Workplace Design, Collaboration, and Discovery

Jason Owen-Smith

University of Michigan
500 S. State St. #3001
Ann Arbor, MI 48109-1382
jdos@umich.edu

Executive Summary.

While no single study credibly establishes the fact, the literature suggests that face-to-face encounters mediate the relationship between workplace design and discovery in science and engineering research. The relationship between workplace design and interaction is itself highly contingent. Organizational, psychological, cultural, and technical considerations moderate the connection between design and interaction. There is thus very little hope for establishing general laws or "one size fits all" solutions that consistently fit the needs of different fields, styles of research, or organizational settings.

Nevertheless, it should be possible to develop and test a more contingent approach that focuses on establishing the conditions under which particular design features exert positive effects on collaboration and discovery. The tensions that make design for collaboration challenging have to do with the balance between individual and collective work, between awareness and privacy, between consultations with known partners and serendipitous discovery of unexpected information, and between more certain and more uncertain or ambiguous research goals. The balance of all these tensions can vary dramatically across teams, organizations, fields, and projects.

There are relatively few systematic studies that offer robust insights into how design shapes the dynamics and outcomes of collaborative science. Even state of the art research falls far short of providing the sort of systematically validated findings that might support a robust socio-spatial science of design for team science. We remain quite a long distance from a systematic and rigorous science of design for collaboration and discovery.

Key Findings

- Most interactions reported by scientists in several studies are unscheduled, face-to-face encounters
- Spaces that "integrate" buildings by connecting to many other areas are often the location of more intense interactions
- Both the actual and the perceived distance between spaces must be taken into account
- The systematic combination of spatial and social network analysis has great potential or future work

Future research should . . .

1) use new technologies such as sociometric badges to naturalistically observe workplace encounters at scale
2) integrate qualitative and experimental work in order to establish
   a) how researchers understand and navigate their workplaces, and
   b) how different organizational, disciplinary, and national cultures shape possibilities for interaction
3) track collaborations and outcomes over long time scales to establish workplace effects on scientific discovery and impact
4) attend closely to other opportunities to substantiate plausible causal claims.

Introduction.

Research that systematically links specific design features of the spaces where team science is conducted to collaboration dynamics, scientific discovery, or impact is rare. Instead work that spans several largely independent fields uses a variety of methods to examine the relationship between physical space, collaboration, teamwork and innovation in contexts ranging from science and engineering, to design, professional and other white-collar workplaces. These lines of research share a broad focus on the dynamics of 'knowledge work' and the affordances offered by features of physical space including building design and the configuration and characteristics of furniture and equipment.

Taken as a whole, these diverse literatures offer few specific and robust findings about the relationship between workplace design and either the collaborative processes or research outcomes in science and engineering. Instead, the general impression I take away from my review in response to the committee's charge is that some important general principles have been more or less established in a variety of settings. These effects, however, are highly contingent when considered in terms of specific design principles. Available evidence suggests that the relationship between workspace design, collaboration, and discovery is moderated by factors ranging from individual psychological differences (Vischer 2008), to the task structure, complexity and tools of different styles of work (Cachere et al 2003; Teasley et al 2000), and organizational influences having to do with hierarchy, workplace culture, formal team structures and incentives (Becker 2005).

As one recent review concluded, there appears to be no direct link between design and productivity or discovery. Instead, design features appear to influence various types of interactions, which themselves depend intimately upon the specific work processes of building occupants (Haynes 2008). While I can locate no study that conducts a credible analysis to support the idea, my read of this literature suggests that a variety of types of interaction mediate the relationship between features of workplace design and the outcomes of knowledge intensive work such as scientific research. The relationship between workplace design and interaction is itself highly contingent. As a result there seems very little hope for establishing general laws or "one size fits all" solutions that might consistently relate specific design features to outcomes across different fields, styles of research, or organizational settings. Nevertheless, I believe that there is room to develop and test a more contingent approach that focuses on establishing the conditions under which particular design features should exert positive effects on the process and outcomes of team science. While significant work needs to be done, new methods and approaches offer potentially fertile avenues to develop a truly socio-spatial science of collaboration that can provide validated insights in support of better design, allocation, and use of research space.

In what follows, I sketch some general themes from the broad literature on workspace design and knowledge intensive work. I confine myself to a discussion of recent empirical research that relates gross features of building design and configuration to either work processes or outcomes such as the rate and impact of new discoveries. In so doing, I explicitly restrict the scope of my discussion to exclude large literatures that examine technologies that might support proximate or distant collaboration (c.f. Finholt and Olson 1997), work that considers the effects of particular organizational policies such as "hot-desking" (Bosch-Sijtsema et al 2010) and studies that emphasize more 'ergonomic' questions about for instance, the effects of different workstation designs and configurations.

