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Longitudinal assessment of the behavior-changing effect of app-based eco-feedback in residential buildings

Guofeng Ma [a], Jing Lin [b], Nan Li [b,*]

[a] Department of Construction Management and Real Estate, Tongji University, Shanghai 200092, China
[b] Department of Construction Management, Tsinghua University, Beijing 100084, China

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ABSTRACT

Eco-feedback as an approach to intervene in energy consumption behavior and encourage energy conservation has achieved considerable success in recent decades. Conclusions about the performance of eco-feedback systems in the literature were mostly drawn based on their short-term performance, during which eco-feedback information was continuously provided. This study, by gradually removing eco-feedback system functions in different phases of an experiment, examines the durability of the behavior-changing effect of eco-feedback under different conditions. The eco-feedback information is delivered using mobile app, which provides a higher level of accessibility than other eco-feedback technologies. A prototype app-based eco-feedback system was developed in this study, and used in an experiment that was carried out in student dormitories. The experiment lasted for fifty-three weeks, and it included four phases, during which the level of functionality of the eco-feedback system varied. The experiment results demonstrated the effectiveness of using mobile app for delivering eco-feedback information. Longitudinal analysis of the results found that the behavior-changing effect of eco-feedback changed over time. The effect was significantly positive in the short term, then became slightly positive in the medium term, and further faded to an insignificant level in the long term. Moreover, analysis of individual participants' energy consumption profiles revealed that their behavior changes were highly sensitive and responsive to whether and how eco-feedback information was delivered. This study advances the knowledge about app-based eco-feedback and its effect in reshaping the energy consumption behaviors of occupants in dormitory buildings over time. Future research can be done to further validate the generalizability of the findings to other types of residential buildings or eco-feedback systems using different technologies, so as to provide important implication and guidance for implementing eco-feedback in practice.

1. Introduction

Buildings accounted for 39.66% of total energy consumption in the U.S. in 2016 [1], making buildings a primary target for energy conservation. Eco-feedback is an emerging approach to addressing the global challenge of building energy conservation [2]. It provides building occupants with their energy consumption information that gradually reshapes their energy consumption behavior [3]. Prior research has reported that eco-feedback systems could save 5–15% of energy usages in residential buildings in general [4] and up to 55% in some cases [5]. These reported behavior changes and associated energy savings were mostly observed during periods when eco-feedback was continuously provided. In reality, however, the effectiveness of eco-feedback may be observed under three different circumstances, including when the eco-feedback system is fully functional and provides extensive behavior intervention (referred to as short term hereafter), when the system is partially functional and provides limited behavior intervention (referred to as medium term hereafter), and when the system completely stops functioning and provides no behavior intervention (referred to as long term hereafter). An understanding of the durability of the behavior-changing effect is important to guide the design of eco-feedback systems whose impact can last in the long term, and is essential for comprehensive cost-benefit analysis and investment decisions to adopt eco-feedback in practice. While studies in various fields have found that benefits from behavior intervention tends to decay in the long term or once intervention is completed [6–8], the durability of behavior changes in building energy consumption resulting from

* Corresponding author.
E-mail address: nanli@tsinghua.edu.cn (N. Li).

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eco-feedback has rarely been investigated in prior research. A few such investigations either were carried out at a coarse granularity, e.g. at the household level [9,10] or room level [9], making it difficult to assess individual behavior changes, or had limited observations and debatable conclusions due to lack of control group [10], or involved participants who were not responsible for paying energy bills [9]. Whether, and if so, to what extent would individual building occupants who are once exposed to eco-feedback continuously save energy in the long term has largely remained unknown, and requires further research. Moreover, the durability of eco-feedback was examined in prior studies by tracking its behavior-changing effect over a certain period of time, during which the eco-feedback system either remained fully functional [11], or shut down completely halfway [9]. It is unclear how durable the behavior-changing effect would be if the behavior intervention by eco-feedback gradually fades over time. The above questions are examined in this study.

