UpStream: Motivating Water Conservation with Low-Cost Water Flow Sensing and Persuasive Displays

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ABSTRACT
Water is our most precious and most rapidly declining natural resource. We explore pervasive technology as an approach for promoting water conservation in public and private spaces. We hope to motivate immediate reduction in water use as well as higher-order behaviors (seeking new information, etc) through unobtrusive low-cost water flow sensing and several persuasive displays. Early prototypes were installed at public faucets and a private (shared) shower, logging water usage first without and then with ambient displays. This pilot study led to design iterations, culminating in long-term deployment of sensors in four private showers over the course of three weeks. Sensors first logged baseline water usage without visualization. Then, two display styles, ambient and numeric, were deployed in random order, each showing individual and average water consumption. Quantitative data along with participants' feedback contrast the effectiveness of numeric displays against abstract visualization in this very important domain of water conservation and public health.

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Sustainability, ambient displays, persuasive technology

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

General Terms
Human Factors, Design

INTRODUCTION

"Water is the driving force of all nature" *- Leonardo Da Vinci*

Water is our most precious natural resource. One out of six people in the world does not have access to safe drinking water (1.1 billion people), over 2.5 billion lack adequate sanitation, and more than five thousand deaths, many of them children, are caused by water-related illnesses every day [32, 33]. Water is complexly coupled with a range of environmental, political and human heath factors, affecting food supplies, industrial demands, and climate variations. These challenges are not confined to developing regions: water depletion affects many parts of the world, with water levels receding as much as 300 feet in some areas during the last decade [14]. Increased demands for freshwater lead to aggressive pumping, resulting in reduced water flow in streams and lakes, land subsistence (collapsing soil), and deteriorating water quality, not to mention greater costs of obtaining freshwater due to its increased depth [31].

Our work aims to raise awareness and motivate water conservation through the design, deployment, and evaluation of several of *in situ* persuasive displays integrated and low-cost water flow sensors (Figure 1). Conservation- even on the personal level- is crucial for the numerous American regions that are threatened by water depletion. The city where our displays were deployed is particularly affected by sewer overflow- another byproduct of excessive water use, which leads to pollution. While reduced water usage in the US may not directly alleviate water problems elsewhere, the scope of our work probes consumption as whole, inspiring curiosity about water practices outside the studied facilities (dish-washing, lawn-watering, laundry, etc). Increased awareness can lead to large-scale personal and societal level changes in other domains such as industrial practices and agriculture.

Figure 1. Persuasive displays designed, and deployed in field studies: public faucet display, pilot shower display, numeric shower display, and ambient shower display.

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Research Goals

We explore the design of pervasive displays in order to 1) motivate immediate sustainable water use such as shorter shower times, reducing water flow at the tap, etc, and 2) to inspire higher-order behaviors that raise awareness (seeking new water-related information, rethinking water consumption in other domains, discussing water usage with friends, etc). We focus on two types of displays: a literal (numeric) and an abstract visualization of water usage data. We evaluate our displays in a pilot study of water consumption in public and semi-public contexts, and a longer-term follow-up study of water usage in private homes. Our work thus confirms and contributes to research in pervasive computing through a novel juxtaposition of public and private appropriations of ambient and digital displays as motivated by a pressing real-world problem (water conservation). We use our findings to derive design implications for physical and persuasive technologies in this very important domain of water conservation and health practices in public and private spaces.

PRIOR WORK

Ubiquitous sensors and displays have been studied in numerous contexts [3], including health [24, 26, 27], fitness [5, 0], elderly care [6, 17, 22] and sustainability [9, 12, 15], leveraging visualization techniques to influence human behavior and awareness. UbiGreen [12] and UbiFit [5] implement a visual metaphor on users' cellphones, with the former showing transporation choices in terms of polar bears' well-being and the latter relating physical fitness to the conditions of a garden. Other systerms foster more tangible intraction: the Breakaway sculpture 'slouches' to discourage sedentary behavior [24], the power-aware cord shows energy use with ambient lighting [15], and the persuasive mirror augments users' reflection with information such as workout schedules or smoking patterns [**Error! Reference source not found.**]. Explorations of personal monitoring systems emphasize social factors and 'habitus'- general world knowledge as key motivations for human behavior [29]. We contribute to these past projects by leveraging ambient displays as a persuasive technology for water conservation.

Ambient Displays and Water Conservation

Research exploring water consumption has focused on high-cost physical redesign of existing showers [4] and in-line water sensors [16]. Our approach differs by employing low-cost, non-invasive sensing that combines individual and collective water usage visualizations into a persuasive interface. We draw from several prior sensing and visualization techniques at the faucet and shower. Arroyo *et al*. leverage water usage data as well as camera sensing to detect user activity at the faucet. Water is illuminated based on temperature and flow, automatically adjusting to user activity [2]. The same work introduces WaterBot, a water flow sensor that conveys individual and average water usage with ambient LED's, audio messages and chimes. We continue to explore interactions at the faucet, differentiating our work from Arroyo *et al*. through extensive field deployment: by installing physical displays in public restrooms and evaluating behavioral impact based on usage data and participants' feedback.