I next turn to a more specific and detailed analysis of the relatively few pieces of research that appear to be directly on point for the committee's concerns about the dynamics of collaboration and discovery in team science. Starting from this base, I briefly sketch new approaches that seem to have excellent potential for future research. Those include the integration of spatial and social network analysis (c.f. Wineman et al 2009; Sailer & McCullough 2012; Kabo et al 2013) and methods that support large scale naturalistic observation of workplace interactions such as sociometric badge technologies (Lepri et al 2012). I believe that turning these approaches to developing systematic, theoretically grounded studies of collaboration processes and outcomes that focus on patterns of motion, interaction, and their relationship to both the topology of built workspaces and the content and impact of team science offer the best hope for developing a strong evidence base to link design to collaboration dynamics and outcomes.

Accomplishing that goal stands to dramatically advance our understanding of collaboration and team science and to remedy the current state of design for science and engineering work. While design is clearly important it too often proceeds "on intuition derived from personal experience or from highly simplified accounts of the academic literature applied without reference to this literature's underlying association of physical design with the nature of work" (Heerwagen et al 2004: 511). Idiosyncratic and intuitive design principles run considerable risk of creating unintended consequences by transposing features that are effective in one setting to situations where they might have less salutary effects.

Likewise, complicated relationships among design, work process and structure, formal and informal organization complicate efforts to develop broad and easily applied design principles. More systematic and rigorous studies of the relationships between features of the designed environment, collaboration dynamics, and scientific outcomes are necessary to provide a validated evidence base to support the creation of more effective spaces for team science.

What is known about design influences on knowledge work?

Before presenting an answer to the first question posed by the committee, it is necessary to do some definitional work. One clear lesson of the literatures I reviewed is that design stands to influence work process and thus discovery in different ways. Understanding those varied effects may require that we acknowledge that multiple types of work processes are often conflated under the labels 'collaboration,' 'knowledge work,' and 'team science.' There is no common language that I can identify. For instance, Kabo and colleagues (2013a) distinguish between activities that support exploration and search, what they call prospecting, and activities that are designed to develop new proofs of concept, pilot data or prototypes and thus require the mobilization of often scarce resources and attention.

Similarly, Toker and Gray (2008) distinguish between consultation, information consumption, and the innovation process, proposing that it is face-to-face consultation with colleagues that mediates the relationship between workplace design and innovation in university research centers. Their focus on information consumption includes both collective and individual work. The importance of private spaces that enable focused concentration is also emphasized by environmental psychologists (Vischer 2013).

Finally, Heerwagen and colleagues (2004) break the process of collaboration into three parts: awareness, brief interactions, and collective work. The last two concepts map fairly cleanly onto Kabo and colleagues ideas of prospecting and mobilization as well as Toker and Gray's distinction between consultation and information consumption. Their additional focus on more passive forms of workplace awareness, however adds something new to the mix.

These and other works suggest that in order to understand how workplace design can offer affordances for scientific discovery we must first recognize that the design-discovery relationship appears to be strongly mediated by work, communication, and interaction. Thus, we should attend to design effects on four partially separable processes. Workplace awareness, unscheduled face-to-face interactions, focused and sustained collective work, and more private, intensive individual concentration need to be considered. The task of designing to support collaboration is complicated by the fact that parts of buildings that support some of these processes are detrimental for others. In what follows I emphasize findings pertaining to awareness and interaction.

Most obviously, the radically open and configurable plans that characterize many 'marquee' laboratory designs may increase awareness while imposing costs in the form of interruptions and distractions on focused collective work and individual concentration.[1] Indeed, in relatively early work on the role of space in the conduct of scientific research, Hillier and Penn (1991: 47) make note of just this tension, saying: "Space, we would suggest, articulates exactly this double need for the individual and the collective aspects of research: how to combine the protection of the solitary with the natural generation of more randomized co-presence with others - the need for which seems to grow the more the objectives of research are unknown." The tensions that make design for collaboration challenging have to do with the balance between individual and collective work, between awareness and privacy, between consultations with known partners and serendipitous discovery of unexpected information, and between more certain and more uncertain or ambiguous research goals. The balance of all these tensions can vary dramatically across teams, organizations, fields, and projects. As a result, a recent empirical review notes ". . . the majority of evidence – in the literature as well as in the empirical studies presented in this paper shows distinct organizational responses to similar spatial configurations" (Sailer & Penn 2009: 5).

