Proceedings of the ASME 2019
International Design Engineering Technical Conferences
and Computers and Information in Engineering Conference
IDETC/CIE2019
August 18-21, 2019, Anaheim, CA, USA

DETC2019-98468

A WIZARD-OF-OZ EXPERIMENT TO DEMONSTRATE WATER REDUCTION AND USER TRAINING WITH AN "AUTONOMOUS" FAUCET

William Jou
Stanford University
Stanford, CA, USA

Samantha M. Beaulieu
Stanford University
Stanford, CA, USA

Adrienne K. Lim
Stanford University
Stanford, CA, USA

Erin F. MacDonald
Stanford University
Stanford, CA, USA

ABSTRACT

Resource-conserving products and commercial smart products abound in the market, but the intersection of the two is largely unexplored from the human-centered-design community. Research has shown that people (users) have different cognitive styles that influence their methods of approaching challenges and how they interpret the world. Utilizing this knowledge of cognitive styles, energy conserving products could (1) reduce resource consumption of its users and (2) increase user satisfaction with interacting with those products. Passive products—such as a flow-limiting showerhead—do not seek to change the user behavior and solely change the behavior of the product to conserve water. In this work, we design and test an "active smart" product to see if it can change users through product interaction. A custom faucet was designed and built to conduct an experiment with the Wizard of Oz (WoZ) technique of remotely operating a device to create the impression of autonomy/smartness. Participants were asked to wash multiple sets of dishes to test if: (1) participants use less water when washing dishes with a smart faucet and (2) participants remember this behavior change and use less water in a alter interaction with a normal faucet. Results confirmed the hypotheses and showed that those interacting with the faucet reduced their consumption by 26.5% during WoZ treatment and, importantly, 10.9% while washing after interacting with the WoZ treatment. Limitations include the implementation of the smart algorithm and the willingness-to-pay for a smart faucet in the home. This study demonstrates that smart products can conserve resources and train for further conservation even when the user is not using the smart product.

1. INTRODUCTION

1.1 Motivation

In the first six months of 2018, households consumed over 20% of the United States' total energy usage, making the residential sector the third highest contributor [1]. However, despite knowing that reducing energy consumption could lead to significant monetary savings, users are still reluctant to change habits [2, 3]. Studies have shown that attitudes toward conservation do not influence consumer behavior. Therefore, energy saving displays equally affected everyone, regardless of whether they identified as active energy savers [4, 5, 6].

Faucets alone compose over 15% of household water usage. Given the potential savings that could come from reducing water usage at the sink, smart faucets are a potential product that could dramatically benefit users and the environment. Typical automatic faucets also consume more water than manually operated faucets [7, 8, 9]. The study presented here suggests that the proposed faucet can train users to reduce water consumption by adapting and modifying user behavior.

1.2 Background

While commercial smart products today, such as the Nest thermostat, may learn about the preferences of a user, they do not learn about how a user actually thinks [10]. Current smart products assume that all people are fundamentally the same, but research has shown that people have cognitive styles that govern how they approach different tasks and interact with the world [11], for example, someone might be more analytical, while someone else may be more intuitive. We are interested in cognitive styles because we believe that interacting with a product that can understand the user improves trust, which would in turn open an avenue to training users to adopt environmentally friendly behaviors. For example, a smart faucet that better understands its users could potentially leverage that knowledge to train users to reduce water consumption or lower the average water temperature. Our motivation here is to take the framework of leveraging cognitive states to develop physical "telepathic" products that better understands its users. Through various studies, we found a smart faucet as a potential "telepathic" product that could dramatically benefit users and the environment. Studies by Mayer et al. that showed that faucets compose of 15% of household water usage [12] and Gauley and Koeller which revealed that typical automatic faucets use more water than regular faucets [13].