Our longer-term study of water consumption in private showers is motivated by Chetty *et al*., who suggest that energy consumption patterns remain invisible to most homeowners [8]. Kappel *et al.* present an ambient visualization of water usage that reduces average shower use by about 10 liters [17]. We strive for similar results by deploying a different sensing technology and a variety of visualization techniques. Our sensing approach, which relies on an external microphone to measure water flow, is inspired by the work of Fogarty *et al.*, Froehlich *et al*., and Chen *et al.* who relied on microphone sensing to infer activities in the home [7, 10, 13]. Our sensor is inexpensive (under $40) and easily–replicable by non-experts. Our display designs leverage prior work in ubiquitous computing as well as theoretical evaluation principles.

Evaluation Metrics

Pousman, *et al*. develop a taxonomy of design recommendations, including four criteria for success: information capacity, notification level, representational fidelity, and aesthetic emphasis [25]. Other approaches propose aesthetic appeal, amount and type of information shown, distraction and appropriate fit with surrounding environment [20, 22, 28]. Matthews *et al*. apply Activity Theory, evaluating displays based on intended function and impact on user activity [21]. Our displays strive to raise environmental awareness by inspiring curiosity during mundane actions (washing hands or showering). We explore ambient and numeric modalities to gain practical insight into the principles derived by theoretical frameworks, including noticeability, aesthetics, effectiveness and information content.

LOW-COST WATER FLOW SENSOR

We developed an unobtrusive sensor that can be mounted onto existing showers or faucet pipes to measure water usage. The sensor was built using a low-cost, off-the-shelf microphone and an Arduino AVR microcontroller. Audio is sampled at 10kHz, and volume thresholding combined with a sliding sample window are used to detect water flow. False positives such as human voice or ambient sounds are minimized by continuously matching the sampled signal against the waveform uniquely produced by water flow (Figure 2). Our first prototype, which was used in the initial pilot study, stored only On/Off water events in non-volatile memory at a resolution of 200 milliseconds for the faucets and 15 seconds for the showers. Our follow-up study leveraged more advanced sensing to estimate the amount of water used based on sound output.

Measuring Water Flow with Sound

Water flow is measured in Gallons per Minute (GPM). The flow of water produces a distinct waveform such that the peak amplitude increases with higher flow rates (Figure 2). This relationship is used to approximate water volumes based on two-point calibration: a known volume is filled

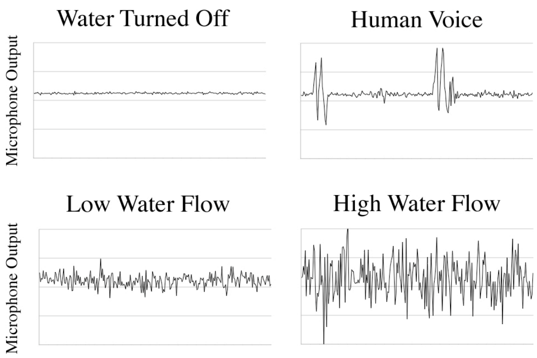

Figure 2. Microphone output for water turned off (top left), human voice (top right), water turned on low (bottom left) and water turned on high (bottom right) events.

twice using different flow rates to interpolate a linear relationship between absolute average microphone output (in mV) and time to fill a known volume. A third datapoint ensures that interpolation is within an error tolerance of 10% per gallon. After calibration, each sensor records the volume of water used during each event at the resolution of 0.2 gallons, as well as the time duration.

PILOT STUDY: WATER USAGE IN PUBLIC SPACES

To evaluate our preliminary sensor and display design as a persuasive technology for water conservation, we conducted a pilot study targeting several faucets in two public bathrooms (men's and women's) as well as one of several shared showers in a female dormitory on a college campus. We chose these locations because they offer unique opportunities for water reflection and awareness: washing hands and showering position people as a "captive audience". Furthermore, an average five-minute shower in the U.S. consumes more water than the amount of water used by a typical person living in a developing country slum over the course of a whole day [30].

Methodology

The sensors without display logged data for 1 day at the faucets and 3 days at the dormitory shower to gather ground-truth usage data. Each sensor was then outfitted with an ambient display showing water consumption in relationship to average and cumulative water usage times that were collected earlier. Due to battery replacement, faucet displays were deployed for non-consecutive periods during 1 week- a total of 103 hours (female) and 47 hours (male), while the shower display functioned for 25 consecutive hours without battery change. In addition, flyers were used to recruit students and staff who regularly use these facilities (6 male and 5 female, ages 19-54). All participants completed a pre-study survey, and six of them completed a subsequent survey, evaluating the displays' impact on behavior and awareness. Participants were compensated $5 for completing each survey and $10 upon finishing both surveys in the study.