<u>Awareness.</u> Individual workplace awareness involves both the ability to know what is going on at work and the ability to make sense of that knowledge (Gutwin & Greenberg 2001). Awareness

[1] Conspicuously 'open' designs such as those that characterize Stanford University's Clark Center appear to exhibit just

depends on the ability to quickly and easily access activities happening nearby. Little research has distinguished between the varied importance of visual and aural access, however work dating back to the 1970s notes that as distance increases visibility becomes more important (Archea 1977; Allen 1977). Important studies of the collaboration process note that high awareness contexts can improve outcomes by increasing the ability to coordinate and monitor work (Bardram & Hansen 2010). Such coordination is aided by access not just to collaborators but also to shared artifacts and representations (Bechky 2003; Hargadon & Bechky 2006). Indeed the coordination and information sharing benefits of high awareness workplaces may underpin the compelling finding that radical collocation can result in impressive productivity gains in fields such as software engineering (Teasley et al 2002; Olson et al 2002).

Where completely open spaces and radically collocated groups are impractical, the design of spaces that increase awareness depends largely upon creating possibilities for visibility by, for instance, opening sight lines that cross multiple workspaces. Compelling methods for analyzing sightlines exist as a part of the broad set of approaches to spatial network analysis called space syntax (Hillier & Hansen 1984)[2]. In this particular formulation, called 'isovit' or 'axial line' analysis (Turner et al 2001) hexagonal sections of floor plans (isovits) are treated as the sources for axial sightlines. Areas where many of those lines intersect are sites where greater visibility-based workplace awareness is possible. Axial line analyses of floor plans can be transformed into network representations that have been used to compare the design of different laboratories (Hillier & Penn 1991) and other creative workplaces (Peponis et al 2007). These studies combine analysis of sightlines with information on interactions in order to develop the evocative idea that the multi-modal relationships among spaces do more than simply enable interaction or patterns of motion. Instead these authors argue, architecture actively encodes, supports, and helps to construct particular

[2] For an introductory review of space syntax terms and techniques see Bafna (2003).

work cultures by creating a physical representation of the more abstract social and knowledge spaces in which collaboration takes place. While the idea and the methods appear to me to have real potential, more systematic and sustained work is needed to establish key relationships between design, awareness, interaction, and discovery.[3]

<u>Encounters.</u>

By far the largest body of work relating building design to collaboration and discovery focuses on the role space plays in facilitating unscheduled face-to-face interactions. This line of inquiry begins with classic work on relationship formation and communication. In 1950, Festinger and colleagues published an extensive observational study of relationship formation among residents in a new MIT dorm for veterans and their families. Their work identified two key spatial constructs, which they dubbed physical and functional proximity. Physical proximity was a straightforward measure of linear distance among the spaces (in this case apartments) occupied by subjects. Functional proximity, in contrast, emphasized the relationship among key spaces that individuals traversed in their daily work (e.g. mailboxes, bus stops, stair wells, and offices) to identify opportunity for 'passive contacts' that might lead to interaction as occupants became more familiar with and aware of one another.

Where physical proximity indexed the difficulty of intentionally seeking out an interaction partner, functional proximity relied on the idea that common motion paths increased the likelihood that otherwise unacquainted people would begin to interact, form relationships and potentially share information. The first idea, physical proximity, was later famously applied to the study of science and engineering collaboration by Allen (1977) whose studies demonstrated (the now eponymously known) relationship between distance and the likelihood of communication among engineers. The

[3] I return to some of these ideas in my discussion of 'specific design features' below.

Allen-curve helped to establish the finding that relatively small distances (in this case 30 meters) dramatically decreased the likelihood of communication between potential collaborators.

The legacy of Festinger's and of Allen's research is two related lines of analysis that relate physical design to interaction rates by appeal to proximities and motion paths. Here too spatial network analyses are often mobilized to understand how the topology of buildings shapes patterns of interaction. The relational focus of this work has also resulted in an increasing effort to integrate spatial network methods for characterizing buildings with social network methods for characterizing and analyzing concrete patterns of interaction. This combination of methods appears to be particularly valuable for the analysis of design effects on collaboration as the most sophisticated and compelling recent work mobilizes some combination of spatial and social network approaches.

