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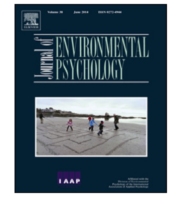

Tracking the human-building interaction: A longitudinal field study of occupant behavior in air-conditioned offices

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ABSTRACT

This paper presents findings from a one-year longitudinal case study of occupant thermal comfort and related behavioral adaptations in an air-conditioned office building. Long-term data were collected via online daily surveys and datalogger measurements of the local thermal environment and behavior. Behavioral outcomes are examined against both environmental and personal thermal comfort variables. Key personal variables include one's currently acceptable range of thermal sensations, which significantly explains inter-individual variations in thermal comfort responses. Results also show substantial between-day clothing adjustments and elevated metabolic rates upon office arrival, which may affect subsequent thermal comfort and behavior trajectories. Behavior sequencing appears complex, with multiple behaviors sometimes observed within a short time period and certain behaviors subject to contextual constraints. By elucidating the nature of the human-building interaction, the paper's findings may inform the improved measurement, modeling, and anticipation of occupant behavior as part of future sustainable building design and operation practices.

1. Introduction

Building occupants interact with their surrounding environments in deliberate and meaningful ways that contribute to both energy consumption and Indoor Environmental Quality (IEQ), and thus warrant significant attention in the building design and operation processes. For example, occupants' thermally adaptive behaviors (i.e., turning on fans/heaters, opening windows) are strongly tied to space heating and cooling loads, which make up 37% and 54% of total site energy consumed in commercial and residential buildings in the United States, respectively (U.S Department of Energy, 2011). These behaviors also modify key thermal comfort determinants like air temperature, air velocity and clothing insulation level (Baker & Standeven, 1997). Recent studies have begun to quantify the magnitude of occupant behavior's influence on energy use and comfort, reporting significant impacts that have intensified the focus on behavior as a key topic of built environment research (e.g. Bourgeois, Reinhart, & Macdonald, 2006; Hong & Lin, 2013).

If the general importance of the human-building interaction is well established, however, the mechanisms behind this interaction are still being explored. Increasingly, this effort has involved the collection of longitudinal data, which allow one to observe occupant comfort and adaptive behavior as they evolve together across the day and season.

Nevertheless, longitudinal studies are time-consuming and expensive to carry out, and existing comfort and behavior data are accordingly limited in their coverage of certain adaptive actions, building types and climates. In particular, few existing studies examine thermal behaviors in air-conditioned buildings, or in buildings in climates with large seasonal variations. Moreover, existing studies do not generally examine action hierarchies across several possible thermal behaviors, and have not fully characterized the relationship between behavior and occupants' personal thermal preferences. Going forward, new longitudinal studies that address such shortcomings are needed to improve the understanding of interactions between building occupants and their interior environments.

This paper presents findings from a one-year longitudinal case study of occupant thermal comfort and several related behavioral adaptations in an air-conditioned office setting in Philadelphia, USA. Offices were chosen as the context for the research because of their significant contribution to energy use in the United States —

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representing the most prevalent type of floor space in the commercial sector, which is currently responsible for 19% of U.S. energy consumption (U.S Department of Energy, 2011). Moreover, multiple longitudinal studies of thermal comfort and behavior have been published for the office setting. The current case study builds a novel longitudinal protocol from the data collection and analysis approaches of these existing studies and from a theoretical framework in the psychology literature, which yields new types of survey response items and behavior data that contribute to a more comprehensive understanding of how and why office occupants interact with a common U.S. office context.

1.1. Theoretical basis

Like many recent studies of thermal comfort and behavior in offices, this paper approaches behavioral action through the general lens of Humphrey's adaptive principle, which states: "*If a change in the thermal environment occurs, such as to produce discomfort, people react in ways which tend to restore their comfort*" (Humphreys, 1997). However, while previous studies mostly focus on the environmental (external) determinants of discomfort and related behavior, the current study also seeks to explore personal (internal) determinants. Social psychologists have long suggested the need to include such internal variables in theories of behavioral action, particularly as part of research on pro-environmental behavior (Clarke, Kotchen, & Moore, 2003; Guagnano, Stern, & Dietz, 1995; Wilkie, 1990). Within this context, internal variables are broadly defined to include one's motivation, environmental knowledge, locus of control, and attitudes, amongst many other concepts.