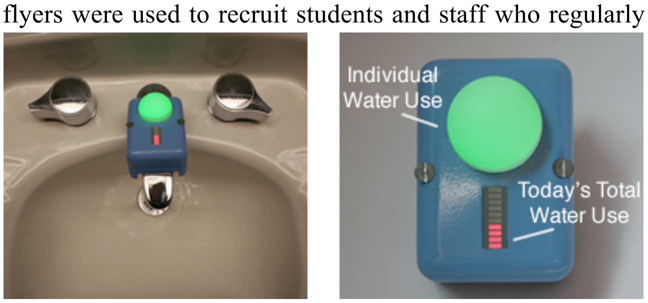

Figure 3. Faucet display mounted onto a public bathroom faucet (left) and each part of the display labeled (right).

Faucet Display

The faucet display (Figure 3) represents individual water use through a 'traffic-light' metaphor. The ambient display is green when water is first turned on, turning yellow if water remains on for more than the previously measured average duration, and red once water has been running for longer than one standard deviation above average. The color sequence culminates in a flashing red light when water is left running for significantly long periods of time (more than 2 standard deviations above average). In addition, an LED bar graph below the ambient light represents collective daily use. Each bar represents one tenth of the water consumed during the day when baseline water usage data was logged. When water is turned on, the next consecutive bar begins blinking to signal individual contribution to the total water usage. Thus, the bar graph gradually 'fills up' over time and resets every 24 hours.

Shower Display

The shower visualization shows cumulative and individual water usage with an LED bar graph. Each LED represents one sixth of the daily water use as initially logged by the sensor before the display was deployed in the cumulative graph, and one third of the average shower length in the individual graph. Again, a traffic-light metaphor is employed, with both bar graphs consisting of two blue, two yellow and two red LED's to represent low, average and above average water use (see Figure 4).

Pre-Study Conservation Efforts and Awareness

Most participants (8 out of 11) have conserved water in the past, with six indicating that they conserve water during everyday activities. Examples include turning off the tap whenever possible (while brushing teeth or drying dishes), reusing clothes to minimize laundry, replacing leaky faucets, not opening the tap fully, avoiding deep baths or taking shorter showers. All participants have been involved in other forms of conservation, ranging from recycling and reducing heat, gas and electricity use at home, to an academic energy-conservation project. Motivations cited for contributing to such efforts include saving money,

Figure 4. Pilot shower display mounted onto a shared semi-public shower (left) and labeled (right).

avoiding recycling fines, convenience, and improving self-image, as well as “investing in the future”, making scarce resources last longer, and “saving the earth”.

When asked to estimate how many people worldwide do not have access to clean drinking water, more than half of participants guessed above the correct answer, ranging from 25% to 98% of the world’s population. One participant explained: “Everyone outside the US?? I have no idea, I just know that when I travel outside of US, I buy bottled water”. Since comments such as these reflect a lack of awareness about global water issues, our work aims to motivate participants to seek additional information and understand worldwide water-related challenges in addition to causing immediate reductions in water usage.

Quantitative Water Flow Data in Public Bathrooms

The initial deployment of the sensors without an active display logged 46 and 91 use instances in the men’s and women’s bathrooms, respectively. The men’s bathroom sensor indicated an average usage time of 5.2 seconds (4.7 sec. standard deviation). For women, the initial average duration was significantly ($p=0.026$) lower, with an average of 3.7 seconds (3.3 sec. standard deviation). During the deployment of the display, 153 and 75 events were logged in the men’s and women’s bathrooms, respectively. Results show a marginally significant ($p=0.14$) 25.7% increase in duration (6.6 seconds average) for men, and a significant ($p<0.001$) 133.5% increase (8.86 seconds average) for women (addressed in our discussion section later). The difference in increase between the men’s and women’s water usage durations (2 seconds) was not significant. There were no significant changes in average durations over time, although the women’s average usage was significantly lower during weekend hours (Figure 5).

Quantitative Water Flow Data in the Shared Shower

The sensor logged 23 shower events without the display, with average shower duration of 8 minutes and 20 seconds (4 min 30 sec standard deviation). After the deployment of the visualization, 4 events were logged, with an average duration of 5 minutes 53 seconds (2 min 27 sec standard deviation). This 30% decrease in average shower time was not statistically significant.