In keeping with the questions raised by the committee, I first offer a consideration of one general principle that appears to hold across multiple organizational settings where knowledge-intensive work takes place. I then turn to an analysis of the ways in which a specific design principle that might be derived from that general regularity has varied effects. The preponderance of research (Hillier & Penn 1991; Serrato & Wineman 1999; Sailer & Penn 2009; Heerwagen et al 2004; Wineman et al 2009) finds that interactions occur more commonly in areas of buildings that are easily accessible to more parts of the whole workspace. Couched in terms of spatial network analysis; spaces that 'integrate' buildings by enabling easy access to many different areas are more often the location of interactions than are more isolated spaces that are difficult to reach. The latter may be more effective for uninterrupted private or collective work.

What does this mean for specific design features? One common form of 'integrating space' is a long corridor that connects many different parts of a building into a single 'thoroughfare.' This kind of design feature has most famously been associated with the hugely productive research facility at Bell Labs. As Jon Gertner (2012a) notes in a recent New York Times article describing his book length study of Bell Labs (Gertner 2012b) much of the productivity of this exceptional interdisciplinary research facility depended on organizational culture, on managerial efforts to mindfully mix disciplines and problems and on the role of proximity in stimulating unexpected conversations and collaborations. Gertner attributes much of Bell Lab's productivity to Mervin Kelly who rose to be Chairman of the Board of Bell Labs. Speaking of Kelly he notes:

> One element of his approach was architectural. He personally helped design a building in Murray Hill, N.J., opened in 1941, where everyone would interact with one another. Some of the hallways in the building were designed to be so long that to look down their length was to see the end disappear at a vanishing point. Traveling the hall's length without encountering a number of acquaintances, problems, diversions and ideas was almost impossible. A physicist on his way to lunch in the cafeteria was like a magnet rolling past iron filings.

This idea, the long hallway that encourages interactions among the occupants of offices whose assignments mixed disciplines and approaches, would seem to be wholly consistent with the general principle that interactions occur in 'integrating spaces.' Indeed it is. Somewhat inconveniently, however, long integrating corridors do not always appear to play this role. Findings about the relationship between integrating corridors and interactions are, to put it mildly, mixed.[4]

[4] The invocation of long corridors at Bell Labs as a justification for designs that incorporate similar features in buildings for other organizations and research teams represents just the kind of 'intuitive' approach to design that I describe in the introduction. The fact that studies of workplace interaction report mixed results when they examine just these design features suggests the potential dangers of that approach to design. Using Bell Labs obvious innovative success as a means to justify the importance of this particular design feature appears to be an instance of what organizational theorist James March (Levitt & March 1988) calls 'superstitious learning.' There can be little doubt that the corridors at Bell Labs functioned as just the kind of interaction hubs that Gertner described and that Peter Galison (1997) has dubbed 'trading zones' in an of high energy physics collaborations. However, the corridors may have worked the way they did at Bell Labs because of other features of the organization (for instance, culture, incentives, or managerial engagement) that were also associated with successful innovation.

For instance, Rashid and colleagues (2009) conducted research that used behavioral observation of interactions in four government offices to explore the relationship between design features and interactions. Their findings are instructive. Across all four offices (even though three of the four had been recently designed to include common spaces intended to facilitate collaboration) the majority of observed interactions occurred in individual workspaces.

Secondary points of interaction were apparent in three of the four offices. In two of those corridors were the location for between 21 and 22% of observed interaction. In a third office, common spaces were the location for a similar percentage of interactions. These differences are apparent despite the fact that very similar types of work are being done in the four offices. Perhaps as a result, Rashid and colleagues attribute the differences they find to the office's disparate "interaction cultures." Similarly, earlier work comparing interactions in two scientific labs (Serrato & Wineman 1999) found again that offices and other individual workspaces were key locations for interaction. In one lab, however, more interactions occurred in corridors that integrate larger portions of the research facility. In the other lab, most encounters happened amidst clusters of spaces that were more closely connected to one another than to the rest of the facility.

Still another study that examined the role of corridors examined co-authorship rather than interaction reports findings that are more similar to the experience Gernter describes at Bell Labs. Wineman and colleagues (2009) studied co-authorship patterns among interdisciplinary social scientists in a professional school where office locations were assigned to mix disciplines and departments. They found a striking corridor effect. Co-authorship patterns in this professional school setting suggest that faculty who occupy offices adjacent to corridors that are well connected to all the other hallways in the building collaborate more. This finding parallels the interaction patterns Serrato & Wineman (1999) discovered in one laboratory, but it too emphasizes not corridors as home to interactions but corridors as motion paths that make interaction in private spaces more likely.

