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Assessing eco-feedback interface usage and design to drive energy efficiency in buildings

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ABSTRACT

In response to growing concerns over climate change and rising energy costs, a number of eco-feedback systems are being tested by researchers. Yet, the interface design aspect of these systems has largely been ignored. Therefore, the role that interface design plays at the component level in driving actual energy savings from users is unclear. In this paper, we evaluate the impact interface design has on eco-feedback performance by investigating five established design components. We conducted a six week empirical study with 43 participants using a prototype eco-feedback interface. Analysis of usage data affirmed a statistically significant inverse correlation between user engagement (measured as logins) and energy consumption. Utilizing this relationship as a basis for performance, we expanded our analysis to evaluate the five design components. The study revealed statistically significant evidence corroborating that *historical comparison* and *incentives* are design components that drive higher engagement and thus reductions in energy consumption. Results for the *normative comparison* and *disaggregation* components were inconclusive, while results for the *rewards* and *penalization* component suggest that a revision to the penalization aspect of the component may be necessary. This study raises pertinent questions regarding the efficacy of various eco-feedback components in eliciting energy savings.

1. Introduction

Advancements in sensor technology and computing have allowed for rapid access to a multitude of information about the infrastructure we utilize and occupy. Drivers can view real-time traffic conditions on their mobile device [1], utility companies can evaluate operational failures without leaving the office [2] and occupants can understand how they interact with the buildings they live in. In response to rising energy costs and the effects of climate change, citizens and governments are searching for innovative ways to increase energy efficiency. In most countries around the world, the built environment accounts for a substantial proportion of energy consumption. In the United States the built environment accounts for about 40% of all energy consumption [3] and consumes more energy than any other sector. To reduce building energy consumption, researchers have responded by integrating sensors and information systems to create eco-feedback systems. These eco-feedback systems provide building occupants with information regarding their consumption behavior with the goal of encouraging energy efficient behavior.

Eco-feedback systems operate on the premise that building occupants are largely unaware of how much energy they consume on a day-to-day basis [4], and once occupants become aware of their actual consumption, they will take steps to decrease energy consumption [5–9]. Researchers have concluded that behavioral interventions alone offer the potential to reduce household direct CO_2 emissions by 20% over the next 10 years [10]. Recent research has shown computerized consumption feedback to be the most effective delivery mechanism for an eco-feedback system [11]. Computerized systems require the development of a user interface that serves as a connection between building occupants and their usage data. While numerous factors can be attributed to the variability in savings associated with eco-feedback studies, the design of the user interface is a key factor to achieve a sustained impact on energy consumption behavior [12]. Therefore, a deeper understanding of the design components of eco-feedback interfaces is crucial to develop interfaces that achieve substantial and sustainable energy use reductions in the built environment. In this paper, we utilize one particular eco-feedback interface to examine how the various components of the interface contribute to user engagement and a reduction in overall consumption.

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2. Background

2.1. Eco-feedback system design

Early eco-feedback research relied on static physical interfaces [13,14] and transitioned to electronic displays [15] as personal computers came into use. More recent studies [6,16–20] relied on internet connectivity to deliver consumption information via web-based interfaces. An examination of past eco-feedback studies [6,13–17,19–27] revealed a lack of consistency between components of eco-feedback interfaces and observed savings. Observed savings ranged from 5% to 55% and system features ranged from simple feedback with graphic visualizations [16,19,27] to complex tools [6,12,26] that allow users to further understand their energy usage and conservation options. One residential eco-feedback study [22] was able to reduce energy consumption by 10% by providing users with historical consumption information while another residential study [17] observed savings up to 26% by providing both historical and normative consumption information to users. A third residential study [6] provided users with historical and detailed appliance-specific consumption information and yielded savings of 5.8%. These three studies illustrate the variability in observed savings and constituting interface components across eco-feedback studies. Some of this variability is likely due to idiosyncratic differences in the interfaces studied. However, given the range of components employed and the widely varying observed energy consumption reductions across studies, the question of if and how the components that make up an eco-feedback system drive energy savings from users deserves attention.