Exploratory studies by Ramaswamy and MacDonald found that parameters of a user's cognitive style such as patience, temperature sensitivity, and resource consciousness affected how they used faucets [14]. Other studies show that cognitive styles can be utilized to encourage pro-environmental behavior. For example, by considering different behavioral groupings of individuals, one study shows that policy makers will have more success promoting their energy-conservation initiatives [15]. A study by MacDonald and She identifies seven cognitive concepts to incorporate into eco-products to influence consumer behavior: responsibility, complex decision-making skills, decision heuristics, the altruism-sacrifice link, trust, cognitive dissonance, and motivation [16]. MacDonald then proposes specific recommendations, which we incorporated into our study. One of these recommendations is that trust can be instilled into a product that is similar to the user. This similarity can be in the form of physical or personality traits that resemble the user's [17]. By understanding and adapting to the user's cognitive style, our faucet will be able to form this trust between user and product.

This paper explores what the physical implementation of such a system could achieve in terms of user behavior change and real-life water conservation. For even if such a system could theoretically work, we wanted to first answer the questions: (1) Would such a system save water? (2) Would there be any residual characteristics shown by participants after interacting a smart faucet? (3) Would participants enjoy the experience and consider bringing such a product home?

To answer the questions we had, we built a custom faucet – depicted in Figure 1 – to conduct a human experiment. The faucet was initially used for pilot testing conducted by Ramaswamy and MacDonald [14] and has since been modified to allow for remote control of the temperature and flow of the water as well as water consumption tracking. While other studies solely rely on feedback from participants in the forms of energy surveys or energy-flow limiting devices, we sought to create a real-time interactive product to elicit true participant responses of a perceived interaction with an autonomous device that "understands" them.

FIGURE 1. MODIFIED PHYSICAL FAUCET FOR COMPUTER CONTROL

2. LITERATURE REVIEW

2.1 Water Conservation

There have been numerous studies conducted on educational or behavioral methods for encouraging water conservation. Flack et. al. tried to implement a policy-related approach to enforce installation of water-efficient fixtures; however, they found it difficult to enforce long-term. They conducted a survey of 19 communities, in which they enforced a variation of water-conservation methods: some communities were metered for the amount of water they used, while others had their water use restricted to certain days of the week and hours of the day. Other communities were given plumbing fixtures with water-saving devices. Flack et. al. found that, while water-saving devices were feasible, they were difficult to enforce. Participants were supportive of the idea, but they were reluctant to introduce new devices to their homes [18].

Other studies attempted to use feedback techniques to convey how much water was being consumed in real time. These studies found that immediate feedback was more important for changing consumers' behaviors than long-term feedback, such as a bill at the end of the month, as shown in a study by Chetty et. al. [19, 20]. One study by Kuznetsov et. al. utilized an in-shower LED display to indicate water usage in real time. The display is green when the water is first turned on, yellow if the water remains on for more than the previously measured average duration, and red once the water has been running for longer than one standard deviation above average. If the water is left running for a significantly long period of time, the red light starts to flash. This feedback proved useful when the device was present, but it was ineffective in changing long-term behavior as participants did not maintain water efficient habits after the device was removed [21].

Meanwhile, numerous studies have attempted to compare different methods aimed at encouraging water saving behavior.

A study by Aitken and McMahon found that cognitive dissonance, when combined with feedback about water usage, helped reduce water consumption in the short term when compared to feedback alone [22]. Other studies found that water efficient devices, such as flow-limiting faucets, were more effective than other techniques such as education materials and real time feedback displays. Hopp et. al. found that low-flow shower heads, combined with flow-limiting faucets and dual-flush toilets could save at most about 114 gallons of water per day for a family of four [23]. Studies also found that using devices marked as water-efficient could also lead to significant savings [24]. However, Geller et. al. finds that these devices do not promote any change in behavior and didn't save as much water as expected based on manufacturing ratings. Therefore, they speculate that the installation of water saving devices, such as flow limiting faucets, might have led residents to be less conscious of their water usage to compensate for presumed savings [25].

2.2 Smart Products in the Energy Realm

When we discuss smart devices, we place them into one of two categories: passive or active conservation products. Passive products, such as Nest, may provide personalized settings for comfort, convenience, and energy savings; however, they do not attempt to change user behavior [10]. Although our study focuses specifically on water, studies on smart products in the water conservation realm are sparse. For a more comprehensive background, we investigated energy conservation smart devices for insight as well.

