Sensing and Feedback of Everyday Activities to Promote Environmentally Sustainable Behaviors

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Abstract
Everyday human behaviors such as home energy consumption and personal travel can have a significant impact on the environment. Feedback has been shown to be one the most effective strategies in reducing wasteful consumption, particularly for home energy, yet there has been a lack of research in other domains. With advances in sensing technologies and computerized displays, we now have the potential to provide personalized feedback in real time for a variety of environmentally impactful activities. In this thesis proposal, I describe both completed and proposed work to further the design, tools and techniques of sensing and feedback solutions of everyday activities to promote environmentally sustainable behaviors.

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Sensing, feedback, environmental sustainability, ambient displays, persuasive technology

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

Introduction
Although often overlooked, our everyday behaviors such as commuting to work, showering, and clothes washing can have significant impact on the environment. Home energy use and personal travel account for 28% of US energy consumption and 41% of US CO_2 emissions [18], while home water use accounts for 50-80% of the US public water supply [19]. However, most people are unaware of how their daily activities affect the environment, and there are few ways to track resource consumption outside of monthly electricity, water and gas bills. Even then, these bills tend to only provide aggregate details on consumption and nothing related to environmental impact.

My thesis focuses on creating computerized sensing and feedback systems to bridge the gap between action and effect and, ultimately, to promote environmentally

Figure 1. The Toyota Prius introduced perhaps the canonical example of an effective energy feedback display, providing real-time information about combustion engine vs. electric motor usage enabling people to drive more efficiently as a result.

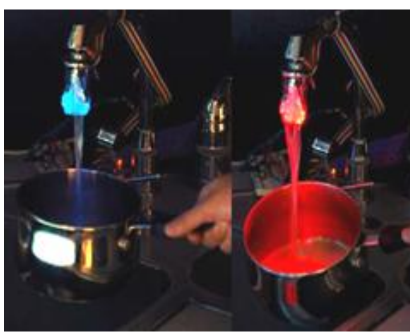

Figure 2. HCI and UbiComp researchers are well positioned to use their expertise in design, information perception, and sensor systems to create a new generation of feedback technology such as HeatSink, a water temperature feedback device by Arroyo et al., 2005.

sustainable behaviors. This work encompasses two primary research questions:

- How can we build novel, highly granular automated sensing solutions of environmentally impactful human activities?
- How can we create informative, engaging, and potentially persuasive feedback interfaces about such activities to improve awareness, to educate and, possibly, to change behavior?

A variety of methods have been used to promote environmentally sustainable behaviors, ranging from informational media campaigns to monetary incentives. However, feedback has been shown to be one of the most effective strategies in reducing wasteful consumption [12]. Over 30 years of investigation into the effect of feedback on home electricity consumption reveals typical reductions between 5 and 20% depending on the frequency, duration, specificity, and type of feedback (see [1], [6] for comprehensive reviews). These are significant reductions. For example, a 15% reduction in electricity use across US households represents nearly 200 billion kWh of electricity per year (equivalent to the power output of 16 nuclear power plants for a year). Similarly, a 15% reduction in water usage across US households would save an estimated 2.7 billion gallons *per day* and more than $2 billion per year [2]. While a majority of research into the effects of feedback on consumption has focused on home energy, it's likely that these findings will transfer to other environmentally impactful activities such as home water usage and personal transportation.

With the advent of low-cost sensing technologies, fast computation, and advances in machine learning, we now have the potential to provide new types of feedback, which are personalized, interactive, increasingly motivating, and, perhaps most importantly, tied to specific activities (e.g., driving to work, taking a shower, watching TV). In this thesis proposal, I describe both completed and proposed work to further the theory, design, tools and techniques of sensing and feedback solutions of everyday activities to promote environmentally sustainable behaviors. Specifically, I propose the following contributions:

- A data collection tool for mobile phones called MyExperience, which provides new ways of collecting data on human behaviors *in-situ*.
- A novel, sensing technique for water consumption, called HydroSense capable of determining water usage down to the fixture level from a single point.
- A series of novel feedback visualizations for water and transportation usage.
- A set of field studies evaluating the automated sensing and feedback techniques used in each system.
- A design framework for feedback technology targeting environmentally sustainable behaviors.

