | 0.0202*** | 0.0200*** | 0.0196*** | 0.0194*** | 0.0053*** | 0.0054*** | 0.0054*** | 0.0054*** | 0.0053*** |
| | (0.00125) | (0.0012) | (0.0013) | (0.0012) | (0.0012) | (0.0008) | (0.0008) | (0.0007) | (0.0008) | (0.0008) |
| Same department | 1.0630*** | 0.5663† | 0.6671* | 0.6125† | 0.7052* | 0.4959 | 0.4040 | 0.6372† | 0.3920 | 0.5013 |
| | (0.3095) | (0.3137) | (0.3102) | (0.3358) | (0.3301) | (0.3826) | (0.4266) | (0.3664) | (0.4199) | (0.3970) |
| Jobcode_academic-academic (reference) | | | | | | | | | | |
| Jobcode_academic-other | −0.0904 | −0.1738 | −0.1426 | −0.1328 | −0.1088 | −0.2745 | −0.3765† | −0.3039 | −0.3193 | −0.2730 |
| | (0.1470) | (0.1466) | (0.1483) | (0.1424) | (0.1437) | (0.2046) | (0.2174) | (0.2048) | (0.2123) | (0.2064) |
| Jobcode_other-other | −0.5242* | −0.6032** | −0.5510** | −0.5712** | −0.5339** | −0.6399* | −0.8194** | −0.7278* | −0.7131* | −0.6373* |
| | (0.2048) | (0.1977) | (0.1999) | (0.1988) | (0.2004) | (0.2834) | (0.2912) | (0.2842) | (0.2910) | (0.2890) |
| Year_2006 (reference) | | | | | | | | | | |
| Year_2007 | 0.1917† | 0.2104* | 0.1892† | 0.2088* | 0.1934† | 0.0775 | 0.0425 | −0.0139 | 0.0791 | 0.0778 |
| | (0.1012) | (0.0981) | (0.0978) | (0.1013) | (0.1011) | (0.1231) | (0.1304) | (0.1216) | (0.1269) | (0.1224) |
| Year_2008 | −0.1819 | −0.1887 | −0.1934 | −0.1893 | −0.1933 | 0.1386 | 0.1113 | 0.0896 | 0.1253 | 0.1404 |
| | (0.1388) | (0.1267) | (0.1274) | (0.1315) | (0.1324) | (0.1462) | (0.1517) | (0.1476) | (0.1486) | (0.1449) |
| Year_2009 | 0.0066 | −0.0109 | −0.0155 | −0.0015 | −0.0046 | −0.1273 | −0.1963 | −0.2193 | −0.1524 | −0.1250 |
| | (0.1285) | (0.1205) | (0.1200) | (0.1251) | (0.1253) | (0.1682) | (0.1681) | (0.1661) | (0.1694) | (0.1658) |
| Year_2010 | −0.4865** | −0.4676** | −0.4693** | −0.4767** | −0.4812** | 0.0666 | −0.0080 | 0.0122 | 0.0252 | 0.0698 |
| | (0.1615) | (0.1491) | (0.1494) | (0.1571) | (0.1582) | (0.1561) | (0.1662) | (0.1592) | (0.1648) | (0.1576) |
| Constant | −3.8368*** | −1.9821*** | −2.0943*** | −2.8373*** | −3.0075*** | −2.4298*** | −0.9378† | −1.3132** | −1.8562** | −2.4579*** |
| | (0.2873) | (0.2999) | (0.3103) | (0.4043) | (0.4069) | (0.4024) | (0.4942) | (0.4818) | (0.6056) | (0.5442) |
| Observations | 44,962 | 44,962 | 44,962 | 44,962 | 44,962 | 11,692 | 11,692 | 11,692 | 11,692 | 11,692 |

*Note.* Robust standard errors in parentheses.
†$p < .1$. *$p < .05$. **$p < .01$. ***$p < .001$.
DV = Dependent Variable

Physical distance is negatively and significantly related to the collaboration index in BLD1 but not in BLD2, confirming H1a and H1b. In the more linear BLD1, controlling for path overlap, increasing the walking distance by 100 feet or the turn distance by 10 turns relates to 35.4% and 30.8% decreases, respectively, in expected counts of the dyadic research collaboration index. In contrast, in the more compact BLD2, the correlation with physical distance is not significant when controlling for path overlap. These findings highlight the limited utility of physical distance as a proxy for the effects of spatial proximity, especially when the focal building has a more compact footprint.

