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Analysis

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Keywords

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

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Abstract

Spatial layouts can have significant influences on 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 (1950) classic description of 'functional distance' as it pertains to social interactions. We operationalize our functional zone concept 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 in both buildings. In contrast more traditional distance measures only influence collaboration in the more linear building. The *functional zone* concept improves our ability to understand relationships and their attendant organizational outcomes.

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 spaces influences workplace interactions and outcomes. People work and interact in the built environment (Grannis, 2011; Hua, Loftness, Heerwagen, & Powell, 2011), thus research that disregards space or that analytically divorces social phenomena from their locations and contexts 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, and the most relevant level of analysis for understanding those based on information sharing, collaboration, or teamwork, may be the dyad (Mizruchi & Marquis, 2006).

Despite the importance of dyads, little work has explicitly emphasized spatial effects on relationship formation among pairs of co-workers. We believe that a full understanding of the formation and effects of social networks requires attention to space. Spatial effects have not been robustly incorporated in such social science models because we currently lack spatial measures that are nuanced enough to operationalize key concepts. This

paper takes initial steps toward more fully integrating spatial and social explanations for the formation of collaborative relationships at work by developing a new measure of physical proximity that more effectively captures classic concepts relating the effects of space on the likelihood of interaction (Festinger, Schachter, & Back, 1950). We then 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 physical distance variables including the metric measures of Euclidean 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 fairly blunt proxy for the subtle ways in which proximity enables or hinders interaction (Cowgill, Wolfers, & Zitzewitz, 2009; Liu, 2010; Sailer & McCulloh, 2012). Physical distance is not discriminating enough to capture the powerful but subtle relational and topological effects of space that we refer to as functional proximity. Unfortunately, physical distance is the only tool that has thus far been available to most researchers interested in relational organizational phenomena such as collaboration. 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 overlaps* 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 socio-spatial organizational research have languished since seminal, but largely descriptive analyses by Festinger and colleagues (1950) and Allen (1977). Festinger, Schachter and Back's 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 little developed. This study drew a distinction between two critical mechanisms through which space shapes interaction. The first is *physical distance*

which captures the costs (in 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 paper operationalizes functional distances 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. However, we begin with the assumption that spatial effects are probabilistic and contingent rather than deterministic and universal (Robert D. Sack, 1993). For example, someone whose workspace is located next door to a popular coffee bar, favorite break space or even much visited rest room (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 cancelling headphones. Proximity need not beget interaction. Likewise the actual costs imposed by physical distance may vary with the overall topology of the building where interactions happen. In what follows, we pursue the latter insight by proposing that the effects of physical distance on interactions will vary across different building designs while more socio-spatial and nuanced functional distance measures will exert more stable effects.

Collaboration and Space

Festinger et al noted that brief passive or unscripted contacts constitute the foundation for new tie formation. A determinant of these chance encounters is what they referred to as specific required paths, such as the one that an individual must take from their apartment to the bus stop. Potential dyad members are more likely to initiate contact to the extent that their required paths cross or overlap. Yet the absolute spatial or physical distance between individuals' spaces is a poor predictor of their potential path overlaps. Path overlap is better predicted by the relative positions of the multiple spaces which people routinely use and navigate in. In other words, if the overall configuration of a physical space and the distribution of commonly visited locations within it requires individuals to encounter one another more often in the course of their daily activities, they will be more likely to interact, share information, and develop social or 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 & Hanson, 1984; Wineman, Kabo, & Davis, 2009). Like social networks, spatial networks can be used at multiple levels of analysis, for example, buildings, campuses, and cities. At the level of buildings, the analytic techniques and measures associated with spatial networks closely mirror their social counterparts as they allow for analysis of spatial relationships that correspond to egocentric, dyadic, and structural levels of social network analysis. This paper seeks to expand our understanding of the socio-spatial dynamics of collaboration networks at the dyadic level. But it is precisely at the dyadic level of analysis that space syntax's contributions to the development of a socio-spatial science start to diminish.

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, especially when the analysis is within- rather than between-floors. In this paper we compare our functional measure of *zone overlap* concept to metric and topological distance measures with respect to capturing the potential for dyadic and unplanned face-to-face encounters. We propose that *zone overlap* better captures the real effects of space on collaboration dynamics than do physical distance measures that index costs of planned interactions (Owen-Smith, Kabo, Levenstein, Price, & Davis, 2012).

Measuring Functional Proximity

Following Festinger et al, efforts to acknowledge the impact of space in intra- and inter-organizational processes were rather coarse-grained. In fact, the incorporation of space in these studies was mostly limited to physical distance, with some researchers even using Euclidean or “as the crow flies” distance (Monge & Kirste, 1980). A simple schematic example illustrates the challenges of applying Euclidean distances to the analysis of real 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 Euclidean distance is 1.414 units. The disparity between walking (five units) and Euclidean (one unit) distances is even greater for individuals A and C. For reasons beyond the scope of this study,

practical conceptualization of functional distance or relational aspects of space lagged the use of physical distance. Functional distance better captures the latent interactions between actors in a specific spatial environment.

Festinger et al defined functional distance in terms of the “positional relationships and features of design” (p.35) that make it more or less likely that two individuals will have unscripted encounters or interactions (Festinger et al., 1950, pp. 34-36). This implies that the “distance” in this term refers to the topological relationships between spatial elements, and given this relational turn in the term we propose to 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 as our interest is in the passing or unplanned contacts that are the wellsprings of relationships. In accord with previous usage of the term “functional proximity,” our concept shares the connotation of accessibility between actors engendering interactions between people (Mainiero, 1989; Moodysson & Jonsson, 2007; Pierce, Byrne, & Aguinis, 1996; G. N. Powell & Foley, 1998). However, our construct is conceptually more focused and analytically more precise, lending itself to application both in empirical and comparative studies.

