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ENB-6518; No. of Pages 13

ARTICLE IN PRESS

Energy and Buildings xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

The effect of real-time context-aware feedback on occupants' heating behaviour and thermal adaptation

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ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form 8 March 2016
Accepted 18 March 2016
Available online xxx

Keywords:
Real-time feedback
Occupant behaviour
Thermal comfort
Adaptive model

ABSTRACT

Studies have shown that building energy demand in identical dwellings could vary by a factor of three. Differences in occupant behaviour–i.e. purchase, operation and maintenance–have been implicated as a strong source of these differences. The literature suggests that feedback on energy use to building occupants–particularly real-time feedback–can be used to prompt lower operation-related energy behaviours. This is particularly true for thermal demand which, in cold countries, accounts for four times as much energy use as non-thermal demand. However, there is little evidence to support this claim. Further, there are concerns that the actions that allow occupants to lower heating energy use could negatively impact comfort and health by lowering indoor temperatures or air quality below acceptable thresholds. We report results from a winter field study that used in-depth energy, environmental and motion sensing to generate real-time context-aware feedback through a smartphone application. Subjective data and clothing levels were concurrently collected through questionnaires. Our results suggest that real-time feedback could lower radiator and room temperatures without significantly affecting occupant thermal comfort or health. The results also show that real time feedback could contribute to an increase in occupant perceived environmental control while prompting lower heating energy behaviours.

1. Introduction

The domestic sector accounts for approximately 24% of the world's energy consumption [1]. In cold climates, 32% of this consumption, on average, is due to space and water heating [1]. However, in highly industrialized countries, heating energy use represents a far higher proportion of the domestic energy demand, *e.g.* 57% in the UK [2].

Building space heating energy consumption depends on several physical factors:

- Geographical factors i.e. the specific local climate and location (rural, suburban or urban);
- Building characteristics i.e. the building type, the building thermal properties (which depend on infiltration, insulation, orientation, glazing, etc.) and the floor area;
- Efficiency of the space heating system used(gas central heating, district heating, etc.).

Non-physical factors such as economic and social factors also have a strong role to play but, since they are more difficult to quantify, little is known about the magnitude of their effects which are often neglected when estimates of building performances are made. The energy behaviour of building users[1] represents the expression of these non-physical factors which act as underlying drivers and antecedents of occupant actions.

Recent research has highlighted the potential impact on heating energy use arising from differences in occupant behaviour [3–6]. For example, occupant characteristics and behaviour have been shown to be responsible for 4.2% of the variation in space and water heating energy consumption in the Dutch residential stock

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[1] In this study, we define energy behaviours as those conscious or unconscious actions taken by occupants that result in energy consumption in the building. See Section 2 for examples under behavioural adaptation.

http://dx.doi.org/10.1016/j.enbuild.2016.03.045
0378-7788/

Please cite this article in press as: M. Vellei, et al., The effect of real-time context-aware feedback on occupants' heating behaviour and thermal adaptation, Energy Buildings (2016), http://dx.doi.org/10.1016/j.enbuild.2016.03.045

[7]. Similarly, in the emerging domain of domestic energy literacy[2] research, several studies have examined the impact of increasing literacy on electricity-related behaviours [8–11]. However, few studies have investigated its effect on the arguably more important topic of heating energy consumption [12]. Further, whilst some studies have begun to focus on the impact of information dissemination on occupants' heating energy use [13–15], to our knowledge, no studies have investigated the effect of real-time context-aware feedback on occupant heating behaviour, specifically thermal adaptation and comfort. Understanding the links between feedback, behaviour and subjective comfort is important if we are to effectively influence energy-saving behaviour since perceived reductions in comfort are a major impediment to end-users accepting feedback and advice [16]. This paper sets out to address this important gap by investigating the effect of *real-time* and *context-aware* feedback on occupants' adaptive actions, thermal comfort and perceived environmental control in the context of their heating energy use.

In a recent critical review on the efficacy of feedback, Buchanan has outlined the importance of the "human factor" when designing effective feedback strategies [16]. According to Buchanan [16], feedback must be designed with a user-centred approach in order to "enable users to readily understand the habits and routines that generate their household energy patterns and thus make more concrete the viable energy saving actions available to them". Following the indications of Buchanan, we adopted *real-time* feedback since many studies in the domain of electricity use have shown that immediacy increases salience and user engagement, and also provides the potential for greater energy savings [17–19]. Furthermore, *context-awareness* was also considered necessary because, in order to show "available and viable energy saving actions", feedback must respond to the context in which the energy behaviour has occurred [16,17].