Kolmuss and Agyeman (2002) highlight motivation as the strong internal stimulus around which behavior is organized, and hypothesize that primary motives (i.e., altruistic, social values) are superseded by more immediate motives related to one's needs (i.e., being comfortable). This hypothesis aligns well with the adaptive principle above, and is considered a good starting point for exploring the key drivers of office occupant behavior. To further frame the current study, we adopt a theoretical formulation of comfort-driven behavior based on perceptual control theory (PCT) (Powers, 1973). Under PCT, behavior is the by-product of a negative feedback loop in which an organism attempts to control the current perception of its environment around some reference level. In the context of this paper, PCT suggests thermal comfort and adaptive behavior may be understood as part of the interplay between one's thermal sensation (current perception) and reference range of acceptable sensations (reference perception). The latter is thus focused on as a personal variable of potentially large significance to observed behavior.

1.2. Existing longitudinal studies

Previous long-term field studies of thermal comfort and behavior in offices generally follow from the data collection and analysis approach of the European Smart Controls and Thermal Comfort (SCATs) project (see Humphreys, Nicol, & Raja, 2007; McCartney & Nicol, 2002). The SCATs project tracked thermal comfort, preference, and related behavioral adaptations (clothing, windows, doors, fans, and heating) from 1997 to 2000 in offices from twenty-five buildings located across Europe (nine air-conditioned; nine naturally ventilated; seven mixed-mode/other). The field monitoring combined longitudinal and cross-sectional field surveys with concurrent measurements of the local environment, establishing a set of environmental and personal variables that have been recorded in many subsequent field studies on comfort and behavior. Analysis of the SCATs data, together with similar data collected in the UK and Pakistan (see McCartney, Nicol, & Stevens, 1998; Nicol, Raja, Allaudin, & Jamy, 1999) also first introduced the concept of simulating occupant behavior stochastically using generalized linear models; here, the probability of a given behavior occurring is modeled on a zero to one scale in terms of relevant predictor variables such as indoor or outdoor temperature.

In the decade following the SCATs project, a number of similar longitudinal studies have been reported in the literature. Rijal et al. (2007), for example, used over one year of longitudinal survey data on comfort and building control use in the UK to develop a simulation algorithm for window opening behavior. The algorithm calculates the probability of a window opening once a $\pm$ 2K deadband[2] around comfort temperature has been breached, in terms of operative indoor and outdoor air temperatures. In the corresponding data analysis, the authors observed both seasonal and diurnal changes in the proportion of windows open, with the greatest observed proportions occurring in the afternoon in summer. The authors also suggest the consideration of "active" and "passive" window users, as previously suggested in Reinhart (2004) in the context of lighting.

Yun and Steemers (2008) conducted a field study in the summer of 2006 in UK private and shared private offices in naturally ventilated buildings. Indoor and outdoor temperatures were monitored along with window state and, for the first week of the study, occupancy (through observation). Data analysis showed significant correlations between window opening and indoor temperature, as well as time of day effects, where openings were far more frequent upon office arrival than during the day. Sub-models of window opening probability were developed for occupant arrival, intermediate, and departure periods, with indoor temperature and previous window state as predictor variables. In a subsequent paper (Yun, Tuohy, & Steemers, 2009), the authors incorporated "active," "medium," and "passive" window users into their modeling algorithm to represent inter-individual behavioral variation.

Herkel, Knapp, and Pfafferott (2008) monitored large and small window states alongside indoor/outdoor temperatures and occupancy in 21 naturally ventilated offices in Germany for 13 months. They observed strong seasonal changes in the percentage of open windows, with a consistently large percentage of windows open in the summer, sudden increases/decreases in the percentage of windows open in spring and fall, respectively, and a low percentage open in the winter. Outdoor temperature was more strongly correlated with window open percentage than indoor temperature in their study. Time of day was also found to be a significant factor, with most window openings and closings occurring upon arrival. The authors developed a series of quadratic functions to predict window opening probability for five segments of the day in terms of outdoor temperature.

Finally, Haldi and Robinson (2008) conducted a longitudinal study in eight Swiss office buildings across the summer of 2006. Several occupant adaptations were surveyed multiple times per day alongside indoor and outdoor temperature recordings. Logistic regression revealed that the probability of occupants interacting with personal and environmental characteristics is better described by internal than external temperature, with the exception of clothing adjustment, which is more strongly related to day-to-day changes in outdoor conditions. A later paper by the authors (Haldi & Robinson, 2009) examined longitudinal data on window

[2] Here, "deadband" signifies a temperature range in which no system action (behavior) is required (i.e., the space temperature is within occupants' collective "cool" or "warm" temperature limits).