Walking distances between the primary spaces (e.g. offices) that individuals occupy offer more accurate and phenomenologically satisfying conceptions of distance than do Euclidean 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 simply notes the walking distance from door to door for the two offices. In the remaining panels the walking distance between offices remains constant, but the placement of stairwells dramatically alters the likelihood their occupants will encounter one another.¹

Panel B represents a configuration where stairwells at end of each corridor would lead office occupants to enter and depart by different paths, lowering the chances they might encounter one another. Given the elbow shaped bend in the hallway it is possible that in this configuration occupants may rarely even see one another. Panel C, in

¹ For the purposes of this discussion, we assume that people typically enter and leave their offices by way of the nearest stairwell.

contrast, places a single stairwell equidistant from the two offices. In this situation, 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 might sometimes walk together briefly as their paths overlap. In addition, one person's path to the stairwell will lead them to pass 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 between the occupants of these offices. Panel E features a shared stairwell, a passed door, and a longer walking path overlap than in Panel D. In the terms we use above, 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.

To say that two individuals are proximate is to infer a degree of nearness or 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 (assuming the existence of more than one), and even prefer to take breaks in a specific area of the building. We define the individual's sphere of operation as the *functional zone* and note that 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 propose four main 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 buildings, and it is also inconceivable that in buildings supporting other kinds of work, such as engineering production or software research, employees' functional zones will not consist of alternative sets of spaces. 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. 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; depending on the outcome in question, the functional zone could be expressed in

terms of its total area or the length of paths in it. Furthermore, with the functional zone concept it is not necessary to pinpoint an individual's primary space or location as is the case with distance-based proximity measures.

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 line does the same for Person 2. While the offices assigned to these investigators (identified by circles) are very close together in both physical and functional terms, their spheres of operation do not overlap to a great degree. Such overlaps are 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 are entering or leaving 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 paper, 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 and the possibilities for intervention.

An individual's functional zone defines his or her sphere of potential interactions with others in a spatial system. As a concept, the emphasis is on the potential effects of space on agents, and not on the reverse issue of how agents control or try to limit access to space either due to an innate biological imperative or as a learned phenomenon. In other words, the functional zone should not be confused with one's territory as is defined in the territoriality literature (Robert David Sack, 1986; Robert D. Sack, 1993; Sykes, 1977). Human territoriality is borne out of a strategic intent to control or influence people and social phenomena such as relationships and social interactions. In this sense, territoriality is everywhere. For example, in the home a territorial strategy would be parents limiting access to a particular room rather than enumerating the objects in that room that children may or may not access. Similarly, zoning prescribes what activities are allowed within certain areas of a city (Robert David Sack, 1986). The crux of territoriality as a strategy is the intent to control differential access to material and human resources including social interactions. While it would be wholly appropriate to use the term "territory" in place of "zone" where the latter merely means the area or sector of the workplace that an individual operates in, we do not

use this term in order to avoid confounding the impact of control over space with the probabilistic effects of simply being present in space on dyadic processes such as relationship formation.

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 critical paths in individuals' functional zones while *areal* measures rely on the total size of the spaces in an individual's functional zone. Whether path or areal, measures of zone overlap allow for dyadic and higher level analyses of critical issues that are often examined using aggregate individual level data. As such this fully relational conception of proximity in space enables new possibilities for analyzing the dynamics and outcomes of interactions in their socio-spatial 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. Moreover distance is by itself a poor proxy for the significance of space in social interactions and relations. Space also acts through adjacencies and contiguities, or rather, functional proximity.

Linear measures of physical distance are sensitive to topology or configuration effects. For example, while consideration of distance is important in many building types, it is one of the fundamental elements of the design brief for airport terminal buildings. An important criterion in the design of airport terminals is the minimization of walking distances (De Neufville, 1995; de Neufville, de Barros, & Belin, 2002). Beyond the rarefied air of aviation buildings, other examples abound of contexts where the consideration of walking distances is a major design factor. Judicial facilities come to mind, where there is an interest in minimizing the distances walked by prisoners and judiciary staff. This is typically achieved by the use of compact floor plans (AIA, 2011).

For further illustration, 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. Calculation of the

mean depth values shows that the spaces in Figure 4 (mean = 3.333, SD = 0.611) are generally at greater distances from each other than are the spaces in Figure 5 (mean = 2.667, SD = 0.377). Even with the shortcomings of a two-unit sample comparison, it is clearly suggestive that the average linear distance between spaces is susceptible to the overall layout of the building or spatial system. Thus,

H1: the greater the physical distance between two people the lower the potential for knowledge transfer between them and the lower their dyadic research collaboration index; this effect should be 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 is more relational and functional in that it emphasizes the relative locations and walking paths of individuals in a potential or actualized dyad. To paraphrase Festinger et al, 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. In other words, we expect functional proximity to be both predictive of dyadic interactions and to have greater utility to the extent that it is more robust to layout effects. Therefore,

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 should be robust to building layouts and therefore significant both for linear and compact layouts.

Methods

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 US in the period from 2006-2010. We analyze data for researchers resident as of the end of 2006 in the BLD2 (n = 94) and BLD1 (n = 166) biomedical research buildings which were opened or initially occupied in 1997 and 2006 respectively. Figures 6 and 7 show that the two buildings have different layouts; one is more linear while the other is more compact. The BLD1 building has an internal atrium that separates the labs and

offices and it is also more linear in relation to the BLD2 building. The single largest contiguous part of the BLD1 building (the northern wing) is 428' long by 86' wide, giving a length-to-width ratio close to 5. In contrast, the BLD2 building, which has a compact central service core instead of an internal atrium, is 223' long by 117' wide giving a ratio roughly equal to 2. The BLD1 building is therefore more linear in its topology, and longer in terms of actual physical dimensions. The two populations were similar in terms of their status and other demographic factors, the main difference between them being that one of the populations had moved at the beginning of the study period while the other had not moved. Prior to the move 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 was to ascertain which offices and labs were assigned to them. We obtained data on the Medical School's regular – that is, non-temporary – faculty from the university's data warehouse with supplements as needed from the Medical School for the time period 2006-2010. With the help of the Medical School staff, we retrieved data on: human resource and financial information including 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. We linked the space location data to work addresses in the human resource dataset to build a comprehensive picture of where researchers were spatially located. Lastly, we worked with the Medical School, the university, and the hospital's facilities administration office to procure ArcGIS and AutoCAD files for the Medical School campus in addition to finer-grained layouts for the BLD1 and the BLD2 buildings.