Participants’ Evaluation of the Display

Display Design

Most participants who completed the second survey interacted with the display at least once (1 person), and as frequently as several times a day (2 participants). All participants said they were curious about the display, for example: “I immediately tried all of its functionality. I even tried to make the daily bars go up”, or “it looked interesting and I wanted to see how it worked”. One respondent remarked: “I liked it, it was kind of like a toy”. Everyone understood the individual usage visualization, but several people were confused about the cumulative bar on the faucet display. One person wondered about its scale, and another was disappointed that the bars always seemed low. Although all participants agreed that the data shown was useful, although more than half indicated they would want to see numerical data, a gauge or labeled units. Some respondents suggested showing water temperature, cost, average use over time, or average use per user. Several respondents did not like the aesthetics of the faucet display design, indicating that they would prefer the display to be smaller, or a different color.

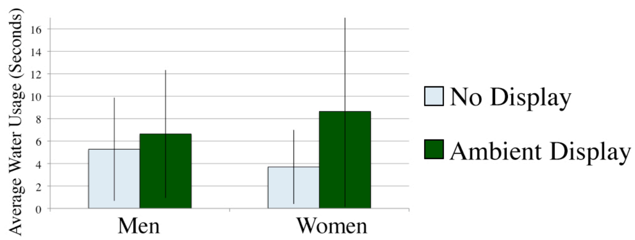

Figure 5. Average water use times and standard deviations for control and intervention conditions in public bathrooms.

Immediate Behavioral Impact

Participants identified the device’s purpose to be reminding people of their water usage, conserving or being more mindful, and most agreed that this purpose was at least somewhat achieved. However, one participant disagreed: “I just wanted to play in the water more to use the display”. A participant who used the shower display stated that the visualization did not effect her shower time since she already showers as “quickly as possible”. All participants said they would feel comfortable sharing their water usage data with friends or strangers. Most also indicated they would prefer to have this device in their home to be more aware of their water use, except one participants who stated “I would play with it too much and use more water”.

Higher Order Awareness

Most participants did not make additional conservation efforts or discuss water usage with their friends since seeing the display. One participant explained: “maybe it’s ‘cause I already do conserve”. Nevertheless, one respondent noticed more news about climate change. Another participant who used the shower display felt more compelled to recycle even if it required “to make more efforts” noting that the device inspired her to “conserve water in everyday life”. Moreover, she searched Google for the number of people without access to clean drinking water and revised her initial answer. When asked again to name the greatest challenge for sustainability, more than half of all participants changed their answer to indicate a lack of public awareness or education.

Discussion

Our display was able to promote a 30% decrease in average shower times in a semi-private setting. Conversely, the public faucet visualization invited people to engage with and question the technology, resulting in significant water usage increase for men and even more so for women. Novelty effects were amplified by the public setting: during the study, displays were accessed by newcomers and it was not unusual to observe people use water simply to watch the system cycle through its states. While this result counters our initial design goal (reducing water consumption), it can in fact be leveraged to promote sanitation and public health practices. People were drawn to use faucets for longer periods of time in order to alter the display (cycle through lighting modes and increase the LED bar). Future work can therefore focus on interactive systems that encourage safer hand washing, especially in public spaces or locations that revolve around human health (hospitals, etc.).

Moreover, the displays affected people's thinking about water and energy. Despite the fact that most participants were already environmentally conscious, results of the post-study survey suggest that they became even more aware of personal and collective water use. Some became conscious of their water consumption and noted publications about environmental issues, and most re-evaluated the primary challenges for sustainability to be human ignorance.

STUDY: WATER USAGE IN PRIVATE HOMES

Our preliminary findings informed the design of a longer-term study that would (1) reduce novelty effects, (2) comparatively evaluate numeric and ambient persuasive displays, and (3) focus on repeated usage of the system in the private, more personal settings. The evaluation of numeric and ambient designs is driven directly from participants' feedback, who specifically requested more concrete water usage representations. Our follow-up study therefore focuses on long-term water usage in private households, exploring two different display designs: numeric and ambient. A new iteration of our sensor measures volumetric water usage in gallons and presents this information in two output modalities.

Methodology

Four sensors were deployed in three private apartments, each inhabited by two people, with two of the sensors placed in separate bathrooms of the same household. In the first phase of the study, sensors were installed without any visualization to log baseline shower usage. Participants were also given a preliminary questionnaire regarding their routine water conservation patterns and awareness of water-related issues. During the second phase, one of the two displays (ambient or numeric, see below) was installed to show participants' water usage. Lastly, in the final phase, the displays were switched, with display order counterbalanced across participants. We did not explain the function/intent of our displays to avoid biasing behavioral change (Hawthorne effects), and to evaluate the intuitiveness of our visualizations. Each phase lasted for about a week (4-7 days, depending on battery constraints and participants' schedules). Participant feedback was gathered through questionnaires or informal surveys at the end of each phase. Participants (4 males, 2 females, age 18-45) were recruited using online postings and compensated $5 for completing each phase and $10 for completing the entire study.

