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Creating Spaces that Understand People

Employing Sensor Technologies to Inform the Design and Operation of Human-centred Spaces

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Abstract

This report highlights the intersection between architectural design research, broadly defined to include the physical space elements of organisational and commercial premises design, and sensor-enabled human behaviour research. Drawing on a multidisciplinary review of scientific literature, the authors identify six groupings at this intersection, offering a fruitful landscape for future research. Specifically, we highlight the role that sensor-enabled human behaviour research can play in the creation of human-centred spaces, following the broadening, holistic nature of the contemporary Building Information Modelling (BIM) paradigm, to represent a data environment where human behaviour at individual and group levels is quantified and understood to inform the creation, design and operation of better physical spaces.

Introduction

Building information modelling (BIM) arose from the development of detailed computer models of the built environment, originally focused on design (e.g. CAD models), before eventually serving to denote comprehensive shared data environments incorporating all aspects of the design, construction and operation of physical assets. This includes the operation of organisations within the built environment, both commercial and social. An interesting feature of the BIM landscape is that incorporating data from human activity and interaction (i.e. the use of space) is an under investigated area.

Occupant Behaviour Modelling (OBM henceforth) (Yan et al., 2015; Feng et al., 2017; Hong et al., 2017; Chapman et al., 2018) offers a path forward, but as a field, tends to focus heavily on indoor environment factors such as temperature, lighting, air quality and noise levels with focal objectives such as managing these factors for comfort and energy management and sustainability considerations (Hoes et al., 2009; Dong and Lam, 2011; D'Oca et al., 2018; Landsman et al., 2018). Common methodological foci include predictive modelling and simulation (Kashif et al., 2013; Kim et al., 2018). Similar such objectives have also been pursued by researchers within the context of BIM (Habibi, 2017). Additionally, there is no shortage of research exploring the modelling of existing building interiors using different types of fixed and mobile sensors (Thrun et al., 2004; Xiong et al., 2013; Murali et al., 2017), meaning all the ingredients to develop comprehensive pictures of how citizens use the built environment exist in somewhat disconnected spheres of science across multiple scientific disciplines.

Contrasted with BIM and OBM perspectives, extant research across disciplines has extensively explored how different aspects of physical space shape human behaviour and vice versa. There is an increasing recognition of the merits of informing the design of space based on human behaviour (Sailer et al., 2007; Sailer at al., 2012; Koutsolampros et al., 2015) especially via the use of data-driven methods (Sailer et al., 2013; Sailer et al., 2015; Koutsolampros et al., 2017), as well as research considering the effect of office re-configurations on employees (McElroy and Morrow, 2010). Additionally, there is increasing interest in incorporating more data intensive techniques into management research (George et al., 2014; George et al., 2016; Pentland et al., 2017), including in the study of teamwork and team performance (Pentland, 2012).

Motivation and Objectives

A limiting factor of the adoption of BIM technologies for facilities management for example is the challenges surrounding information requirement specification (Cavka et al., 2017), possibly explaining the relative lack of research in applying BIM in this way (Pärn et al., 2017). This, along with the possibility of using BIM to foster human-centred design for the creation of physical spaces and the organisations that inhabit them motivates this report. Additionally, leveraging new digital data sources within the BIM sphere, including user-generated data, and data profiling the needs and behaviours of users is regarded as the next frontier for the field (NBS, 2017; CDBB, 2017).

More specifically, the aim of this report is to discuss the current state of research across discipline, to define best practice in extending thinking about BIM-based data environments to allow physical asset designers, operators, and end users to create spaces which are (a) more conducive to wellbeing, (b) that foster the goals of inhabiting organisations (in terms of both express goal and purpose, and contributing factors such as user harmony, communication and necessary form and function aspects for productivity), and (c) foster a climate of relevant soft-processes (e.g. creativity and innovation, employee engagement, customer-centricity).

This report is also motivated by interest in creating human-behaviour feedback within the physical environment, by proposing relatively non-invasive scientific approaches to studying how people use spaces. On the one hand, this opens doors for the development of contrived studies at different stages of the physical asset design-creation-operation process. On the other, many of the mentioned approaches offer possibilities for scalability and limited invasiveness for on-going deployment.