Next we converted electronic BLD1 and BLD2 layouts into spatial networks. We used a hybrid approach where individual, public, and circulation spaces – offices, labs, break rooms, restrooms, elevators, stairways – were treated as discrete elements while the connectors were decomposed into convex spaces, or the 'fattest' spaces where any point within the spatial boundary is visible from any other point (Hillier & Hanson, 1984; Peponis, Wineman, Rashid, Kim, & Bafna, 1997). These elements or spaces constituted a spatial network where the nodes were connected on the basis of accessibility and adjacency (see Figures 6 and 7).

Calculating Zone Overlap

After generating the spatial network we used the space location dataset to map the individuals in our sample, define individuals' functional zones, and calculate the zone overlaps between individuals. There are three major steps in the calculation of the zone overlap between the individuals in a dyad. First, as outlined above, the floorplan 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 the zones were bounded by the following nodes: their workspaces (offices and labs), nearest public spaces (restrooms), closest circulation spaces (elevators and stairways), and all of the connector spaces that link them. Each person's zone is stored in a database 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 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).

Using the centroids of their assigned spaces as reference points we also applied Dijkstra's algorithm to calculate the minimum physical distances between individuals (Dijkstra, 1959). The zone overlap and physical distance measures (walking and turn) were treated as independent variables in our models. In Table 1 we show the variables that we used in our regression models and analysis.

Dependent Variable

Collaboration Index. For any given year from 2006-2010, we created a composite index of research collaboration, the extent to which a given dyad produced collaborative outputs relating to the early stages of a project, by merging the following outcomes for each dyad: applications to institutional review boards, animal research protocols, and grant applications to external sponsors. The resultant count dependent variable, "collaboration index," is overdispersed and has a left-skewed distribution.

Independent Variables

Path Overlap. Having computed the zone overlaps as previously discussed, we applied “path overlap” (measured in feet) in our regression models as it lent itself to a comparison with physical distance in addition to being more intuitive to interpret. Moreover, both measures of zone overlap were highly correlated ($r = .986$) and this gave us the confidence to use any of them in isolation as an expression of the zone overlap concept. From Tables 2a and 2b we also see that the correlations between measures of physical distance and path overlap are negative and low, suggesting that they capture complementary aspects of space.

Physical Distance. Two measures were generated to capture physical distance in feet: the first was metric and captured walking distance (“walking”), and the second topological or relational distance (“turn”). For each measure, the distance between individuals was calculated as the distance between the centroids of their primary space with the order of precedence being labs then offices. For individuals who had both labs and offices or labs only (typically junior researchers or staff), their designated primary space was the lab. However, for those whom we were able to map only onto an office space, then this was presumed to be their primary space. Walking distance was computed as the actual distance between these centroids therefore taking into account walls and other barriers as well as whether there was a physical connection between spaces. Topological distance was calculated as the minimum number of turns it took to get from one space to another. Walking and topological distances are highly correlated ($r = .911$). A third measure of physical metric distance, Euclidean distance, was generated for the logit equation predicting the incidence of dyadic collaborations (discussed in the next section). Euclidean distance was computed as the distance between centroids of spaces without consideration of barriers and physical accessibility or connections between these spaces.

Control Variables

Collaborativeness. We considered a collaboration to exist whenever two people appeared together on IRB applications, animal research protocols, and grant proposals to external sponsors. In order to control for the extant overall levels of and propensities for collaboration for the two people in the dyad, we coded all collaborations that the dyad had with all other people in their respective sample including the dyad itself. The resultant count variable was named “collaborativeness.”

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 coded as one if the two people in a dyad were in the same department at any point in that particular year, and zero otherwise.

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. In order to account for the fact that differences in job types may be a determinant of interactions and collaborations in a potential dyad, we used the human resources dataset to code each individual's position on the basis of whether it was: tenured or tenure track, coded as "academic," and research track or clinical, coded as "other." At the dyadic level, a three-level categorical measure was created and coded zero if both dyad members had "academic" positions, one if only one dyad member had an academic position, and two if both dyad members had "other" positions.

Year. We created a categorical variable for years, with each level in the variable corresponding to each of the years in the period from 2006-2010 because the space use and utilization data only dates back to 2006, making this the cutoff for the regression analysis and models.

Statistical Analysis and Model Specification

The class of Poisson regression models is the 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. The dependent variable here is overdispersed because the variance is greater than the mean (Tables 2a and 2b), a more appropriate model would be a negative binomial regression, which corrects for overdispersion. Even so, a major reason for the overdispersion is the large number of zero counts for the dependent variable. The zero counts reflect the fact that many potential dyads have never formed and thus there is no likelihood of there being any research collaboration between the two people in the unconsummated relation. 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 actually has

two equations, a logit model to predict whether or not research collaboration occurs, and a main negative binomial model to predict differences on the counts of the research collaboration index (Long & Freese, 2006).

The logit equation takes the form:

$$\log(p/1 - p) = \beta_0 + \beta_1 EUCL + \beta_2 DEP + \hat{\epsilon} \quad \text{(Equation 1)}$$

Where:

p = the probability of a research collaboration occurring

EUCL = Euclidean distance between dyad members

DEP = whether dyad members are in the same department

$\hat{\epsilon}$ = error term

Euclidean 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. For the main equation, the log of the research collaboration index is predicted with a linear combination of the predictor variables (Long & Freese, 2006). The basic negative binomial equation is:

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

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

$\hat{\epsilon}$ = error term

We created two different zero-inflated negative binomial regression models corresponding to each of the buildings in order to account for differences in spatial layout; the first model focuses solely upon researchers who had moved to BLD1 by the end of 2006; and 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 3). 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 be more productive than collaborator's with less functional overlap. We test the effectiveness of the path overlap measure as a predictor of the dyadic collaboration index relative to metric and topological measures of physical distance for two samples of biomedical researchers in the period from 2006-2010. The two samples work in different buildings, and the differences in 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 in order to facilitate cross-comparisons of different buildings.