Sensor Calibration

Sensors were calibrated for the water flow of each shower at the beginning of the study. Measurable flow rates ranged from about half a gallon per minute to 2.3 gallons per minute based on participants' showerheads and water pressures. The error rates did not exceed 6%.

Shower Displays

Two styles of display were developed to visualize water usage in the shower. The numeric display presents current usage to the nearest tenth of a gallon. When the shower is turned on, this number increases based on water flow rate. In addition, the average usage, which was computed during the initial (logging) phase of the study, is also shown below (Figure 6). The ambient visualization presents this same information as an ambient orb, leveraging a 'traffic light' metaphor (Figure 7). First, the orb shows a green light while water usage is below average, fading to yellow and then red as water usage reaches average and 150% of the average amount of water is used, respectively. The light sequence culminates with a flashing red light when usage exceeds 200% of the average.

Pre-study Conservation Efforts and Awareness

Data from our pre-study questionnaire suggests that participants were not especially conscientious about their water or energy usage. Three respondents mentioned reducing water flow or turning off the tap in the 'soaping phase' of washing the dishes or while brushing teeth, but no one consciously conserved water during showering or hand washing. All participants recycled, and one participant also mentioned turning off lights and unplugging unused electronics. All participants mentioned saving money as the motivation for sustainable actions, and some also cited conserving resources for the future, and "saving our earth". Laziness and a lack of effort were the most commonly cited deterrents for engaging in more conservation efforts.

Similar to our pilot study, participants did not know the number of people without access to clean water, with half of respondents guessing a few hundred million. Furthermore, none of the participants knew the cost of producing and delivering one gallon of hot water to their homes. Thus, our long-term sensor deployment again aims to raise awareness amongst participants as well as reducing shower usage. Lastly, when asked which style of display (numeric or ambient) they preferred to have in their shower, 4 participants chose the digital display (to see "exact" usage and compare it from day to day), 2 preferred ambient, and 2 did not complete the pre-study survey.

Quantitative Water Usage Data

During each phase of the study, sensors logged 5-12 shower events, with several sensors exhausting batteries prior to the completion of deployment. Baseline average shower usage varied from about 7 to 18 gallons per shower. The numeric display did not affect average water usage for two of the participants, but reduced shower usage by an average of 2 gallons or more in two other households (Figure 8). This decrease was marginally significant in one household (2.7

Figure 6. Numeric shower display showing current and average water usage (left) and installed in a shower (right).

gallons, p=0.08). When ambient displays were installed, average usage decreased by more than 1.5 gallons for all participants, with two of the decreases being marginally significant (2.1 gallons, p=0.09 and 1.7 gallons, p=0.11).

Ambient Display: Evaluation

Display Design

Participants tended to notice the ambient display several times during each shower, "occasionally looking" at it "out of curiosity". Unlike our pilot trial, none of the participants intentionally turned on their showers to play with the display or watch the entire color sequence. All users understood the green light to be an indicator of low or "acceptable" usage, while red signified more water than a certain "high number". One participant guessed that red color meant a "max limit of our average water consumption" and another suggested it meant "above average". Most participants, however, did not identify the color sequence as a comparison between their current and average water usage. One person noted that seeing green at the end of their shower served as a "mild positive reinforcement" and two others were excited to report: "it's always green, it only went red once!" Another participant described the display as starting with "a gentle green light", emphasizing: "sometimes, I did not even make it to red".

Overall, participants liked the ambient display and most preferred it to the numeric visualization ("the sensor worked perfectly", according to two participants), indicating that they would like to have this device permanently in their homes. One participant favored the

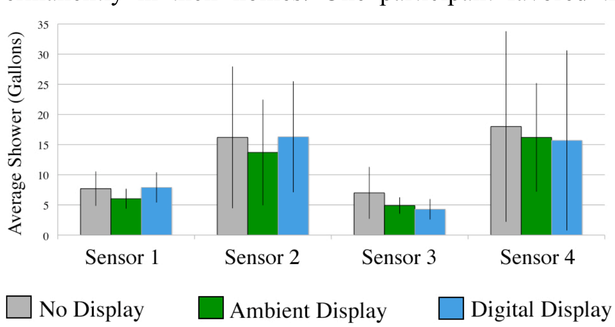

Figure 8. Average shower use (in gallons) and standard deviations as logged by sensors without display, and with ambient and digital visualizations.