Investigating Human Behavior via Automated Sensing and Self-Report

Understanding human motivation, choice, and decision-making remains one of the grand challenges in the social sciences and has direct implications for the design of effective feedback systems. A variety of tools and methodologies have been developed to provide different insights into the human experience such as ethnography, surveys, and interviewing. In situ, self-report procedures such as the diary method and the experience sampling method (ESM) have been used extensively in psychology [16] and HCI/UbiComp [4] to

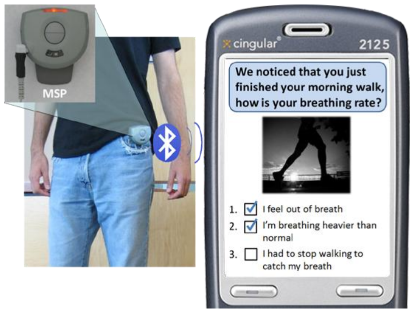

Figure 3. MyExperience allows researchers to trigger self-report surveys at automatically sensed points of interest. In the above scenario, a question about breathing rate is asked after an activity-inference sensor detects the end of a morning walk.

Figure 4. The UbiGreen Transportation Display automatically updates the background display of a user's mobile phone based on green transportation usage. The interface serves as a personal ambient display, visible whenever the user picks up the phone for everyday purposes (e.g., to make a phone call or send a txt message).

capture data on participants' thoughts, feelings, and behaviors *as they are experienced*. In-situ methods are useful because they reduce recall bias and allow the collection of ongoing details of a person's life.

MyExperience [8] is the first phone-based tool to incorporate a new type of experience-sampling, called Context-Aware Experience Sampling [14]. Context-triggered sampling uses sensor data to automatically infer when an event of interest has occurred and prompts the user accordingly (Figure 3), making *in-situ* self-report more targeted and less burdensome on the participant. Even in the case when no self-report data is collected, MyExperience can be used to automatically log interesting human behavior via sensing (e.g., inferring a person's daily travel behavior based on GPS sensors). This data can then be used to inform the design of new UbiComp algorithms and applications.

MyExperience[1] was open sourced under the BSD license in 2006 and released in the spring of 2007. Since then, it has been downloaded over 1,200 times and used in more than a dozen research projects including human memory and the recall of routine activities [15] and studying home exercise interventions and weight gain for premature infants [13]. We have also used MyExperience in our own studies of environmentally related human behaviors, which I cover next.

Sensing and Feedback of Personal Transit

Because transportation is inherently a mobile activity, mobile devices are well suited to sense and provide feedback about these activities. We created the *UbiGreen Transportation Display* (UTD) [9], a mobile phone application that semi-automatically senses transportation behavior (such as riding the bus or train, walking, biking and carpooling) using a combination of wearable sensors and self-report and feeds back this information on the mobile phone. The display (Figure 4) uses iconic and evocative imagery on the background (also called wallpaper) of a user's phone that changes based on transportation activity. The UTD is the first application to automatically track different forms of everyday personal transportation (from bicycling to carpooling) with the goal of reducing CO_2.

The design of UTD was based on a formative study of people's everyday transportation behaviors, using the MyExperience tool. In that study, we found that participants engaged in green transportation *less* than reported in a pre-study retrospective survey and that convenience was the critical factor in influencing transportation choice (environment was only a top three factor 17% of the time). The UTD feedback display thus includes a value icon bar that emphasizes values other than the environment for each green transit activity (e.g., exercise, cost-savings).

We conducted a three-week pilot study of the UTD with 13 participants across two cities: Seattle and Pittsburgh. We found that using the background screen of the mobile phone increased personal awareness and stimulated reflection about transportation activities (the subjects reported that the information felt "omnipresent"). The participants also appreciated the unfolding stories that would occur on their phones as they engaged in green behavior (Figure 5) and suggested that "new stories" should be available each week. Finally, three common requests amongst our participants were the ability to view quantitative data

[1] http://myexperience.sourceforge.net

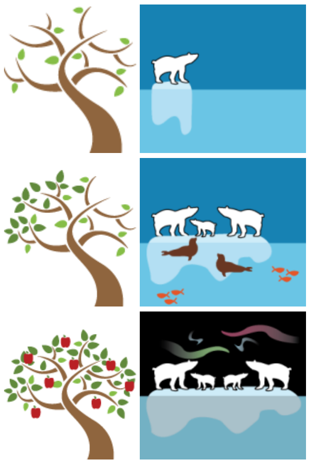

Figure 5. A sample of the tree and arctic ecosystem interface progressions.