Results

The results of the regression models are shown in Tables 4a and 4b. Our analysis and interpretation of the results will concentrate on the full models (4, 5, 9, and 10). Though not shown here, the logit or zero-inflation models confirm that affiliation (being in the same department) and interactions costs or frictions (Euclidean distance) had significant effects on the likelihood of the existence of a dyadic collaboration.

Across the two buildings, path overlap has a significant and positive effect even controlling for the physical distance between dyad members, thus confirming **H2**. In BLD1, a 100-foot increase in path overlap in a dyad leads

to 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 results in 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 results in significantly higher outputs of IRB applications, animal research protocols, and grant applications to external sponsors.

Physical distance has a negative and significant effect on the collaboration index in BLD1 and no significant effect in BLD2, confirming **H1**. In the more linear BLD1, controlling for path overlap, increasing the walking distance by 100 feet or the turn distance by 10 turns leads to 35.4% and 30.8% decreases respectively in expected counts of the dyadic research collaboration index. In contrast, in the more compact BLD2, physical distance has no significant effect 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 were some differences between the two buildings in the “year” and “same department” variables. In both BLD1 and BLD2, the overall “collaborativeness” of the members of a potential dyad was a significant and positive predictor of their dyadic research collaboration index. An increase of 10 units in dyadic “collaborativeness” of (IRB applications, animal research protocols, grant applications to external sponsors) results in 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 effect in BLD1 and no significant effect in BLD2. At BLD1, departmental affiliation leads to a 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 nontenure-track positions. In BLD1 all “other” dyads face 41-44% decreases in expected counts of the collaboration index. The corresponding numbers for BLD2, 47-51% decreases in expected counts, are even larger. Lastly, the year dummies had no significant effect on the

collaboration index, with the exception of the year 2010 in BLD1. With 2006 as the reference level for the year dummies, in the year 2010 there was a roughly 38% decrease in the expected collaboration index counts.

Discussion

Our analyses offered strong support for the hypotheses **H1** and **H2**. Regarding **H2**, path overlap has a significant effect on the research collaboration index and its influence is similar across buildings. These effects are both substantively and statistically significant, lending credence to the utility of this dyadic spatial measure of functional proximity. Within building micro-level differences in proximity clearly influence the collaboration index of dyads. 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, with respect to **H1**, physical distance was a significant predictor of 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 both because the occupants are relatively new to the space and because of differences in the spatial topologies of the BLD1 and BLD2 buildings (Figures 6 and 7), and especially the fact that BLD1 is more linear than BLD2. Despite its ease of interpretation and calculation, physical distance clearly has its limits.

Future analysis of research collaboration in academic settings should address the roles that formal affiliation and job types play in fostering and maintaining collaborative efforts. Investigators are more likely to have non-zero counts of the dyadic collaboration index with within- rather than between-department dyads. Moreover, our results suggest skewed relations between tenured or tenure-track, and nontenure-track researchers. Dyads composed of tenured and tenure-track researchers are more likely to have non-zero research collaboration counts than are dyads comprised of nontenure-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 both 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, but 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 (for example, 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.

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 dramatic new possibilities for research that develops class theoretical ideas while having immediate relevance for policy and design.

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Figures

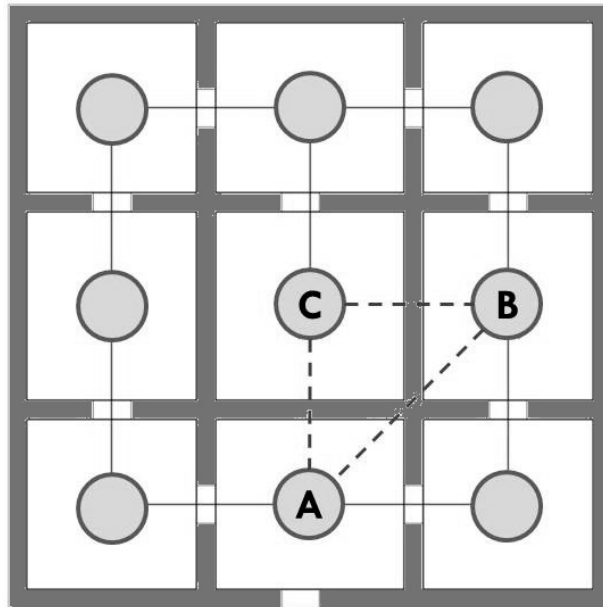


Figure 1. An illustration of Euclidean and walking distances between individuals A, B, and C in a simple spatial layout. For simplicity, individuals are restricted to orthogonal movements. Walking movement paths are depicted using solid lines while the Euclidean paths are shown as hatched lines.