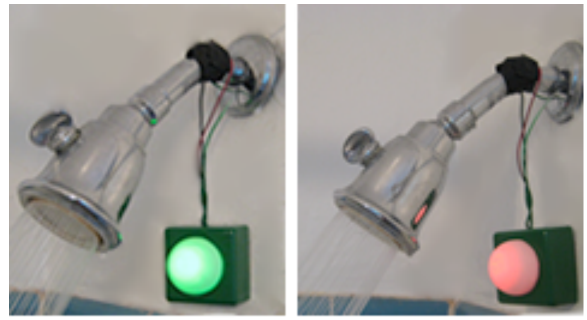

Figure 7. Ambient shower display mounted onto a shower in green state (left) and red state (right).

ambient approach because it was "more gradual" and "less stressful" than the constantly increasing number of gallons on the numeric display, as well as easier to notice without being distracted. Another user noted that unlike the numeric display, the ambient visualization is a better indicator of "the correct amount to be used". Similarly, one respondent liked the flashing red light because it was more effective at getting her attention and conveying negative information, although she suggested even more negative reinforcement. Lastly, the participant who preferred the numeric feedback to the ambient still agreed that "aesthetically, the ambient one looked nicer". Everyone felt comfortable sharing this visualization with their friends and seeing their friends' data, although one person emphasized, "I would not specifically ask for it" or "pay for it".

Immediate Behavioral Impact

While all participants considered the red color to have negative connotations, its behavioral impact varied. Two participants claimed that the visualization did not affect their shower usage at all. One person explained: "if I wasn't doing anything unnecessary and it was red, I didn't feel too bad about it". Another participant noted that although the flashing red light was "irritating" it did not have enough negative reinforcement to impact her actions, suggesting more drastic feedback such as "electric shock" or an analogy to the "number of baby seals killed per gallon of wasted water". However, one participant admitted that seeing the red color directly affected his water usage: "I was taking a shower and I saw it and thought... oh OK I better turn it [shower] off". Similarly, another participant said: "I felt like wrapping it up, but I did not feel a sense of urgency".

Higher Order Awareness

Since sensors were installed in apartments inhabited by two people, participants tended to discuss the visualization with their roommates, especially focusing on the red state of the display. One participant explained: "We talked about it a little bit, mainly joking around. I'd give him [roommate] a hard time: you didn't make it red, did you?" Similarly, another respondent told us: "When it went red, we talked. I said, hey it turned red".

Many participants indicated that they became more aware of their overall water and energy usage since the installment of this display. Two people mentioned that they tried to "slow down the tap" while doing the dishes, while one person remembered that he was more careful about "turning out lights when I leave the room and not letting water run needlessly", and another participant admitted to "being more conscious of turning off the water and not leaving it running". However, a few other participants stated that having this display did not specifically affect their sustainability efforts outside the shower. They justified this lack of change due to the fact they were already conscientious, with one participant explaining: "my water usage is already pretty reasonable". Contrary to this participants' self-assessment, our sensor logged the highest average usage of 18 gallons per shower in his household.

Numeric Display: Evaluation

Display Design

Participants tended to use the numeric display similarly to the ambient, looking at it occasionally ("once or twice", "a couple of times") throughout their showers. One participant noticed the display working only once during the entire week, and another pointed out that during one usage the current number of gallons stayed at zero. Two participants were confused what "average" meant, with one guessing that it was based on "the data that was collected one week before", and another thinking it was a general average for all people. One participant described her first experience seeing it: "I turned on my shower, and it [the display] started turning. I found it interesting but it had no effect". Another user pointed out that the display seemed to "jump" to a high number every time she looked at it: "the second time I looked it was already at nine". The same person also felt that the display was not very noticeable due to its placement: "It's very hard to see, you never look back behind you [while showering]".

Moreover, several participants expressed strong dislike for this display. One person felt that the "rapid countdown" induced too much guilt, making showering unnecessarily stressful: "Normally a shower is a leisurely, relaxing experience, so to see that rapidly moving number… and being like I'm wasting water – was a little bit too intense... or a little uncomfortable". Another participant criticized the display for not providing an "ideal value" to indicate "how low we should go". This participant suggested adding a "recommended" usage: "If that value was there we could work toward getting average close to that." Two participants did prefer the numeric display because it was "more informative". Although one of these participants claimed the display did not affect his shower usage, he said he would choose it over the ambient if he was actually concerned about his water consumption: "I'd want the one that provided me with the most information to deal with that, which would be the digital [numeric]."

Immediate Behavioral Impact

None of the participants could name a single precise number of gallons used during one of their showers, nor did they compare their separate usages throughout the deployment of the visualization. All participants could remember at least an approximation of their average ("six point some gallons", "sixteen something"), and, regardless of the number, many felt that it was too high. "I know that shower[ing] uses a lot of water, but how much it was surprised me", said one participant. When looking at the display, participants tended to compare their current usage to the average number of gallons. One participant was frustrated by such comparison: "it seemed that it was going way beyond and way beyond". However, most participants claimed that these numbers did not affect their actions. One participant explained this lack of change: "I'm normally pretty responsible in water use, I don't take… half-hour showers". Another participant stopped watching the display after a few days: "For two days, I watched [the display] and then I stopped… I didn't care".