The control variables performed as expected, but there are some differences between the two buildings in the "year" and "same department" variables. In BLD1 and BLD2, the overall "collaborativeness" of the members of a potential dyad is significantly and positively related to their dyadic research collaboration index. An increase of 10 units in dyadic "collaborativeness" relates to 21%-22% and 5%-6% increases in counts of the collaboration index at BLD1 and BLD2, respectively.

Being in the same department had a positive and significant correlation in BLD1 but not in BLD2. At BLD1, departmental affiliation is associated with an 84%-102% increase in collaboration index counts. The "jobcode" variable shows that, despite the general trend of a steady decline in tenured and tenure-track faculty in academic institutions (Ehrenberg & Zhang, 2005; Snyder & Dillow, 2012), researchers fitting this description are still more likely to form or initiate new collaboration dyads relative to those in non-tenure-track positions. In BLD1 membership in all "other" dyads is correlated with 41%-44% decreases in expected counts of the collaboration index. The corresponding numbers for BLD2, 47%-51% decreases in expected counts, are even larger. Finally, the year dummies are not significantly related to the collaboration index, with the exception of the year 2010 in BLD1 where there was a roughly 38% decrease in the expected collaboration index counts relative to the reference year 2006.

## Discussion and Future Directions

Our analyses offer strong support for the H1a, H1b, and H2. Regarding H2, path overlap is significantly related to the research collaboration index and this correlation is similar across buildings. These effects are substantively and statistically significant, lending credence to the utility of this dyadic spatial measure of functional proximity. Within building micro-level differences in proximity are clearly correlated with the extent to which pairs of scientists collaborate. While more research is needed to test the zone overlap concept in other settings, our analysis suggests that a dyadic spatial measure such as ours would contribute significantly to research on relational organizational processes.

In contrast, walking and turn distances were significantly correlated with the dyadic collaboration index only in the more linear BLD1. We suspect that these differences result from the characteristics of the building layouts. We conjecture that distances matter more in BLD1 because the occupants were relatively new to the space and it is more linear than BLD2. Despite the ease of interpretation and calculation of these measures of physical distance, their ability to capture the impact of spatial relations on social relations may be limited. One implication for future research is that there may be gains to using a tile-based computational approach to analyze more detailed layouts.[5] The larger point, however, is that more research in various types of spaces is needed to test our finding that path overlap is more strongly associated with collaboration among scientists than are walking and turn distances.

Our analysis is restricted to two buildings, making broad generalizations problematic. It is possible that the observed effects of path overlap, and walking and turn distances are due to unobserved differences in the two buildings. For example, while we attribute the differential impacts of walking and turn distances in BLD1 and BLD2 to the divergent effects of linear versus compact buildings, this could be the result of BLD1's more fine-grained interior detail than BLD2. While we do not think that this would demonstrably reduce the salience of zone overlap, we recognize that there are discernible differences when spatial networks are constructed with higher versus lower levels of interior details.

We make the simplifying assumption that individuals take the shortest path available within their functional zones. While this facilitates the computation of zone overlap, we are cognizant of the limitations of this assumption. For example, the better quality coffee available in a break room farther away might make an individual take a longer path in lieu of the shorter path to the nearby break room. More importantly, an individual might forego a shorter path to avoid or see a particular researcher. Identification of the actual paths individuals take would also enable more advanced conceptualizations of functional zones. We employ a fairly simple conceptualization of functional zone; more work is needed to operationalize the different types of zones that are salient for specific workplaces.

Finally, we acknowledge that there is endogeneity in the assignment of primary spaces. Prior relationships can influence office location and the likelihood that current encounters are related to future collaborations. The retrospective nature of our study precluded random assignment to labs and offices, raising the real possibility that there are unobserved variables that influence whether individuals collaborate and the subsequent success of those collaborations.