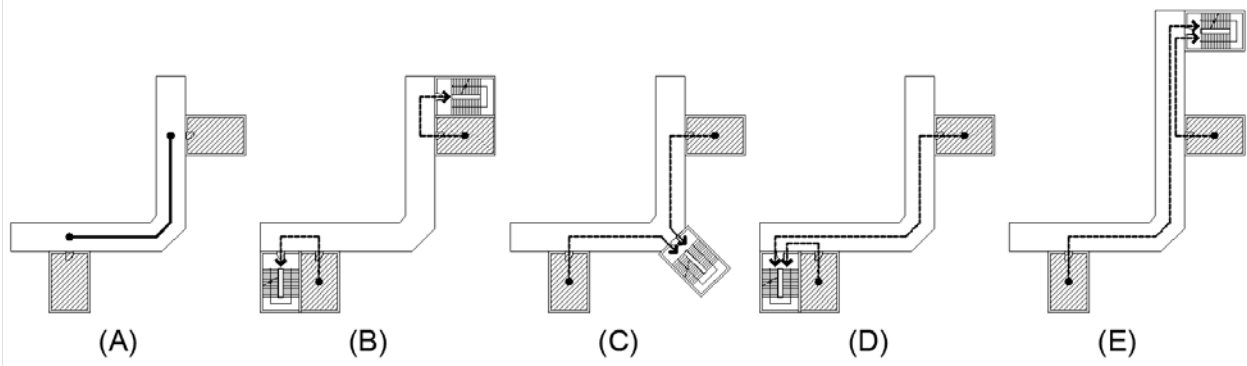


Figure 2. Further demonstration of the limitations of physical distance as a robust proxy for the finer-grained effects of spatial proximity. The physical distance is held constant, and the changes in the relative locations of the individuals in the latent dyad lead to dramatic differences in the expected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

ZONE OVERLAP

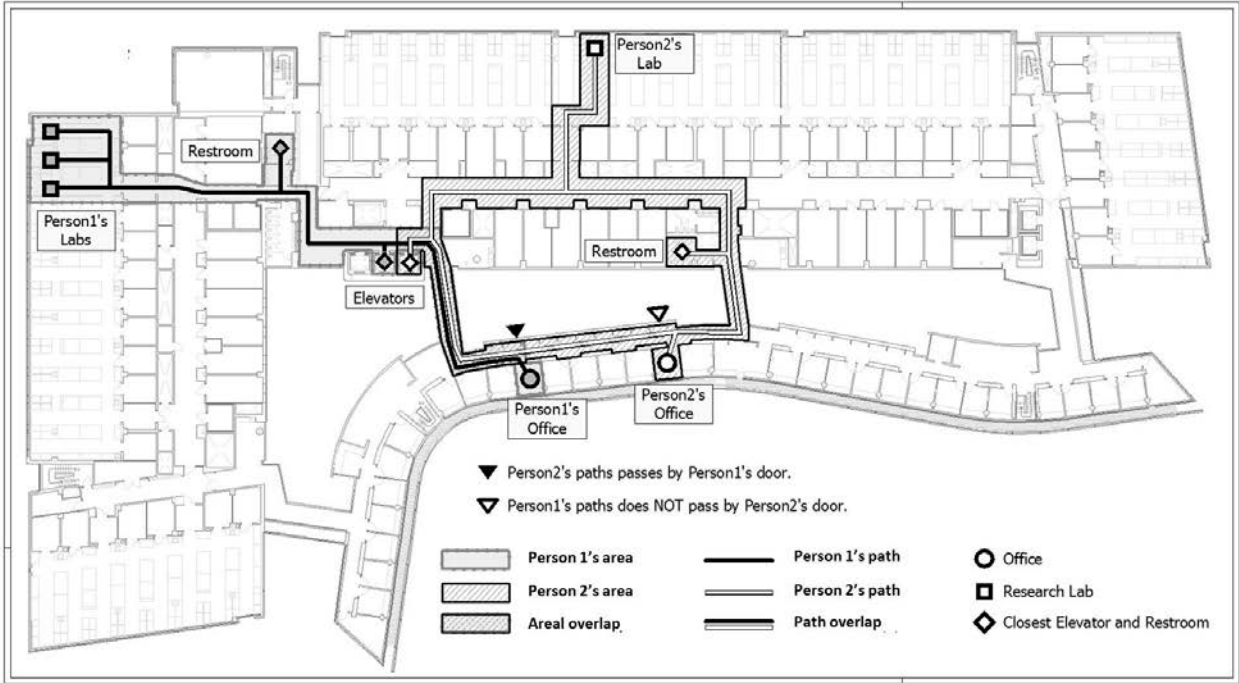


Figure 3. An illustration of the two measures of zone overlap (areal and path) using the BLDI building. Also shown is the related concept of “door passing.” The shared spaces that bound each person’s functional zone in the example above are the elevators and the restrooms.

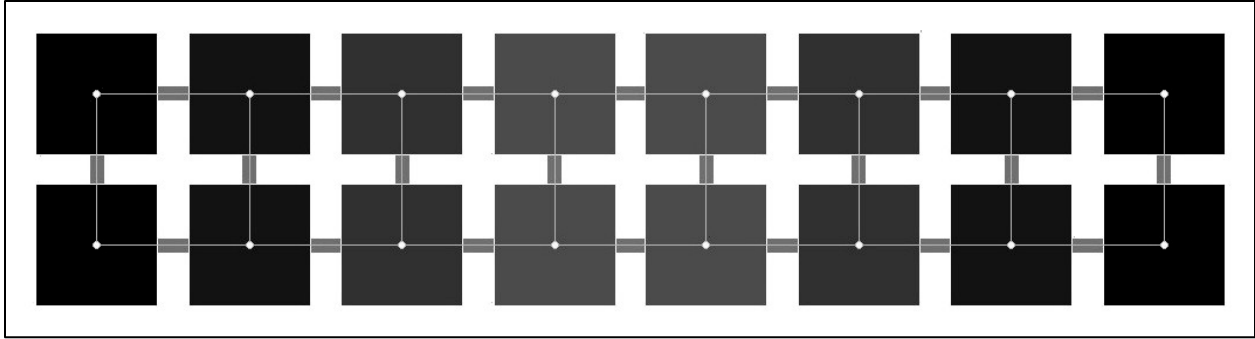


Figure 4. A more linear 16-space layout with the links between the spaces shown as light gray lines. From darkest to lightest, the spaces are coded according to their mean depth. The four values of mean depth are 4.267, 3.467, 2.933, and 2.667.