While it is clear that corridors sometimes matter for interaction and by extension for collaborative discovery, how they matter is highly contingent. Indeed, Backhouse and Drew's (1992) close qualitative analysis of videotaped interactions in one English design firm found that more than 80% of conversations were unplanned, that common movement paths created interaction 'hotspots' that were difficult to predict from the topology of the building alone, and that interactions depended not just on proximity but on subtle, often non-verbal signals, that stationary and mobile workers were available to be "recruited" for unscheduled interactions. The signals mobile and stationary workers sent to indicate their willingness to engage in interactions represent one important complication for efforts to understand how design shapes interaction in scientific workplaces and how, by influencing interaction, space affects discovery.

Indeed, close observational studies such as those conducted by Backhouse and Drew have great potential to more fully specify the features of 'interactional cultures' that can lead similar design features to have disparate effects. In the case of Bell Labs, the fact that "A physicist on his way to lunch in the cafeteria" collected interactions and conversational partners "like a magnet rolling past iron filings" may have as much to do with the physicist, his colleagues, and the broader culture of the research organization as it does with the mere fact that work takes place in a building defined by long, integrating corridors.

The broad finding that spaces which are globally well connected to other parts of buildings are the location of more intense interaction appears to be the closest thing to a truism in the literature I reviewed. However, a closer look at one common form of such 'integrating' spaces, well-connected corridors, suggests that the picture is more complicated. Indeed the relatively few recent studies that match nuanced spatial analysis with studies of collaboration and productivity in research settings raise more questions about the relationship between design, interaction, and discovery than they answer.

Recent and Relevant Studies.

There are relatively few systematic studies that offer robust insights into how design shapes the dynamics and outcomes of collaborative science. To date no single study or set of studies seems to me to represent a 'gold standard' set of findings. Instead a small set of recent articles each present a small piece of a larger mosaic. All five of the pieces I review here draw, in one way or another, on spatial network measures to understand the relationship between design and collaboration in research work. Three include some effort to link features of space with the productivity and success of scientific collaborations. These works report important and interesting findings, but methodological limitations, convenience samples, difficulties with large scale naturalistic observation, challenges in establishing causality, and the difficulty of fully specifying the complicated relationship between design, interaction, and discovery mean even state of the art studies fall far short of providing the sort of systematically validated findings that might support a robust socio-spatial science of design for team science.

Toker and Gray (2008) most specifically address the specific concerns of this committee in a detailed study of spatial arrangements, interaction, and self-reports of research outcomes for six university research centers (URCs) in the United States. Five of those six centers emphasize interdisciplinary life science with a focus on genetics and genomics, the sixth is dedicated to physical science research on optics. Centers were systematically sampled to represent three different spatial profiles. Four centers occupied "intact" spaces, buildings or parts of buildings where all members of the center could physically reach one another without having to traverse space 'owned' by another unit or group. Two of those centers included both office spaces and laboratories. The other two had no labs. The remaining centers occupied spaces that were not intact because researchers were located in multiple buildings or in spaces isolated by public use areas or spaces dedicated to other programs.

These authors propose (though they never systematically test) a "three-ring chain" mediation model that explicitly links workspaces to consultations among researchers and that makes those consultations the key to "innovation process outcomes" (Toker & Gray 2008: 310). They draw on space syntax methods, weeklong activity journals completed by researchers and follow-up surveys to establish several interesting findings. Activity logs reported 1763 consultations across all six centers. Of those, more than 80% were unscheduled interactions that took place either when one scientist visited another's office or when two researchers encountered one another outside of their offices. Another 8% of consultations were 'programmed' encounters such as scheduled office visits and group meetings. The remaining 12% of consultations took place via phone or email (Ibid. 319).

In addition to self-report data about information sharing, Toker and Gray used floor plan data to calculate several measures of proximity and distance. After identifying the spaces occupied by individuals who completed activity logs, the authors calculated walking path distances, levels of visibility, and integration for each space. In both descriptive and (uncontrolled) regression analyses they demonstrate that all three measures were associated with increases in the number of unscheduled consultations reported by scientists. Across all six centers, scientists that occupied more visible and more integrated spaces reported more unplanned encounters with colleagues as well as more email and phone contacts. Similarly, scientists whose workspaces were a greater (walking distance) remove from their colleagues reported fewer unscheduled interaction. Walking distance had no statistically significant effect on reported frequency of email and phone communication.

At the level of centers as a whole the authors use qualitative comparative case methods to demonstrate that centers that occupy intact spaces whose floor plans are more easily navigable have higher overall rates of reported encounters.[5] Using data from follow-up surveys with center scientists, they also demonstrate that more intact and navigable centers have higher rates of self-reported scientific productivity in terms of both subjective measures of satisfaction and self reports of rates of publication. These findings lead them to draw a single 'design related' implication from their findings.