Types of Sensors

Common examples of sensors employed in wearable devices for the analysis of human behaviour include different proximity sensors (e.g. Bluetooth (see: Montanari et al., 2017b), Infrared (see: Montanari et al., 2018), different MEMS sensors such as accelerometers and microphones. RFID is also widely used (e.g. Barrat et al., 2010; Cattuto et al., 2010; Brown et al., 2014a; Brown et al., 2014b). The sociometric badges for example (Kim et al., 2012) combine accelerometers with front and back microphones and Bluetooth and infrared sensors. Lederman et al. (2018) introduce a similar device focused on vocal activity, location and proximity, also introducing hardware size and cost reductions (Lederman et al., 2017). Closely related work in indoor positioning employs approaches such as wi-fi tracking (e.g. Cooper et al., 2016; Jing et al., 2016), with work in this space extending to include more specific social aspects. For example, Sapiezynski et al. (2017) used inference based on wi-fi signals to examine social interactions. Other commonly deployed hardware focuses on different

pulse and heart activity measures (see: Kandasamy et al., 2014; Kandasamy et al., 2016; Mozos et al., 2017) and skin-conductance (e.g. Mozos et al., 2017) as measures of physiological arousal or stress. Other researchers have also made use of sensors in consumer wearables (e.g. Cadmus-Bertram et al., 2015; Diaz et al., 2015). Relatedly, researchers have also made use of smartphone apps, such as in the case of ecological momentary assessment studies tracking health behaviours (e.g. Spanakis et al., 2016). Along similar line Lathia et al. (2017) combined self-report smartphone application data with passively acquired accelerometer data to examine mental wellbeing and physical activity. Sandulescu et al. (2015) present a smartphone app for monitoring stress levels based on vocal features.

Outside of wearable technology, computer vision is also widely employed for tasks concerning the analysis of groups of people (e.g. Alahi et al., 2017) with similar commercial solutions for foot traffic monitoring also available. Marinescu et al. (2018) have also explored the use of facial thermography using thermographic cameras to detect physiological markers of cognitive load. Electroencephalogram (EEG) sensing hardware is also widely used to measure neuro-physiological responses (e.g. Banaei et al., 2017), but the usual form factor of such hardware (i.e. head caps) makes natural and relatively non-invasive deployments potentially more challenging.

Approach

This report presents the results of a systematic literature review across multiple scientific disciplines. We focus in particular on the areas where a clear intersection between a specific built environment theme, and a possible sensor-enabled research theme already exists in the literature. The literature review spanned multiple disciplines including computer science, human computer interaction, ubiquitous and pervasive computing, environmental psychology, ergonomics, architecture and design, construction, psychology, biology and life sciences, psychology and neuroscience, sociology, network science, management and organisational behaviour and marketing research. The review was focused on areas where a scientifically relevant intersection between architectural design research and sensor-enabled quantified human behaviour research could be identified. Next, we present a backdrop discussion, before discussing insights arising from the literature review.

Background

Clark (1987) marks the point of de-industrialization, where the declining primary and secondary industry sectors meet the ever-growing tertiary industry sector. From agriculture to manufacturing to services, each of these three entailed different workplace environments and collaboration patterns. The inception of modern work environments occurred at a similar historical moment and culminated with Robert Propst's concept of "Action Office" (Long, 2004), the precursor of the cubicle office furniture system mid-20th century.

The modern work environment is meant to support the performance and satisfaction of its occupants in performing at minimum cost. Improving the bottom line by manipulating the spatial arrangement (also known as workplace strategy) can be achieved by using the available space effectively. The efficiency spectrum spans from private (or cellular) offices, through open plan offices (Long, 2004), to activity-based workplaces (Duffy et al., 2004), to flexible working (Owen, 1977), to desk-sharing (or "hot-desking") (Dubey, 2009). While from a business perspective the cost-efficient functionality is a perquisite that tilts the scale towards open-plan offices, from an occupant (i.e., employee) perspective literature and practice call for identifying the optimal balance between open- and closed-plan spaces (Elsbach and Pratt, 2007). The ubiquitous "cubical jungle" was and still is widely adopted as it is expected to enable interaction and communication between co-workers, thus enhancing workplace satisfaction and team-work effectiveness; in practice, the cost-efficient workplace strategy backfired as employees are signalling decreased job satisfaction, concentration and performance, mostly due to growing distractions (Kim and De Dear, 2013).