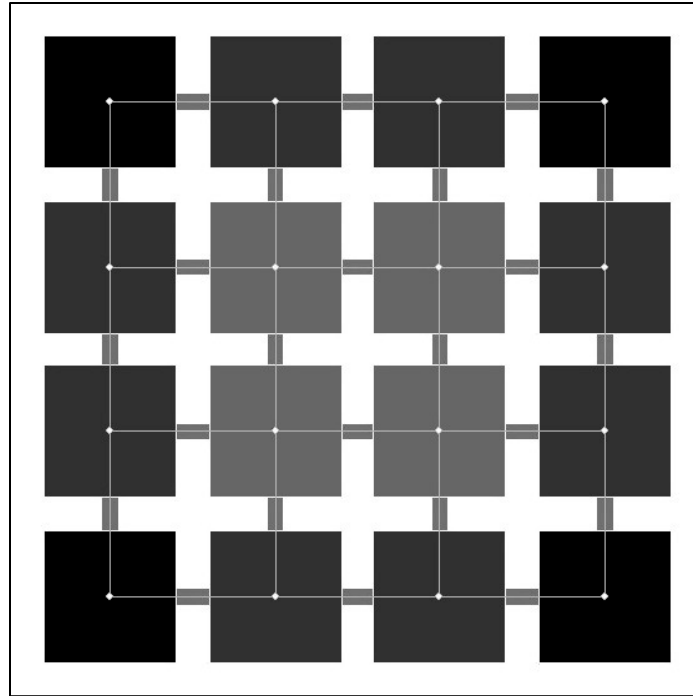
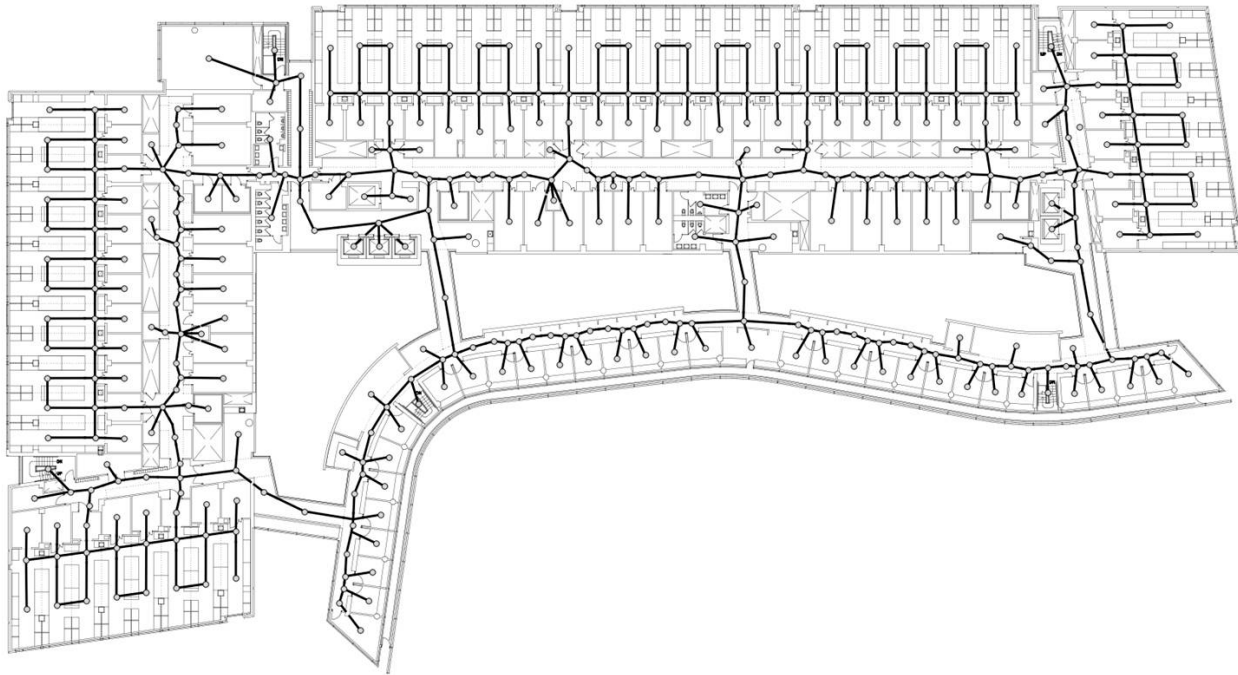


Figure 5. A more compact 16-space layout with the connections between the spaces shown as light gray lines. The spaces are coded from darkest to lightest to correspond with the three levels of mean depth (values are 3.200, 2.667, and 2.133).

BLD1



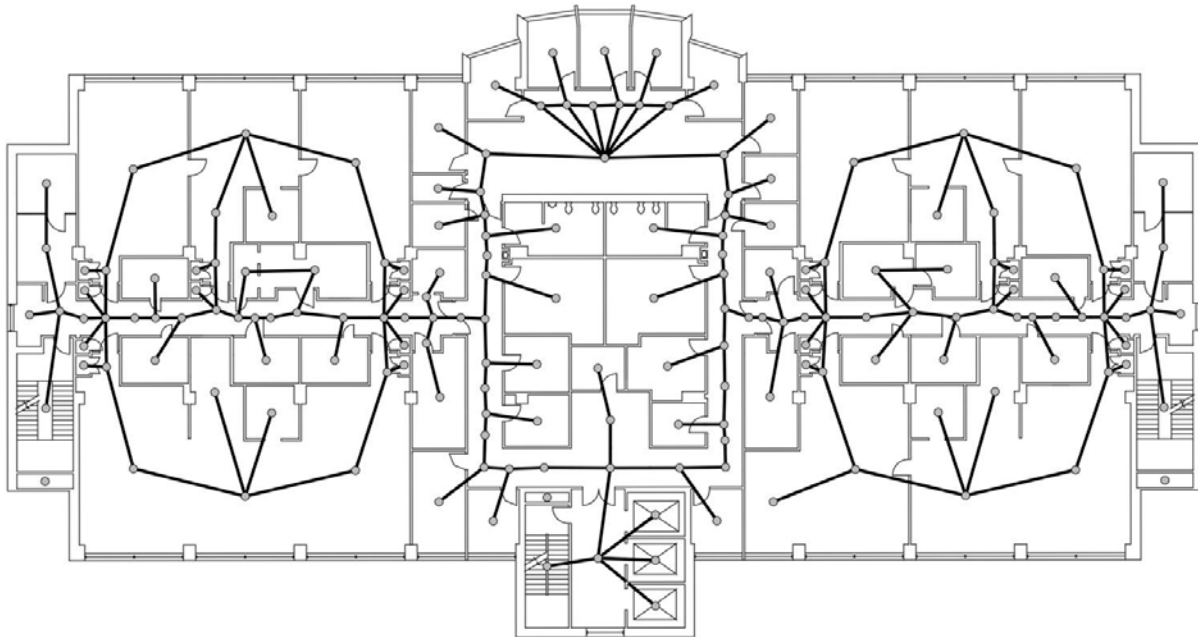
[Non-zero values only]

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. The image above 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.