> For the research management community, including university CEOs responsible for planning new research buildings on their campuses, the major message from this study may be "you get what you pay for". From a practical point of view, it needs to be emphasized that non-intact URC territories, including use of ad hoc space on campus, inhibit face-to-face consultations through segregation of offices and laboratories, long walking distances, decreased configurational accessibility levels, and non-territorial connections between offices and laboratories (Ibid. 327)

While this article reports some interesting and suggestive findings, underspecified models, and a lack of any direct test of the mediation model the authors propose at the individual level of analysis as well as a reliance exclusively on self report data of interactions and outcomes over a relatively short time period suggest that further research is needed to establish the causal links these authors propose among design features, information sharing, and scientific outcomes. Nevertheless, the

[5] The overall navigability of spaces is measured using a space syntax variable called 'intelligibility.'

move to associate multiple nuanced spatial measures with different types of encounters and some measures of outcomes at multiple levels of analysis is to be applauded.

A very similar mix of strengths and weaknesses characterizes another recent study. Sailer and McCullough (2012) use spatial network methods to operationalize configurational and linear measures of distance and proximity in two university departments, a high energy physics research center and a media design firm. These measures are then mobilized in exponential random graph models of social network tie formation. Information on interactions was drawn from online surveys. Quantitative analyses were supplemented with information from ethnographic observations and interviews in each workplace. In addition to using sophisticated social network models to evaluate spatial effects on tie formation, the analyses reported in this work use a set of reasonable controls for network structure, membership in the same research teams, and subjective evaluations of the usefulness of conversations with potential interaction partners. While Sailer and McCullough (2012), thus offer more nuanced and defensible findings about the relationship between the topology of physical space and the likelihood of reported interaction in several different knowledge-intensive workplaces, their research offers no insight into the effects of either interaction or proximity on collaborative outcomes such as scientific discovery.

Nevertheless, there are interesting findings here. First, the authors demonstrate that more nuanced measures of distance that use space syntax techniques to establish the walking distance, and number of angle changes in pathways between investigator offices outperform more simple (as the crow flies) measures of distance. In three of four settings (the two university departments and the high energy physics institute) walking distance appears to offer the most parsimonious explanation for reported patterns of interaction (net of network structure, shared team membership and perceptions of usefulness). In these three settings, increases in walking distance result in significant decreases in the likelihood two scientists will report an interaction in surveys.

Walking distance appears to be the most important predictor in the physics institute, which is organized around a series of very long integrating corridors that result in the creation of relatively long but simple walking distances among offices. In contrast the design firm's open floor plan has relatively short walking distances among all workstations but unlike the physics institute traversing those relatively short distances requires following complicated, highly angular walking paths. In this context, walking distance exerts a much less telling effect on interaction. As a result, Sailer and McCullough (Ibid. 56) suggest that attention should be paid to both actual distance and perceived distance.

More angular routes, even if short, introduce a degree of cognitive complexity to individual efforts to navigate the workplace and as a result the long but simple paths created by corridors may result in "perceived closeness and actual distance." In contrast the complicated walking paths created by an open office plan crowded with cubicles and shared workspaces may "generate structures of perceived distance and actual closeness." The role integrating corridors play in reducing perceived distances among investigators may offer another insight into the source of Gertner's (2012) description of Bell labs (discussed above) while the cognitive complexity created by efforts at co-location in open floorplan spaces might raise questions about the possible negative effects of radically configurable spaces such as the open labs that increasingly characterize new construction such as Stanford's Clark Center. Once again a close and detailed study suggests that the relationship between space and interaction is complicated though in this case the complications arise not from cultural differences but from the cognitive limitations of people who tend to favor simpler and more linear routes when navigating the physical environment (Conroy Dalton 2003).

Another recent study compares several measures of distance and proximity in an analysis of interdisciplinary social science collaborations. Wineman, Kabo, and Davis (2009) analyze patterns of co-authorship among the faculty of an interdisciplinary professional school that allocates office space in a fashion designed to mix researchers from multiple departments in an explicit effort to generate interdisciplinary collaborations. Where the articles discussed earlier focus on self reports (via activity logs and surveys) of interaction, Wineman and colleagues collected no data on interactions or consultations. Instead they infer social network connections by tracking patterns of co-authorship.