From a wellbeing and overall workplace satisfaction perspective, the overwhelmingly most unsatisfactory dimension of the open-plan office formats is 'sound privacy' followed by temperature', 'noise level', and 'visual privacy' (Kim and De Dear, 2013; de Croon et al., 2005; Ferguson, 1983; Kaarlela-Tuomaala et al., 2009; Yildirim et al., 2007). These factors have been shown to decrease performance (Hongisto et al., 2008) and increase stress (Vischer, 2007a; Vischer, 2007b). As the trend towards flex-spaces and hot-desks increases so does desk ownership that, in turn, affects employees' health due to the lack of inability to adjust workspaces (leading to headaches, neck and back pain, etc.) and unhygienic shared desks (Kim et al., 2016). As empirical research seems to have reached the conclusion that over-optimizing work-floor spaces and their associated costs (Vischer, 2007a) has long-term detrimental effects on employee's health and performance, we need to reconsider the concept of "effective work spaces".

Literature in workspace design shows evidence to support both the fact that removing physical barriers is conducive to increased casual interactions and, in equal amount, that open spaces

decrease privacy and do not encourage informal interactions, on the contrary (Fayard and Weeks, 2011). “Not functioning as intended” open spaces can be explained by affordance theory that explains how the actual design of an entity might affect the ways it is used. In light if this theory, designers might overlook the way people perceive the affordances of objects and workspaces and their value-in-use (Fayard and Weeks, 2011).

So where is the “goldilocks zone” of collaboration in the closed-open workspace continuum? Both social anthropology and environmental psychology agree that human behaviour is a dependent on the individual and the environment.

The former discusses the matter at a macro (i.e., societal and geographical) level and at a micro (i.e., domestic) level, with little focus on meso (i.e.,organisational) level (Bubolz and Sontag, 2009). In this literature stream, space is relational; this means that it shouldn’t be conceptualized in and of itself in absolute terms and that it is a product of the relations between social phenomena. Spaces are created actively to accommodate human interactions and, in turn, the shape of said interactions affect social and power structures (Pader, 1993).

The latter, departing from its traditional and deterministic form, offers a new perspective wherein human behaviour is a function of the individual and the environment (Lewin, 1943). Thus, the interpretation of and interaction with said space are influenced by the individual experiences and expectations. Barker (1968) adds the concept of “pre-conceived social etiquette” to Lewin’s framework giving the environment an added layer of significance due to its intrinsic capability to enforce behavioural norms (e.g., public spaces such as libraries). In terms of territoriality and privacy, Hall’s (1963) Proxemic Framework offers a holistic taxonomy of distances (i.e., intimate, personal, social, and public) and their effects. The social distance, identified as optimal for work-related interactions (i.e., estimated to occur in the 1.2 to 2.1 m interval) is intruded by 1.1 to 1.4 m wide touching desks typical for open space designs. Beyond the previously mentioned audio-visual distractions, these layouts are doomed to be perceived as an intrusion of personal space and cause psychological discomfort (Oseland, 2009).

Spaces can bring people together and foster social interactions (i.e., sociofugal spaces) or, on the contrary, discourage them altogether (i.e., sociopetal spaces). These two concepts were introduced by Osmond (1957) who examined seating arrangements but the classification can be extended to circulation patterns and environmental settings. The seminal Yerkes-Dodson Law (Yerkes and Dodson, 1908) warns about the inverted U-shape relationship between an individual’s performance and their level of excitement or interest (i.e., arousal). The theory explains that a person’s performance is proportional to their motivation (that enhances their arousal level), but too many stimuli can lead to

stress and thus reduce performance. The caveat is that individuals have varying arousal levels (i.e., depending on introversion-extraversion, locus of control, age and gender) and their tasks have fluctuating complexity (i.e., demanding tasks require subdued environments and menial tasks require stimulating environments).

The individuals' motivations are deeply influenced by the nature of their work that drives the types of tasks they ought to tackle (i.e., analytical, creative, decision-making, coordination, administrative/ managerial, etc.) The general trend in work environment is increasingly tipping towards knowledge-based (Becker, 2007) which is complex in nature, highly dependent on social skills, technological acumen, occurs under time pressure (Kampschroer et al., 2007). Management research is increasingly focused on the creation of engaged and resilient communities through workplace design as part of organisational culture (Chan et al., 2007; Brown and Duguid, 2000). One of the fundamental challenges of this approach is identifying the suitable assessment methods for the performance of workplace designs (Chan et al., 2007). A seminal integrative framework considers the three constituent levels of performance namely Individual Task Performance (ITP), Collective Teamwork (CTW), and Organizational Effectiveness (OE) while considering the effects of the environmental comfort (composed by physical comfort, functional comfort, and psychological comfort) (Vischer, 2007a).