2. The dynamic model of thermal adaptation

The *building indoor climate* (*e.g.* humidity, dry-bulb temperature, radiant temperature, air speed) and occupant *personal physiological factors* (*e.g.* age, gender, health situation, clothing, activity level) affect occupant thermal situation producing different *environmental stimuli* (Fig. 1). If we imagine two occupants ideally exposed to the same *environmental stimuli*, their thermal perception is not the same but depends on their subjective *thermal expectations and preferences* (Fig. 1). In fact, according to the adaptive model of thermal comfort [20,21], thermal comfort is not merely the result of a body's thermal balance but is the outcome of a continuous process of adaptation involving three types of self-regulatory actions: physiological, psychological and behavioural.

Physiological adaptation is any physiological alteration which happens in response to ambient thermal changes [22]. According to Brager and De dear [20], for the conditions and the activities typically encountered in residential and office buildings the slow process of physiological acclimatization has only a minimal influence on the thermal experience and, therefore, only psychological and behavioural adaptation affect occupants' thermal acceptability.

Psychological adaptation includes any psychological reaction to sensory information (*e.g.* habituation, relaxation of thermal expectations, gradual change of preferences, etc.) [23]. Many recent studies [24–27] have tried to identify and quantify the role of *cognitive and psychological factors* in the process of psychological adaptation (Fig. 1); those factors include:

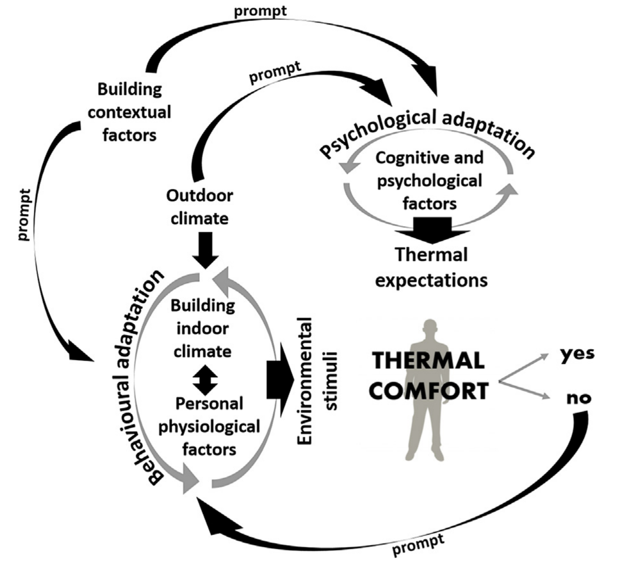

Fig. 1. The dynamic model of thermal adaptation.

- perceived environmental control,
- personal beliefs and cultural values,
- past thermal experiences,
- habits,
- perceived rewards and benefits:
  - in terms of comfort/health
  - monetary

In particular, the literature highlights that occupants' perceived ability of environmental control is a key psychological variable in defining occupants' thermal expectations [21,28–31]. High perceived levels of control have been found to positively influence both thermal satisfaction [28,32,33] and productivity [34]. Occupants' perceived control depends on *building contextual factors* i.e. on the availability, accessibility and transparency of means for exerting adaptive opportunities in buildings (*e.g.* the presence of openable windows). Since people in homes have more possibilities for thermal adaptation and have higher levels of perceived control, they are generally more satisfied with their environment than in their offices [35]. Several studies have also demonstrated that open plan offices are the environments with the lowest acceptance among their occupants [35]. This is due to the limited adaptive opportunities available as well as to the low perceived levels of environmental control.

Behavioural adaptation refers to all the conscious or unconscious actions that, when the *environmental stimuli* are perceived as discomforting, a person can take in order to modify the building indoor environment, their personal situation or both of these (Fig. 1). This is in agreement with the fundamental precept of the "adaptive model": "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" [36]. Of the three forms of adaptive opportunities, this is the one in which the occupants have the opportunity to play an active role. Adjustments are both personal[3] and environmental and their availability,

[2] "Energy literacy" in this context may be defined as occupants' awareness of the impact of their individual behaviours on building energy use.

[3] Personal adjustments include: (a) putting on/taking off clothing,(b) changing activity level (e.g. having a siesta in the hottest moment of the day, (c) taking a walk inside or outside, starting cooking), (d) changing posture of the human body (e.g. curling up/cuddling up), (e) moving to a different location (e.g. going to bed, visiting a friend),(f) taking in hot/cold food or drinks, (g)taking a hot bath/cold shower.4 Environmental adjustments include: (a) modifying shadings, (b) switching on the fan or the air-conditioner, (c) turning up the thermostat, lighting a fire, (d) open-