Figure 6. (clockwise from top) A shared bicycling station; a user checking out a bicycle; a shared bicycling kiosk.

about their travel behaviors (e.g., number of bus, bicycling, walking trips for the week), the ability to compare their current week's performance with previous weeks, and a feature to recommend alternative forms of transit based on observed travel.

Sensing and Feedback of Shared Bicycling

Whereas the UTD project focused on sensing a diverse set of personal transportation behaviors, this next project focuses on one: shared bicycling. Community shared bicycling programs offer an environmentally friendly, healthy, and inexpensive alternative to automobile transportation. We have been studying [11] one shared bicycling program in particular, called Bicing, which launched in March of 2007 in Barcelona, Spain and has 390 bicycle stations with 6,000 bicycles and over 150,000 yearly subscribers (Figure 6). In comparison to the UTD project, here we look at sensing and feedback of *aggregate* bicycling behaviors rather than *individual* transportation behaviors.

We conducted an online survey of nearly 200 Bicing users and found two common problems: (1) when looking for a bicycle, 76% of respondents reported difficulties in *finding a station that contained available bicycles;* (2) when on a bicycle, 66% of respondents reported that they had difficulty *finding a station that had empty parking slots*. Our goal was to create a sensing and feedback system to mitigate these issues, thus promoting shared bicycling usage in Barcelona.

Using two months of data scraped from the Bicing website, we developed predictive models of station behavior capable of predicting station usage down to within two bicycles. We also found that Bicing usage varied based on the city location and underlying topography of the station. For example, stations at high elevations tended to have less activity than stations at low elevations, and stations along the city's perimeter behaved similarly.

Proposed Work: Shared Bicycling Feedback Interfaces
We plan to use these results along with our shared bicycling sensing infrastructure to design a set of feedback applications. The first is a mobile application that recommends drop-off stations based on a user's selected destination, their expected arrival time and the station's predicted usage at that time (Figure 7). The second application rewards Bicing users for picking-up/dropping-off bicycles at particular stations in order to better load-balance bicycles across the city in a self-sustainable manner. The rewards may come in the form of points (which vary based on station distance, time to reach station, etc.) and could go towards earning actual benefits (e.g., free Bicing subscription, subway tokens). Finally, the last application is a social application that allows friends, families and the users themselves to track their shared bicycling usage and compare it to others. These three applications are meant to explore different aspects of the feedback design space, which I briefly describe in the last section of this paper.

Sensing and Feedback of Home Water Usage

Few people have a good understanding of their water usage in the home. HydroSense [10] is a water sensing system capable of tracking water usage *down to the fixture level* (e.g., a particular toilet, a kitchen sink, a dishwasher) from a single installation point (Figure 8). Current water metering solutions can only provide this level of detail with multiple installation points (i.e., sub-metering), which is costly and requires pipe modification during installation. HydroSense works by

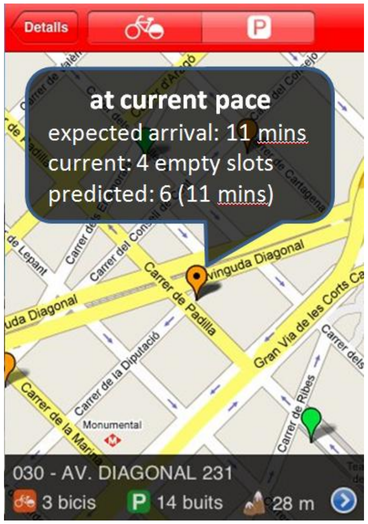

Figure 7. An example feedback application that recommends stations with predicted empty parking slots based on the user's expected arrival time.

Figure 8. An early version of the HydroSense water sensor, capable of sensing water activities down to the fixture level (e.g., toilet, shower, etc.) from a single installation point.

sensing the unique pressure signatures created by water fixture valve open/close events and estimates flow volume based on changes in pressure.

Using data collected experimentally in ten homes, we were able to automatically identify the usage of individual fixtures with 97.9% aggregate accuracy. We also found that a calibrated system could estimate water flow with error rates comparable to empirical studies of traditional utility-supplied water meters.