Several recent studies have begun to address the impact of eco-feedback system design. Wood and Newborough [28] concluded that optimal design of an eco-feedback system will facilitate the greatest amount of energy savings for the maximum amount of users. These conclusions were derived from literature in adjacent fields such as human computer interaction (HCI) and not examined using empirical results from eco-feedback systems. Eco-feedback empirical studies addressing design have been limited to qualitative user surveys [9,12,29] and focus groups [18,19]. Karjalainen [30] expanded on these qualitative studies by examining key features of prototype eco-feedback interfaces in interviews with users. This study provided insight regarding eco-feedback system user preferences, but the relationship between system components and the intended or actual performance of an eco-feedback system has not been empirically established. Therefore, research that establishes whether a relationship exists between eco-feedback design components and performance is needed.

2.2. Design components of eco-feedback

A study of user interfaces [30] introduced the following key design components into the eco-feedback literature: *historical comparison*, *normative comparison*, *incentives* and *disaggregation*. These four design components were augmented by the findings of Jaccuci et al. [12] to add an additional design component, *rewards* and *penalization*. In the following paragraphs, we explore each of these five design components in detail.

Historical comparison is defined as the ability of users to view their current consumption relative to past consumption. For example, an eco-feedback system with a *historical comparison* component could provide users with a graph that displays their energy consumption over the last 24 h, week or month. From observing these graphs and recalling their activities, users can begin to deduce the reasons for higher energy consumption and develop strategies to change their energy consumption patterns. In a review of eco-feedback studies, Darby [8] concluded that the most useful eco-feedback to be provided to users was *historical comparison*. This conclusion is further corroborated by the success of several eco-feedback interfaces that have incorporated *historical comparison* into their design [6,13–17,21–23,26,31]. A meta-analytical study of eco-feedback systems also revealed that *historical comparison* is a primary tool necessary to achieve energy savings [11]. In addition to Karjalainen, other interface studies [12,28] have introduced *historical comparison* as a key design component for eco-feedback interfaces. The *normative comparison* design component operates in conjunction with *historical comparison* by contextualizing both current and historical consumption in relation to a user's peers. By allowing users to compare their own consumption information with their peers, *normative comparison* has been shown to persuade users to modify their behavior to conform to social norms [11,32] and thereby reduce energy consumption. In other words, users have been shown to curb usage to match the consumption patterns of their peers. Several studies [17,23,33] that deployed eco-feedback systems with a *normative comparison* component have been observed to drive substantial energy savings from users. Other studies [28,30] have highlighted that *normative comparison* is a key component of eco-feedback interface design and researchers in the HCI community have also demonstrated the potential of *normative comparison* in motivating energy efficient behavior through competition and public perception [27,29].

The *rewards* and *penalization* design component provides users with the ability to earn rewards for saving energy and be penalized for wasting energy. Current literature advocates the use of *rewards* and *penalization* to encourage both conservation behavior and discourage wasteful behavior [12]. Additionally, a study in the field of psychology [34] concluded that the use of both positive and negative feedback can likely yield gains in human performance, which would translate into additional energy savings for eco-feedback interfaces. The importance of the *rewards* and *penalization* component is further supported by its use in real-time electricity pricing, in which users are rewarded for electricity use during off-peak hours and penalized for electricity use during peak hours [35]. The *rewards* and *penalization* design component addresses only those activities which result in rewards or penalties, so a separate design component, *incentives*, is necessary to address the types of awards users will receive for reducing consumption. The *incentives* design component can provide users with both financial and non-financial awards. For instance, if users accumulated points for saving energy through the *rewards* and *penalization* component, the *incentives* design component would enable them to redeem the points for a credit on their electricity bill (financial) or a new energy efficient lamp (non-financial). *Incentives* have been shown [20] to support sustained interaction and consumption reduction from users in long term studies. Wood and Newborough [28] also included *incentives* as a key design component of eco-feedback systems, but concluded that only financial *incentives* are effective at driving energy use reductions. Others have concluded that financial *incentives* do not provide sufficient motivation for users to become engaged and adopt energy conservation measures [10,36]. Successful eco-feedback interfaces have introduced non-financial *incentives* such as prizes [12,16] or game-like levels [37] as a means to motivate behavior change. These conflicting conclusions demonstrate the need for further research on the *incentives* design component.

The *disaggregation* design component allows users to disaggregate energy consumption data to the appliance level. Fischer's review [11] of eco-feedback studies affirmed the need for interface tools that draw a direct link between specific actions or appliances and consumption. Providing such granularity allows users to increase self-efficacy associated with consumption behavior modifications [5]. The need for such disaggregation tools is further bolstered by survey responses of eco-feedback users, which indicated a strong desire to know usage relative to individual