In dyad-level analyses of the likelihood two faculty will be observed to co-author papers, they demonstrate that (net of belonging to the same department) greater distance between researcher's offices are associated with a decreased likelihood of co-authorship. The measure of distance used here is called 'step depth' a simple measure of the number of separable spaces (e.g. offices or corridor segments) one must traverse in order to move from one office to another. Wineman and colleagues also conduct an exploratory regression that uses the degree to which an individual faculty member's office is globally integrated with other spaces in the building to explain the rate at which that individual collaborates. They find strong evidence that faculty who occupy more easily accessible offices write more collaborative papers. While this finding is suggestive of how features of space are associated with the productivity of collaborative research, questions of causality and a complete lack of controls for potentially confounding factors imply the need for further research to nail down the relationship between office location and productivity.

Finally, consider two new papers that build on Festinger and colleagues' (1950) idea of functional proximity to develop an approach to understanding spatial effects on the dynamics and outcomes of collaboration by appeal to overlapping motion paths. Where every other paper reviewed thus far measures proximity and distance by appeal to more or less nuanced calculations of the point to point distance between spaces (e.g. pairs of faculty offices) or by the relative positions of individual spaces (e.g. the degree of spatial integration of individual faculty offices), recent work by Kabo and colleagues (Kabo et al 2013a, 2013b) begins with the recognition that individuals move between multiple spaces in the course of their work days. These authors develop a new measure, which they dub 'zone overlap,' that they hypothesize will index the likelihood a pair of investigators in to interdisciplinary life science buildings will have unscheduled encounters in the course of their daily work.

This approach begins by defining the 'functional zone' of individual faculty. In this case Kabo and colleagues identify key workspaces (offices and labs), shared facilities (bathrooms) and methods of ingress and egress (elevators and stairs). For each faculty member the shortest walking path linking these spaces defines their 'zone' in the building. The functional proximity between pairs of faculty is then conceptualized in terms of the extent to which their individual zones overlap measured in terms of linear feet of shared pathway among these spaces. One published paper (Kabo et al 2013a) documents methods for calculating these measures and demonstrates that increasing the degree of overlap between faculty zones is strongly associated with more intense collaborations in models that also take walking distance, departmental affiliation, and academic rank into account.

A second working paper (Kabo et al 2013b) demonstrates that increasing overlap between a pair of scientists is positively associated with the likelihood that they will form a new collaboration. Conditional on the formation of a collaboration, increasing zone overlap is also associated with receipt of a new external grant within a three year window. In both papers, the authors draw evidence of collaboration from administrative data. Collaboration formation and intensity are measured by observing joint filings of human subjects or animal use applications and joint submission of grant proposals. Funded proposals represent a first indication of collaborative success. In other words a new measure that pays attention to how individuals habitually occupy and move through their spaces appears to have interesting possibilities for understanding both the formation and the success of interdisciplinary collaborations.

The five papers reviewed here appear to me to represent the state of the art for studies of the relationship between the design of physical space and the dynamics and outcomes of scientific work. While they present interesting findings, none of these papers is without major flaws. In particular, problems with establishing causality, relatively short time periods of observation, over-reliance on self-reported data, a lack of commonly shared measures, difficulties with naturalistic observation of the social interactions that are the wellspring of collaborations, and a systematic lack of attention to the productivity and impact of scientific collaborations suggest the need for extensive additional research. We remain quite a long distance from a systematic and rigorous science of design for collaboration and discovery. However, these and other works suggest important next steps.

Conclusions and Future Directions.

All five of the pieces reviewed in the preceding sections are distinguished by their efforts to combine insights from social network analysis (SNA) with methods and discoveries derived from space syntax (SS) approaches to characterize physical spaces in relational, configurational, terms. My review of the literature suggests that this combination of approaches has the most potential for developing the kinds of rigorous, replicable findings that might support a spatially oriented science of team science. However much work needs to be done to fill in key lacunae. In what follows I briefly highlight four important directions for future work to develop socio-spatial network analysis (SSNA) of collaboration and discovery in team science.

(1) Naturalistic observation of interactions at scale.

A general review of the literature suggests that space exerts effects on collaboration and outcomes by altering patterns of informal (and particularly unscheduled) interactions and consultations among scientists. The field needs to more clearly establish the role of spatial design in fostering (a) unexpected interactions that spur new collaborations and serendipitous discoveries and (b) regular but unplanned interactions that may facilitate successful collaborations by allowing many opportunities for ongoing consultation and monitoring.