Prior research has also reported that different eco-feedback technologies could lead to different behavior-changing effects [12]. Website, email, billing and in-home display are mainstream eco-feedback technologies that have demonstrated different behavior-changing effects [4,12]. Mobile app is an emerging eco-feedback technology that provides a promising alternative for delivering eco-feedback information. Mobile app technology, a preferred way for occupants to receive eco-feedback information [12], can provide similar content and representation to traditional information delivery methods with constrained screen space and resolution of mobile phones [13]. Nowadays, most people have constant and immediate access to mobile phones, and use them regularly for various services that different mobile apps provide. The ubiquity and user friendliness of app-based systems make them ideal for eco-feedback applications [13]. Furthermore, compared with traditional eco-feedback systems, an app-based system does not require users to install additional hardware, and is easier to modify and update [14]. A major factor that distinguishes mobile app-based eco-feedback system from those built on other technologies is its higher level of accessibility resulting from the ubiquitous computing capabilities. Accessibility, which refers to "the degree to which the system and the information it contains can be accessed with relatively low effort" [15], is an important attribute of information systems. Accessibility influences user engagement with a system [16], which in turn influences how well the system achieves its goal. How mobile app-based eco-feedback system performs, in terms of both its short-term behavior-changing effect and its long-term effect beyond system implementation, is another important question that remains to be investigated.

The study presented in this paper aims to address the above gaps. Specifically, the first objective of this study is to conduct an assessment of the effectiveness of app-based eco-feedback system in reshaping individual occupants' energy consumption behaviors in residential buildings. An app-based eco-feedback system was developed in this study and implemented in student dormitories. The effectiveness of the app-based eco-feedback system was analyzed in an experiment that lasted for fifty-three weeks. The second objective of this study is to longitudinally assess the effectiveness of app-based eco-feedback. The aforementioned experiment included a pre-experiment phase, and three experiment phases that corresponded to short, medium and long terms of eco-feedback application. The effectiveness of eco-feedback was compared between different terms to examine the time dependency and durability of behavior-changing effect of eco-feedback. The remainder of this paper is organized as follows: Section 2 reviews related research, followed by Section 3 that introduces the app-based eco-feedback system developed in this study. Section 4 explains the methodology in this study, and Section 5 presents results and findings. Section 6 concludes the paper.

2. Related research

2.1. Eco-feedback technologies and system accessibility

Eco-feedback is widely considered as an effective way to encourage energy conservation [17], which is achieved through improving awareness of habitual energy consumption behavior with behavior intervention [18]. Prior research studied various factors that could impact the effectiveness of eco-feedback. Examples of such factors include interface design [19], cultural background [3,20], social influence [21] and peer network position [22]. Technology used in building eco-feedback systems is another important factor, as the literature has shown that performance of eco-feedback systems built on different technologies varies significantly [12]. Traditionally, eco-feedback information is delivered to energy end users with bills and posters [4]. With the rapid development of Internet and computing technologies, an increasing number of eco-feedback systems are built on website interface, providing a new way to deliver eco-feedback information [13,23]. More recently, with the development of mobile data communication technologies and infrastructure, mobile app provides another promising alternative technology, featured by its ubiquitous computing capabilities and frequent usages in daily information inquiry [23], for developing eco-feedback systems [13]. Victor et al. reported that weekly email reminders contributed to the performance of the eco-feedback system [24]. A major difference between the mobile app-based systems and systems built with traditional approaches and technologies such as displays and websites is their accessibility. Accessibility is an important dimension of system quality. Prior research has reported that perceived accessibility of users would significantly impact users' acceptance of a system and information the system presents [25]. For eco-feedback systems, in particular, Bartram [13] argued that information accessibility was a major challenge in eco-feedback systems that should deserve further attention. Several other studies suggested that eco-feedback systems with higher physical and information accessibility tended to be more effective [4,17,26]. This is possible because eco-feedback system is an information system aiming at changing energy consumption behavior, which depends on attitude [27] and engagement [28] on which accessibility can be impactful [29,30].

2.2. Durability of the impact of eco-feedback

Durability of behavior change has been studied in various fields such as healthcare and social skill training [31–33]. Impacts of behavioral intervention are usually larger in the short term than in the long term [31]. For instance, the durability of behavior intervention on multiple health-related behaviors was studied with baseline, 3-month, and 12-month experiments in [34]. The results showed that some behavior changes, such as moderate exercise, sustained in the post study period (12 month), while other behavior changes, such as alcohol use, decayed in the long term. Similar results were found in a ten-year study, which observed noticeable long-term intervention effects in smoking consumption but none in alcohol consumption [35]. This result suggested that with the same way behavior intervention was conducted and the same characteristics of subjects, the durability of behavior change might differ depending on the nature of the behavior being changed. Pro-environmental behaviors including energy conservation behavior were studied in [36]. Results proved that energy consumption reductions caused by small-group intervention were lasting and that participants continued to make changes to their lifestyles after the intervention ended.

The durability, which is a critical criterion of success of behavior intervention [37], of eco-feedback-caused behavior change is a