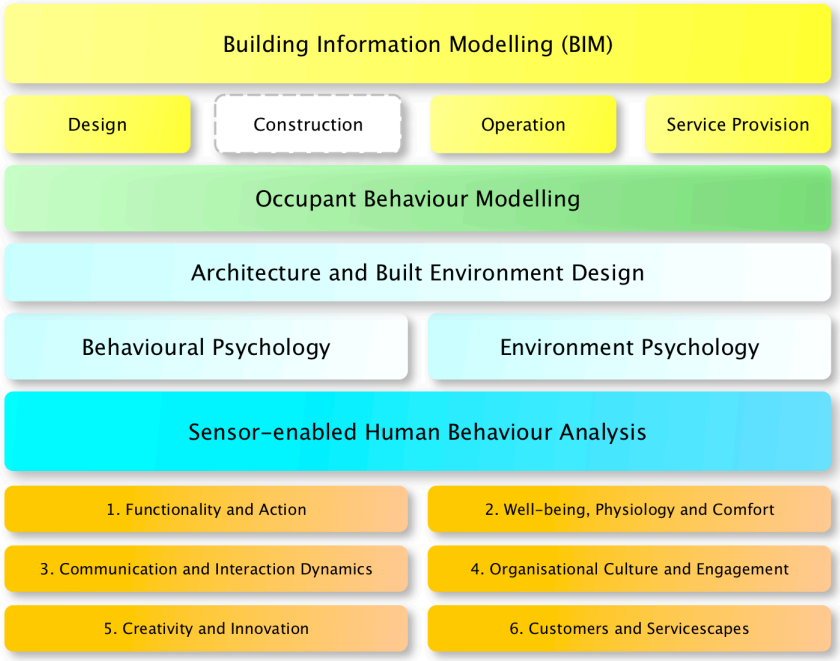
The individual / team tandem is crucial for innovation especially when considering the social-physical axis. This particular type of knowledge-workers has the arduous task of joggling both routine (performance) tasks as well as non-routine (innovative) tasks intermittently. Recent managerial literature advocates for open and interaction-conducive spaces for creative industries (Ratti, 2016; Waber et al., 2014), but fall short to identify the downside and stress levels of their employees. Fayard and Weeks (2011) offer an alternative approach considering both physical and social aspects: proximity, privacy, and permission. First, physical proximity as well as "functional centrality" (meaning closeness to functional areas such as the water cooler, hallways, photocopiers, entrances, etc.) lead to increased informal interactions. Thus, the geography of social interactions is contextual and dependent on its physical layout. Second, genuine privacy allows individuals to control the level of intrusion other have to be able to avoid interaction if so needed and this in turn leads to flourishing informal interactions. Third, returning to the concept of spaces and social norms (Barker, 1968), not all spaces have clear and universal norms such as public libraries; permission reflects the interplay of company culture (e.g., conversations as part of the creative process), physical space (e.g., designated spaces for informal interactions), and artefacts (e.g., photocopiers). Fayard and Weeks (2011) also offer suggestions drawn from practice and field studies on how to put these three principles into practice. The delicate equilibrium between the three can easily backfire if one of them is over- or under-emphasized.

The lessons learned in previous paragraphs on the modern work environment could be extended from interactions within companies to interactions between companies and their customers especially in terms of the work of front-line employees (Brady and Cronin, 2001). Improving the bottom line by manipulating the spatial arrangement applies to the design of servicescapes conducive to extending the customer journey and improving service perceived satisfaction (Noone et al., 2009). The quality of the experience is also influenced by similar dimensions of interior design such as audio-visual stimuli (Orth and Wirtz, 2014; Mattila and Wirtz, 2001) and temperature (Hadi et al., 2012). Depending on the type of service, proxemics literature could guide the design of servicescapes by considering the type of spatial arrangements and social interactions are conducive to higher perceived service quality (Hall, 1963; Osmond, 1957) and the pre-conceived social etiquette associated with the type of service or with the service provider (Barker,1968).