Future analysis of research collaboration in academic settings could address the role of departmental affiliation in fostering and maintaining collaborative efforts. Investigators are more likely to collaborate with those in their department. Whether this simply reflects common research interests or constraints on the cross-departmental collaboration is impossible to disentangle with the data analyzed here. Moreover, our results suggest skewed relations between tenured or tenure-track, and non-tenure-track researchers. Dyads composed of tenured and tenure-track researchers are more likely to have nonzero research collaboration counts than are dyads comprised of non-tenure-track peers, who would include those with research track, clinical, adjunct, and visiting positions.

Shifting the focus of spatial analysis away from measures of distance and toward conceptions of functional zones and their overlap also suggests interesting future directions. Similarly, attention to zones and overlaps at multiple levels of analysis could shift the emphasis of design and space allocation processes in support of research or other organizational outcomes in subtle but important ways. The most important area for future research is the examination of how people define, occupy, and traverse functional zones. We conceptualize such zones in fairly simple terms; it may be the case that other public spaces should be included in the definition. By the same token, all types of zone overlaps may not be created equal. For instance, paths that overlap as people move to and from tasks (e.g., between labs and offices) may have different effects than overlaps that happen on the way to and from the restrooms or as investigators enter and leave the building. Future research could shed more light on the actual paths taken by individuals in the workplace and focus on factors that most affect path choice. A promising line of inquiry is the analysis of rich location data from wireless tracking technologies which capture the paths taken by individuals, permitting analysis of temporal and other factors in the determination of path choice.

Potentially, future research could build on earlier work that showed associations between rates of interactions and types of rooms or spaces that people occupy or move through (Peponis et al., 2007). It would be useful for future work to elucidate how occupation of or movement through different types of spaces in the workplace engenders differential levels of awareness of others and of work activities and in turn affects the likelihood of dyadic collaborations and the probability of success for these collaborations.

It is also imperative that researchers think creatively about how to further unpack the nested effects of spatial layouts and organizational processes and structures. For example, future research would benefit from a quasi-experimental approach randomly assigning individuals to primary spaces, assuming that both were feasible and in line with broader organizational goals.

Parsing the inherent endogeneity between individuals' spatial locations and organizational goals and outcomes requires more research on the link between physical space and phenomena such as collaboration.

Finally, this approach suggests new ways to consider the global impacts of small design changes. If bathrooms, for instance, are important markers of functional zones, then buildings that separate male and female facilities at opposite ends of long hallways will systematically increase zone overlaps between same sex pairs while diminishing them for mixed sex pairs. In that case, our findings strongly suggest that such a design will increase rates of same sex collaborations while decreasing the incidence of mixed sex collaborations. This possibility hints at some of the subtle mechanisms by which decisions about the design and allocation of space serve to create, sustain, or ameliorate significant workplace differentials. Conceptualizing and measuring proximity effects in terms of flexible, overlapping zones of activity that take into account the contingent ways individuals occupy and make their way through buildings offers new possibilities for research that advances theory while having immediate relevance for policy and design.

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The first two authors contributed equally to the preparation of this article.

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## Notes

1. In this example, the path is only "required" if the individuals in the dyad take the bus and not alternate forms of transportation such as cars or bicycles. Whether one follows the presumed path depends on social, economic, and cultural factors. But given all of those, the overlap of paths affects the probability of interaction.
2. For the purposes of this discussion, we assume that people typically enter and leave their offices by way of the nearest stairwell.
3. In any spatial environment, individuals take certain paths to and from their primary spaces, however, these are defined. The emphasis here is on the likelihood of encounters between individuals given the paths they are likely to take in their specific environments. Individual, organizational, and sociocultural factors play a vital role in determining whether potential ties are consummated into actual relationships. That is an important question, but is neither the focus of this study nor a precondition for the salience of the zone overlap concept. It will influence the relationship between zone overlap and collaboration in different social contexts, and this is an important topic for future study.
4. In results not reported here, the logit or zero-inflation models confirm that affiliation (being in the same department) and interactions costs or frictions (straight line distance) had significant effects on the likelihood of the existence of a dyadic collaboration.
5. This in turn would require efficient logics for decomposing large spaces into smaller tiles at reasonable computing costs.

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