BLD2



[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. The connections between adjacent and accessible spaces are shown (black lines).

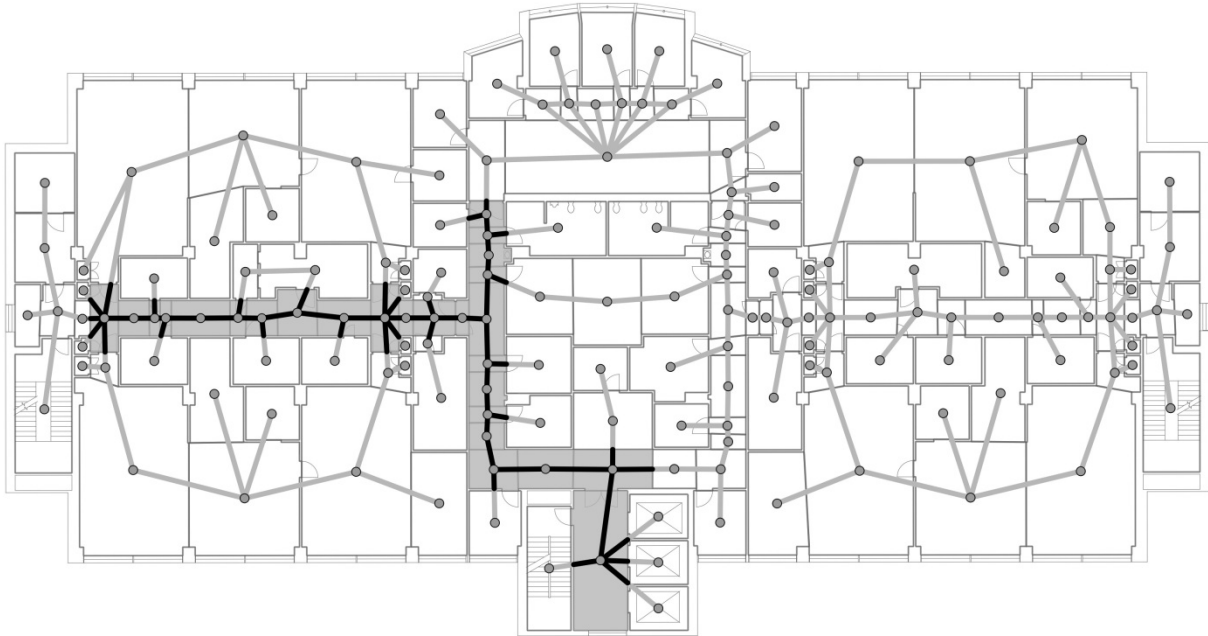


Figure 8. The zone overlap between two individuals was computed by obtaining the intersection set of their functional zones (areal overlaps), and by summing the lengths of the paths in the intersection set (path overlap). The spaces in the intersection set are shaded in gray above while the path is shown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

Tables

Table 1. Descriptions of Variables

Variable	Type	Description
Collaboration index	Count	Yearly combination of applications to institutional review boards, animal research protocols, and grant applications to external sponsors
Path overlap	Continuous	The length of the overlap in feet of the paths in the functional zones of the two people in the dyad
Walking distance	Continuous	The actual distance in feet between the labs of the two people in the dyad
Turn distance	Count	The number of 90-degree turns between the labs of the dyad members
Euclidean distance	Continuous	The straight-line distance in feet between the labs of the two people in the dyad
Collaborativeness	Count	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	Dummy	Coded as 1 if the two people in a dyad were in the same department that year
Jobcode	Categorical	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	Categorical	The variable has a value for each of the five years in the period 2006-2010

Table 2a. Summary Statistics and Correlations of Variables, BLDI

Variable	Mean	SD	Min	Max	1	2	3	4	5	6	7	8	9
1. Collaboration index	0.024	0.256	0	11	1.000								
2. Path overlap	45.232	139.277	0	1044.5	0.252	1.000							
3. Walking distance	322.580	116.127	0	646	-0.168	-0.558	1.000						
4. Turn distance	28.895	9.723	0	53	-0.176	-0.567	0.901	1.000					
5. Euclidean distance	235.392	93.186	0	490.4	-0.150	-0.487	0.940	0.818	1.000				
6. Collaborativeness	28.460	33.478	0	299	0.128	0.032	0.040	-0.019	0.014	1.000			
7. Same department	0.077	0.267	0	1	0.218	0.447	-0.343	-0.362	-0.312	0.022	1.000		
8. Jobcode	NA	NA	NA	NA	-0.039	-0.016	0.006	0.044	0.029	-0.267	-0.020	1.000	
9. Year	NA	NA	NA	NA	0.025	0.013	-0.001	-0.028	-0.015	0.381	0.023	-0.131	1.000