Insights

The review revealed six distinct groupings of academic literature where future research can advance the understanding of the use of physical spaces by humans using sensor technologies. These are (1) *Functionality and Action*; concerning the functional aspects of workplaces, (2) *Wellbeing, Physiology and Comfort*; concerning the study of characteristics of spaces most conducive to occupant wellbeing and how to create spaces that elicit certain positive physiological responses, (3) *Communication and Interaction Dynamics*; which concerns the design of spaces most conducive toward quality interaction among occupants, and the ways in which human dynamics can be conceptualised and studied in physical space, (4) *Organisational Culture and Engagement*; concerning the means by which physical space can foster focused organisational cultures and encourage employee engagement, and the ways in which this can be quantified, (5) *Creativity and Innovation*; a branch of both the architectural design and quantified human behaviour literatures concerning the creation of spaces that foster a forward-thinking and creative workplace environment and employee mind-set, and (6) *Customers and Servicescapes*; concerning the design of effective commercial spaces and means for quantifying success in this setting. These groupings are discussed next.

Figure 1: Focal Areas and Insights Arising from the Literature Review



1. Functionality and Action

Functionality and action concerns the functional design and layout of workspaces and encompasses both physical elements and their conduciveness toward certain work and job role defined actions. This also broadly encompasses the way in which people using workspaces behave. Seminal work in this area was conducted in the context of seating arrangements (Mehrabian and Diamond, 1971; Patterson et al., 1979), with more recent research has also investigating furniture and related items which fill the physical space and define functionality, and by extension, a great deal of workspace behaviour (e.g. Ju et al., 2007; Grønbæk et al., 2017). Recently and relatedly, Munday et al. (2017) also explored the impact of computer-facing time on the clinical work of medical staff.

Activity-based workspaces have also been extensively explored (e.g. Gerdenitsch et al., 2017; Wohlers et al., 2017; Wohlers and Hertel, 2017; Hoendervanger et al., 2018; Rolfö et al., 2018), including through the use of wearable sensors to examine tie strength and team dynamics in such settings (Montanari et al, 2017a). Such environments involve the allocation of space to employees based on activities or tasks, rather than designating particular desks (Montanari et al., 2017a), in some ways an extension of earlier work on traditional office formats versus open office formats (Oldham et al., 1979; Brennan et al., 2002). Along similar lines, Hartog et al. (2018) examined the role of personality in shaping satisfaction with multi-tenant shared workspaces; a particularly timely theme the

rise of shared working spaces in the context of start-up incubation spaces and early-stage co-working environments.

2. Wellbeing, Physiology and Comfort

Wellbeing, Physiology and Comfort concerns the study of characteristics of spaces most conducive to occupant wellbeing and how designers can go about creating spaces that elicit certain positive physiological responses. A number of applications of wearable technology have focused explicitly on industrial safety (see for example: Sandulescu and Dobrescu, 2015, and examples in: Francu et al., 2017). This research also relates somewhat closely to extant research on the use of devices for tracking different medical emergencies, for example, in the context of fall detection using MEMS sensor tools (e.g. de la Concepción et al., 2017).

However, here we refer more to the general sense of wellbeing people experience in workspaces, and particularly with reference to workspaces with relatively limited safety risk factors. This includes general happiness and wellbeing in the workplace, encompassing job satisfaction. This builds upon Building-in-use assessment research, which has considered workplace psychology factors; linking space and productivity including factors such as psychological comfort and functional comfort (e.g. Vischer, 2018). Of note however, Potter et al. (2015) investigated contact networks in organisations with a focus on the transmission of illness, an important consideration for densely occupied workspaces. A number of studies have also explored how to reduce sedentary office behaviours such as excessive sitting time. (e.g. Evans et al., 2012; Torbeyns et al., 2014; Healy et al., 2017).

Perhaps a defining piece of research within this grouping; Danielsson and Bodin (2008) compared different office types (in terms of functionality and architectural features) to establish what features shape employee wellbeing and job satisfaction. There also exists seminal work on the importance privacy in office environments (Sundstrom et al., 1982) a topic that has been extensively revisited in more recent times (Lee, 2010; Kim and de Dear, 2013). Similarly, Kim et al., (2016) examined how reduced territorial atmosphere in the workplace can improve satisfaction, productivity and wellbeing.