Proposed Work: HydroSense 2.0
Our initial HydroSense work was limited to controlled experiments of water activity in ten homes and the analysis was done offline. As a result, we were not able to test whether our inference algorithms were capable of identifying partial valve open events, compound fixture events (i.e., multiple fixtures being used at once), and automatically distinguishing between hot and cold water usage. We are currently working towards a more naturalistic deployment; we hope to collect at least four weeks of labeled water activity data in 4-8 homes. Our goal is to be able to auto-categorize water usage events into high level fixture categories (e.g., shower, faucet, toilet), automatically detect and segment compound events, and automatically disambiguate hot and cold water usage.

Proposed Work: Ambient Water Feedback for the Home
The proposed improvements to HydroSense will allow us to create detailed feedback interfaces for water usage in the home. We believe that such detail is important as it creates *actionable* information. For example, water heating accounts for nearly 10% of energy usage in the home [5]. Providing feedback about how much cold vs. hot water is being used by each fixture in the home allows residents to better determine where to invest in their conservation efforts (e.g., low flow appliances or showerheads).

Our water feedback interfaces (e.g., Figures 9 and 10) will provide real-time feedback on water consumption broken down by fixture category and spaced across user-selectable time units (daily or weekly). Based on findings from the UbiGreen Transportation Display study, the interface will also provide historical data, allowing people to compare their day-to-day or week-to-week performance. In addition to this quantitative data, we also expect to incorporate more abstract and evocative representations of water usage, similar to our UbiGreen designs but more water focused (e.g., a lake level wanes with excessive usage).

We will evaluate our feedback interfaces in a three month study of 15-30 households broken into a control and an experimental group. Our analysis will focus on comparing the experimental group performance to the control group as well as to baseline data (e.g., from utility bills). The results of this study should inform the design of future feedback interfaces and provide evidence for the benefits of displaying itemized usage information.

Feedback Design Space
Finally, I hope to adapt and evolve the design space dimensions initially proposed here [7] into a design framework with recommendations on particular features and visual elements. This framework will attempt to map out the most effective strategies in motivating environmentally sustainable behavior through feedback technology and use existing systems and studies to help illustrate these strategies.

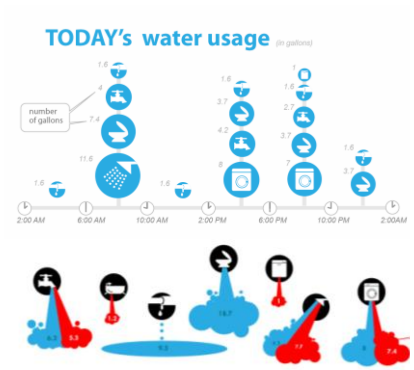

Figure 9. Some proposed water feedback interfaces broken down by fixture and hot and cold water usage. Designed by Marilyn Ostergren, a PhD student in the Information School at UW.

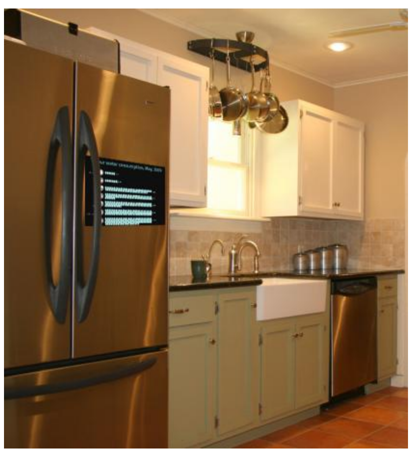

Figure 10. The kitchen may be an ideal location for a water usage feedback interface, such as the mock-up display on this fridge.

Conclusion

Feedback interfaces have incredible potential to inform, educate, and change behavior. Nearly thirty years of research in environmental and behavioral psychology have provided a strong theoretical foundation into the motivations of personal conservation and environmental impact. In my thesis, I incorporate these findings and combine them with the principles of UbiComp (e.g., calm computing) and HCI (e.g., ambient interfaces) to build the next generation of sensing and feedback systems to reduce consumption. In particular, my dissertation research offers a novel tool called MyExperience to study human behavior and inform the design of technologies, novel sensing and feedback systems for transportation and water usage, and a set of field studies evaluating these systems.

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