Table 2b. Summary Statistics and Correlations of Variables, BLD2

Variable	Mean	SD	Min	Max	1	2	3	4	5	6	7	8	9
1. Collaboration index	0.083	0.557	0	15	1.000								
2. Path overlap	71.412	149.588	0	793.3	0.203	1.000							
3. Walking distance	219.561	75.460	0	354	-0.187	-0.727	1.000						
4. Turn distance	19.927	7.775	0	36	-0.145	-0.578	0.887	1.000					
5. Euclidean distance	158.807	53.301	0	264.1	-0.165	-0.637	0.895	0.805	1.000				
6. Collaborativeness	68.168	79.901	0	622	0.205	0.040	-0.037	-0.023	0.003	1.000			
7. Same department	0.176	0.381	0	1	0.215	0.152	-0.169	-0.133	-0.165	0.262	1.000		
8. Jobcode	NA	NA	NA	NA	-0.104	-0.030	-0.020	-0.031	-0.051	-0.368	-0.051	1.000	
9. Year	NA	NA	NA	NA	0.057	0.006	-0.050	-0.027	-0.041	0.384	0.066	-0.128	1.000

Table 3. Yearly Incidences of Dyads and Researchers

Year	BLD1		BLD2	
	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

Table 4a. Effects of Functional Proximity and Physical Distance on Dyadic Collaboration Index, BLDI

VARIABLES	DEP. VAR. = COLLABORATION INDEX	(1)	(2)	(3)	(4)	(5)
Path overlap	0.00208*** (0.000327)				0.00136*** (0.000352)	0.00147*** (0.000353)
Walking distance			-0.00654*** (0.00134)		-0.00438** (0.00145)	
Turn distance				-0.0593*** (0.00963)		-0.0368*** (0.0110)
Collaborativeness	0.0189*** (0.00125)	0.0202*** (0.00123)	0.0200*** (0.00125)	0.0196*** (0.00119)	0.0194*** (0.00120)	0.0194*** (0.00120)
Same department	1.063*** (0.309)	0.566+ (0.314)	0.667* (0.310)	0.612+ (0.336)	0.705* (0.330)	0.705* (0.330)
<i>jobcode_Academic-Academic</i> (reference)						
<i>jobcode_Academic-Other</i>	-0.0904 (0.147)	-0.174 (0.147)	-0.143 (0.148)	-0.133 (0.142)	-0.109 (0.144)	-0.109 (0.144)
<i>jobcode_Other-Other</i>	-0.524* (0.205)	-0.603*** (0.198)	-0.551** (0.200)	-0.571** (0.199)	-0.534** (0.200)	-0.534** (0.200)
year_2006 (reference)						
<i>year_2007</i>	0.192+ (0.101)	0.210* (0.0981)	0.189+ (0.0978)	0.209* (0.101)	0.193+ (0.101)	0.193+ (0.101)
<i>year_2008</i>	-0.182 (0.139)	-0.189 (0.127)	-0.193 (0.127)	-0.189 (0.132)	-0.193 (0.132)	-0.193 (0.132)
<i>year_2009</i>	0.00661 (0.129)	-0.0109 (0.120)	-0.0155 (0.120)	-0.00153 (0.125)	-0.00463 (0.125)	-0.00463 (0.125)
<i>year_2010</i>	-0.486** (0.162)	-0.468** (0.149)	-0.469** (0.149)	-0.477** (0.157)	-0.481** (0.158)	-0.481** (0.158)
Constant	-3.837*** (0.287)	-1.982*** (0.300)	-2.094*** (0.310)	-2.837*** (0.404)	-3.008*** (0.407)	-3.008*** (0.407)
Observations	44,962	44,962	44,962	44,962	44,962	44,962

Robust standard errors in parentheses
 *** p<0.001, ** p<0.01, * p<0.05, + p<0.1

Table 4b. Effects of Functional Proximity and Physical Distance on Dyadic Collaboration Index, BLD2

VARIABLES	DEP. VAR. = COLLABORATION INDEX	(6)	(7)	(8)	(9)	(10)
Path overlap	0.00252*** (0.000386)				0.00177*** (0.000518)	0.00256*** (0.000450)
Walking distance			-0.00619*** (0.00177)		-0.00261 (0.00177)	
Turn distance				-0.0402*** (0.00947)		0.00133 (0.0128)
Collaborativeness	0.00535*** (0.000796)	0.00537*** (0.000823)	0.00540*** (0.000749)	0.00540*** (0.000815)	0.00540*** (0.000815)	0.00534*** (0.000771)
Same department	0.496 (0.383)	0.404 (0.427)	0.637+ (0.366)	0.392 (0.420)	0.392 (0.420)	0.501 (0.397)
<i>jobcode_Academic-Academic</i> (reference)						
<i>jobcode_Academic-Other</i>	-0.274 (0.205)	-0.376+ (0.217)	-0.304 (0.205)	-0.319 (0.212)	-0.319 (0.212)	-0.273 (0.206)
<i>jobcode_Other-Other</i>	-0.640* (0.283)	-0.819** (0.291)	-0.728* (0.284)	-0.713* (0.291)	-0.713* (0.291)	-0.637* (0.289)
year_2006 (reference)						
<i>year_2007</i>	0.0775 (0.123)	0.0425 (0.130)	-0.0139 (0.122)	0.0791 (0.127)	0.0791 (0.127)	0.0778 (0.122)
<i>year_2008</i>	0.139 (0.146)	0.111 (0.152)	0.0896 (0.148)	0.125 (0.149)	0.125 (0.149)	0.140 (0.145)
<i>year_2009</i>	-0.127 (0.168)	-0.196 (0.168)	-0.219 (0.166)	-0.152 (0.169)	-0.152 (0.169)	-0.125 (0.166)
<i>year_2010</i>	0.0666 (0.156)	-0.00799 (0.166)	0.0122 (0.159)	0.0252 (0.165)	0.0252 (0.165)	0.0698 (0.158)
Constant	-2.430*** (0.402)	-0.938+ (0.494)	-1.313** (0.482)	-1.856** (0.606)	-1.856** (0.606)	-2.458*** (0.544)
Observations	11,692	11,692	11,692	11,692	11,692	11,692

Robust standard errors in parentheses
 *** p<0.001, ** p<0.01, * p<0.05, + p<0.1