Higher Order Awareness

The numeric display seemed to facilitate less discussion than the ambient visualization, with only one household discussing the data: "We shared our average numbers… mine was like seven and hers was sixteen… and I was kind of shocked". The display also raised awareness of water usage outside the shower for some participants. One participant mentioned that the numeric visualization made her reduce water usage elsewhere, for instance at the sink, as "a way of balancing it out": "If I want to take a longer shower, then maybe I'll try [lowering water usage] in other areas to make up for it". Another participant began to wonder "how much am I using to wash all these dishes by hand, I wonder how much the dishwasher uses". Other participants, however, were less motivated by this display and did not think about it outside the shower. One person explained: "It didn't add any perspective", referring to a need for comparison between personal water usage and the data of others.

Participants felt comfortable sharing numeric water usage data with their friends, with one person suggesting a "friendly competition" between friends as a motivation for using less water. Another participant said the display would be better if it showed other people's (not necessarily friends') data: "Suppose you are conducting this experiment in ten different places. I want to know where exactly we fit in based upon all ten people… because then we can realize – oh, our consumption is too high".

Discussion

Our ambient visualization successfully reduced water usage by nearly 2 gallons per shower for all participants, while the numeric display achieved this result in only half of the households. Although both visualizations were used similarly- occasional glancing during showers- they led to different perceptual impacts and behavioral changes. We now contrast and evaluate our displays using several design principles conceptualized by prior evaluation metrics.

Noticeability and Aesthetics

Our displays provide peripheral cues to support human actions rather than being the focus of an activity. According to Matthews *et al.*, such cues are to be used at the level of "operations" rather than actions, without interfering with conscious function [21]. Our ambient display achieved this effect by showing "aesthetic" and "gentle" representations of water usage. Color cues were not attention-intensive: the light was either green, yellow or red. Interpreting the numeric display, however, required conscious comparison of current use against the average. This evaluation was not engaging, as participants were more likely to remember the ambient color rather than their concrete usage in gallons. Moreover, the increasing number of gallons caused confusion when participants saw usage 'jump' each time they glanced at the display.

Information Content

While participants deemed the numeric display to be more information-rich than the ambient, most people did not actually use this information to track their usage. Moreover, numeric data frustrated participants who wanted to see a recommended benchmark. The average number of gallons per shower did not provide perspective, leading participants to want to compare to other people's usage or an "ideal" value. The abstract visualization was based on the same data as the numeric display, yet users perceived the ambient color as an acceptable indication of how "good" or "bad" their water usage was. The ambient display thus provided an authoritative element of persuasion and was therefore more effective, consistent with prior related findings such as traffic light food labeling in the UK [11].

Effectiveness

Quantitatively, numeric visualization was less effective than ambient, reducing water usage in only half of the households. Perhaps this is due to the display's lack of a clear-cut threshold for appropriate consumption: participants did not see an appropriate stopping point, although one person did express guilt at the rapidly increasing number. Conversely, all participants interpreted the green light of the ambient display to be a positive reinforcement, while red implied negative behavior (wasteful water usage). Qualitatively, the modality of the displays impacted *how* users thought about water consumption outside the shower. The ambient display inspired specific conscientious behaviors such as turning off lights, reducing water flow in the sink, etc. The numeric display, which showed no 'good' or 'bad' benchmarks, afforded more curiosity, inviting users to make their own judgments. Participants wondered how many gallons they were using while doing the dishes or how their water use at the faucet compared to usage in the shower. Lastly, ambient displays facilitated additional light-hearted discussion amongst roommates, possibly because users tended to remember color states rather than specific numbers.

Perceived Behavioral Change

Finally, our findings show disparities between participants' hypothetical preference for display style prior to usage and their evaluation after experiencing each display. Over half of participants preferred the numeric display over the ambient at the beginning of the study. However, post-study interviews suggest that after experiencing both systems, the majority of participants favored the ambient visualization with some even strongly disliking the numeric. In addition, our data suggests another disparity between participants' own self-assessment of behavioral impact and actual quantitative changes in water usage. Contrary to many participants' perceptions that their shower usage did not change over the course of the study, quantitative data measured a decrease in water consumption in all households during the deployment of ambient displays as well as lower usage in two households during the numeric display deployment. Thus, our findings suggest that field deployment is critical in evaluating output modalities.