In this context, ambient conditions have also been extensively explored. For example, Yadav et al. (2017) examined multi-talker acoustic intensity and auditory distractions within open-plan offices, and Banbury and Berry (2005) examined ambient noise and its effect on employee concentration, while Kim et al. (2018) explored individual heating preferences for climate-controlled chairs in an office environment. Relatedly, Mills et al. (2007) examined the effect of colour induced by lighting on employee performance and wellbeing, broken down into factors such as concentration and fatigue.

Another important aspect of workplace wellbeing is workload. This broad topic has been investigated widely in the context of health, covering topics such as job efficiency, multitasking and out-of-hours workload (Milne et al., 2016; Perez et al., 2016; Simpson et al., 2017), with Sharples et al. (2015) exploring the deployment of ubiquitous sensor technologies for related purposes. Related to workplace efficiency, Hughes et al. (2015) studied navigation within large hospital environments highlighting the importance of fluid navigation for employee wellbeing and patient safety.

In terms of studying physiological responses to the built environment, Banaei et al. (2017) took a nero-architecture perspective and on studying how different interior formats elicit different neuro-physiological responses using EEG devices. Uniquely, Mozos et al. (2017) combined analysis with sociometric badges and other wearable sensors combining electrodermal activity and hear rate measures to gauge stress induced in social situations, a study which although does not refer to the physical environment specifically, does capture social dynamics, an important aspect of designing spaces (discussed next).

3. Communication and Interaction Dynamics

Communication and interaction dynamics concerns the design of spaces most conducive toward quality interaction among occupants, and the ways in which human dynamics can be conceptualised and studied in physical space. Research employing wearable sensors has for example explored social network structures, and face-to-face interaction patterns (e.g. Isella et al., 2011; Barrat et al., 2013; Smieszek et al., 2016) including analysis using wearable sociometric devices (Onnela et al., 2014), including comparing online and offline (with RFID measurement devices) contact networks (e.g. Barrat et al., 2010). This domain centres greatly on non-verbal behaviours (e.g. Bonaccio et al., 2016), with scope to be extended to include verbal behaviours (e.g. following recent work by Ponsot et al., 2018). This includes both speech characteristics (e.g. the tone of speech as measured by pitch and volume) as well as the transmission of actual content. For instance, Panisson et al. (2012) for example deployed wearable proximity sensors to examine the spread of messages in social gatherings.

A major aspect of research into creative environments concerns chance interactions between individuals. For example, Brown et al. (2014a) examined serendipitous interactions in office environments, recognised as especially important for creativity and innovation outcomes (discussed separately). The authors did so with a deployment of wearable RFID tags.

On the subject of workplace layout and innovation, other researchers have considered the role of laboratory and office layouts on communication in the context of research-intensive organisations (Allen and Fustfeld, 1975; Boutellier et al., 2008).

4. Organisational Culture and Engagement

Organisational Culture and Engagement encompasses organisational culture and employee engagement as shaped and reinforced by the built environment. Zerella et al. (2017) examined the effect of office layout on organisational culture, as perceived by employees, as well as their attitudes toward their job roles. The authors particularly emphasised aspects such as architecturally determined privacy, social proximity and equality of individually allocated facilities between employees. Relatedly, Hongisto et al. (2016) examined the effect of refurbishing open-plan offices on employee satisfaction with the resulting upgraded environment and job satisfaction. Morrow et al. (2012) worked towards understanding how organisational commitment can be influenced via office redesign, with an emphasis on soft processes, such as design features that encourage and enforce innovation, collaboration and appropriate levels of formality. Along similar lines, Sailer (2014) examined how organisational learning is shaped by physical space, with a particular emphasis on interaction patterns. Within this area, flexible work arrangements (e.g. flexible time and work location) have also been explored, encompassing among other factors, workplace format (e.g. Gerards et al., 2018).