To date no systematic method for long term and large scale naturalistic observation of interactions has been used in this literature. Instead, authors typically rely on a mix of observation (Backhouse & Drew 1992) self report through activity logs and surveys (Toker & Gray 2008; Sailer & McCullough 2012) or archival data such as patterns of co-authorship derived from published papers (Wineman et al 2009) or research administration records (Kabo et al 2013a 2013b). While each of these methods has proven useful direct observation is labor intensive, necessarily limited in scale and relatively short term. Likewise surveys, activity logs and other self-reports of interaction are dependent on often intensive time commitments of participants and are thus subject to both issues with response rates and to cognitive biases in recognition of interactions (Smith et al 2011). While they are more systematic and can be used at scale, archival methods rely on traces of realized collaboration either in completed papers or in intermediate products such as IRB and grant applications. In both cases reliance on archival data seem likely to miss precisely the kinds of unscheduled and informal social interactions that theory, observational, and self report data suggest are the key to both the formation and functioning of collaborative knowledge work.

The most promising methods for overcoming these problems are just becoming available for research use. Sociometric badge and other methods for tracking motion and co-presence of individuals in buildings (Kim et al 2012; Pentland 2012) offer new possibilities for large scale analysis of informal social interactions in collaborative science. **Future research should mobilize these technologies in concert with spatial network techniques and archival data in order to more firmly establish the links between design features, interaction, and outcomes in team science.**

(2) Socio-Cultural and cognitive dimensions of collaboration

Another key theme in the literature I review is the complicated relationship between spatial features of workplaces and the activities of their occupants. Consider, for instance, the very mixed findings about the role that long corridors play in sustaining interaction that I review above. The general finding that more 'integrating' and thus easily accessible spaces are the location of more intense interaction holds across many studies. However, a particular design feature, long integrating corridors, is sometimes associated with greater interaction and sometimes is not. The differences, my review suggests have as much to do with local 'interactional cultures' (Rashid et al 2009) and with the often non-verbal signals scientists and others send to recruit potential conversational partners to interaction or to indicate that they are not open for such communication (Backhouse & Drew 1991). **Understanding the relationship between specific design features and interactions thus seems to me to require more detailed qualitative analyses that attend: (1) to the meanings participants ascribe to different parts of their workplaces; and (2) to the organizational, disciplinary, and even national cultural differences in styles and likelihoods of interaction.**

Another interesting and related finding suggests that the relatively simplicity of paths that traverse long corridors makes longer distances less salient for participants while more complicated spaces (such as crowded open floor plans) where distances are much shorter are perceived to be more challenging (Sailer & McCullough 2012). These findings build on a small but very interesting literature that uses experimental techniques to identify how individuals navigate complicated structures (e.g. Gollege 1995; Conroy Dalton 2003). This 'way finding' literature has much to offer and **future research to establish how cognitive and perceptual dimensions shape the relationship between space, movement and interaction should be another important component of any rigorous socio-spatial science of collaborative discovery.**

(3) Discovery and outcomes.

The literatures I review imply (though no published work I can find systematically demonstrates) that features of space influence scientific discovery in collaborative settings largely by shaping the likelihood and costs of planned and unplanned face-to-face encounters that enable information sharing and consultation. The first link of the implied mediation model (connecting design features of workplaces to observable interactions) has largely been studied in isolation from the second (connecting changes in interaction and consultation patterns to the productivity and impact of collaborative research). While social network analyses of various sorts offer potentially useful insight into the interaction-discovery relationship (Burt 2004; Obstfeld 2005; Powell & Grodal 2005) more systematic work should be done to track spatial effects on interaction and outcomes.

Relatively little work of this sort exists in the literatures I review. One recent piece published in Plos One (Lee et al 2010) uses data from the Harvard Medical School in descriptive analyses that suggest the citation impact of collaborative papers is increased when more members of the authorship team occupy the same building on campus. The effects appear particularly pronounced when both the first and last authors on papers work in the same building, but beyond offering another indication of the importance of co-location this work considers no specific design features.

Other work I review demonstrates some broad effects of spatial locations on individual rates of collaborative publication (Wineman et al 2009) on self reports of scientific productivity and satisfaction (Toker & Gray 2008) and on the likelihood of successful grant proposals (Kabo et al 2013). But much more work remains to be done. **Another important future line of research will follow research collaborations for a long enough period to both see how different combinations of spatial and social relationships are related to both the productivity and impact of collaborative science.**

(4) Establishing causality

Finally, I note that every study I review here presents either descriptive findings or inferential analyses that suffer from the lack of potentially important controls. While this research has yielded important insights, moving toward a scientifically validated basis for design decisions to support team science requires greater attention to establishing plausibly causal relationships. Because field experiments base on large scale randomized assignment of laboratory and office spaces seem likely to face logistical difficulties, **future research should take special care to take advantage of quasi experimental opportunities and econometric techniques commonly used to identify causal relationships in longitudinal data in order to establish relationships between particular features of scientific buildings and both the collaboration dynamics and outcomes of their occupants.**

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