DESIGN IMPLICATIONS AND GENERAL DISCUSSION

Our pilot and long-term deployments of water usage displays revealed different behavioral outcomes in public spaces (bathrooms) opposed to the semi-private (shared showers) and private showers. Our playful design inspired curiosity about the interface resulting in increased usage (novelty effects) in public bathrooms, while similar displays effectively decreased water usage in the private showers during the pilot study and long-term deployment. Public displays were continuously accessed by new people who were able to explore the technology (cycle through all ambient lighting modes) without providing identifiable data. Conversely, private displays showed individual data to the same people, facilitating faster adoption. This tension between curiosity and anonymity in public spaces and identifiable usage and ownership in private settings highlights the importance of context for pervasive technology. Ambient displays, especially with clear positive or negative behavioral benchmarks, may encourage water conservation for long-term users who are familiar and accustomed to the technology in private settings. Moreover, curiosity and anonymity in public spaces can be leveraged to motivate public health and safer hand washing through interactive visualizations.

Our studies also expose the natural tension between abstract and literal output modalities for datasets designed to promote conservation. To encourage reflection, curiosity and awareness, our initial designs intentionally chose ambient visual cues (color and graphs). However, while users asked for numeric data, our further exploration of the design space between the abstract and the literal suggests that information-rich numeric displays can in fact be less effective. Although literal displays offer greater detail, interpretation of this information requires attention and processing from users who are already engaged in activities such as showering. Appropriate pacing is also crucial. The usage number rapidly advanced at every tenth of a gallon, proving to be too fast and even stressful for some users who only occasionally glanced at the display. However, a display that updates too slowly may appear broken as users look to ensure some model of correct operation.

The peripheral use of our displays (*i.e*. occasional glancing) suggests that persuasive technologies must provide a clear, easily perceptible indication of good and/or bad behavior. Our ambient visualization communicated acceptable or excessive water usage through obvious light cues, and proved effective for more participants than the numeric display. The advantage of numeric feedback, however, is that it invites participants to personally define acceptable ranges, inspiring analysis and curiosity about the impact of activities outside the shower. The persuasive "sweet spot" thus lies within a hybrid of this design territory where users can experience details of the data as well as view less distracting benchmarks for their usage. Future work can focus on exploring the range of these hybrid ambient-numeric output modalities and persuasive design landscapes.

Another design opportunity exists in the space of data sharing and displays that afford inter-person comparisons. None of our participants considered their water usage data to be private, nor did they feel uncomfortable sharing it with others. Moreover, several people felt that seeing their friends' data would add incentives for lowering water usage through competition. In addition, one participant wanted to see the data of strangers (other people in the study) to gain perspective of personal usage compared to other people. Such comments motivate a design space that incorporates visual sharing of personal water usage across individuals and households.

Lastly, we note that the numeric display was ultimately less liked and less effective, despite participants' initial preference and requests for the numeric modality. Thus, while user preferences can identify functional needs and help narrow design scope, actual design, construction, and *in situ* deployment of such technologies is vital to measuring and evaluating the ultimate impact and success of such persuasive systems.

Limitations and Future Work

Our work is limited by the non-trivial technical challenges of deploying working devices for use in real and uncontrolled environments. Design aesthetics confined battery space, resulting in nonconsecutive deployment of the faucet displays to allow for battery replacement, and shorter deployment of displays in the shared shower (4 uses with display vs. 23 uses without display). Follow-up studies can explore more robust, longer-term deployment. Moreover, the number of usage events was inverted for data collected with and without displays in public bathrooms. Perhaps men regarded the baseline (no visualization) sensor with caution, but became curious once the display was installed, resulting in increased usage. Conversely, women were less willing to use faucets with working displays-possibly to avoid damaging the devices or affecting study data. Future work can focus on the role of gender differences for persuasive technologies. Lastly, we note the possibility of Hawthorne effects: the study itself (in addition to the specific devices) may have motivated participant awareness and behavior towards water conservation. Future work can explore a longer term study, leveraging displays to motivate public health and safer hand washing, and rewarding good behaviors with display changes.

CONCLUSION

We have presented the design and evaluation of several persuasive displays integrated with low-cost water flow sensing to encourage public awareness and sustainable behavior around water conservation. Our evaluation of abstract and numeric output modalities across a range of public and private spaces suggests design tensions between the principles derived in prior literature: noticeability, aesthetics, informativeness, and persuasion. Our long-term deployment of the ambient water visualization was able to effectively motivate water reduction in private homes for all participants. Moreover, our displays have led participants to reflect on their behavior and reconsider sustainability and environmental issues beyond water usage and showing. We have presented our findings along with several design considerations for persuasive interfaces, particularly in the domain of motivating conservation and environmental awareness in public and private spaces. We hope that our work inspires future research that applies HCI and ubiquitous computing practices to the pressing issues of water conservation and public health.

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