5. Creativity and Innovation

Creativity and Innovation concerns branches of both the architectural design and quantified human behaviour literatures concerning the creation of spaces that foster creative workplace environments and employee mind-set and outcomes, both individual and at group levels. Generally, the environmental psychology of the workplace is recognised as being shaped by ambient conditions, layouts and furnishings as well as process and functionality considerations (Vischer, 2008). Recently, such research has emphasised flexibility and spaces that encourage human interaction, with particular focus on not only workplace productivity, but also on creating workplaces conducive to creativity and innovation (Ratti, 2016; Waber et al., 2014). This builds on the general push in the management literature toward understanding which organizational and human resource management approaches are most conducive to innovation (Haneda and Ito, 2018), with behavioural perspectives encompassing individuals, including team leaders (Keller, 2017) as well as social network perspectives (Perry-Smith and Mannucci, 2017). Recent work by Alexandersson and Kalonaityte (2018) also highlights for example the concept of ‘playful’ office design. This focus has also encompassed sub-elements of the built environment, with Schmitt et al. (2012) conducted research on digital table-top interfaces to aid creative brainstorming.

On the one hand, an examination of creativity in the workplace involves abstract processes and mechanisms, such as divergent-convergent thinking (Berg, 2016) and employee engagement (Minor et al., 2017). On the other, state-of-the art management research recognises, despite the rise of digital

communication and collaboration technologies, the increasing importance of the physical world (Waber et al., 2014; Ratti, 2016) and on understanding the invisible, but important markers of human behaviour and interaction, including non-verbal behaviours (Bonaccio et al., 2016).

In terms of physical space design studies, Sailer (2011) discusses the inextricable link between creativity and social and spatial factors. Similarly, Kallio et al. (2015) explore how the design of physical space can create an environment that fosters creative organisational culture. Thoring et al. (2018) recently focused on the design of physical spaces to support creative learning and working spaces for design professionals. Loosely related, Muldner and Burleson (2015) employed different wearable devices to examine student creativity in digital environments.

In terms of sensor-focused research, Brown et al. (2014b) employed wearable RFID tags to study social interactions in different workplace formats with an emphasis on innovation, revisiting the early sociological work of Granovetter (Granovetter 1973; Granovetter 1977; Granovetter, 1983) emphasising the importance of 'weak ties'.

6. Customers and Servicescapes

Customers and Servicescapes concerns the design of effective commercial spaces and means for quantifying positive responses from customers in this context. Marketing researchers have for example examined foot-traffic data in the form of path analysis using technologies such as RFID tags on shopping trolleys in retail settings (Larson et al., 2005; Hui et al., 2009a; Hui et al., 2009b; Seiler and Pinna, 2017), which has implications for customer navigation and assortment planning. Psathiti and Sailer (2017) customer seat preference in a hospitality setting, while Nguyen et al. (2015) used bluetooth data to customer behaviour in a hospitality setting. Importantly, social interaction aspects of servicescapes, such as pace of the service (Noone et al., 2009) and the role of interactions with staff (Brady and Cronin, 2001) have also been investigated. Researchers have examined customer responses to various 'servicescape' characteristics, including interior design (Orth and Wirtz, 2014) as well as olfactory and auditory factors (Mattila and Wirtz, 2001), and the role of temperature as a source of haptic sensory information being highlighted by Hadi et al. (2012). Across these examples (individual activity, social interaction in service environments and consumer response to design elements), there exist many opportunities for research directions enhanced with sensor-based research. This is however an under-explored domain.

Conclusion

In this report, we particularly sought to emphasise the intersection of architectural design research (and related fields) and sensor-enabled human behaviour and interaction research. We hope the identified groupings and potential research questions serve as a basis for future research in this area. Future research will develop around the deployment of sensor technologies to understand the use of physical space, and the way in which physical space shapes behaviour and vice versa, with a particular emphasis on shifting towards scaled deployments of such technologies, building on research based on contrived theory-development focused studies. Additionally, future research will further advance sensor-enabled human behaviour research in the BIM context, by studying the ways in which the data types articulated in this report can be formally, and more importantly, usefully, integrated into BIM data environments for the design, creation and operation of physical spaces.

Other future research directions include scaling further into pervasive computing, such as via social media platforms enabled by mobile smartphone devices (e.g. Daggitt et al., 2016; Lansley and Longley, 2016; D'Silva et al., 2017; Rajapaksha et al., 2017). Such technologies facilitate the sensing of human behaviour and dynamics at macro-levels, and have already been recognised as important sources of data for the use of the built environment (Rabari and Storper, 2014; Higham et al., 2017). Examples include the use of location-enabled social media tools, generating detailed maps of human activity, as well as platform users narrating their behaviours within their everyday lives, or major events, and as such, creating valuable layers of scaled participatory crowd-sourced data (Guo et al., 2016).

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