2.2.1 Passive Products Han and Lim designed a system that can provide a sustainable experience for homeowners by linking new and easy to use digital technologies aimed at conserving energy automatically. This design relies on sensors that track the current temperature, lighting, etc. and automatically adjust to a more energy efficient setting on its own [26]. Automated devices that use sensors, like the prior example, have been proposed as a further advancement to the simpler mechanical based approach to reducing energy consumption, like water flow-restricting devices [27, 28]. Another system created by Capone et. al. adopts a generalized method for household appliance management and then gathers information from a sensor to adapt to user behavior. The user profiling process includes a mechanism for recording events that can help characterize a user's interactions with their home devices and then utilizes a learning algorithm to meet the user requirements [29]. Our design, like Han and Lim and Capone et. al., adapts to individual users by tailoring the faucet to behave similarly to users' current behaviors, while still promoting water conservation through small changes.

Given the difficulty of changing user habits, studies have proposed employing technology-centered approaches to encourage energy savings without harsh changes in behavior [30, 31]. However, despite these advantages, many users feel disconnected from the technology behind the passive systems. For example, Nest users found the system frustrating and difficult to understand, reporting that many of its features do not operate as expected and the system could not understand the intent behind an individual's behavior [10].

2.2.2 Active Products Meanwhile, active products, such as the smart home energy efficiency devices presented by Jahn et. al, aim to train users to better use certain resources. The system implemented by Jahn et. al. connects various devices and appliances within a home to coordinate energy savings. Their system incorporates feedback from multiple devices, which provides users with a visual of their energy usage, and how the system is adapting. This added awareness and knowledge empowers users to identify where and how they waste the most energy and change their habits to save more energy [32].

Eco-feedback devices represent a large subset of active products in the energy realm. These devices operate on the idea that educating people on their energy consumption through active displays will make them more aware of how their actions impact the environment and, therefore, encouraging behavior change. However, there are few that explore or measure the behavior change aspect [33]. One study that aims to understand the saliency affect of eco-feedback devices, conducted by Lynham et. al., conducted a three phase experiment, in which three groups have their electricity consumption measured for 30 days. While group 1 acts as a control, having their electricity use monitored for all three periods, the two experimental groups receive an in-home display (IHD) that gives real time feedback on electricity consumption for 30 days. Finally, one of the two experimental groups, the continued treatment group, keeps the IHD while the other, the discontinued treatment group, has theirs removed for a final 30 days. While there was some learning effect briefly after the IHD is removed, it declined over time. The study found that while knowledge and understanding of electricity consumption increased over long periods of time, the IHD did not change the participant's habits [34].

A review of thirty-eight studies aimed at household energy conservation by Abrahamse et. al., shows that certain techniques have proved more successful at promoting user behavior change than others. While some methods, like providing the user information about energy waste, have not been shown to motivate behavior change or energy savings, other methods, like rewards or active feedback, have had higher levels of effectiveness (with some degree of variability) [35]. A study by McClelland and Cook used household monitors displaying electricity use in cents per hour and found that households with the installed monitor used 12% less electricity [36]. However, despite this success, these studies either only take place in the short term or even show that the effectiveness of the method diminishes with time [35].

2.3 Cognitive Styles

Studies have found links between peoples' cognitive styles and learning behavior. These styles can be broken down into many dimensions including field perception, impulsivity when making decisions, and convergent versus divergent and holistic versus focused problem-solving strategies [37].

Many different models of cognitive styles exist. Of note, Witkin et. al. discusses the application of learning styles to an education environment. This study suggests that the field perception dimension of cognitive style can be applied to further understand how students learn and teachers teach, how students and teachers interact, and how students ultimately make choices about their education and work [38]. Hauser et. al. discusses morphing the content, look, and feel of websites to match the user's cognitive style, which can be inferred from clickstream data [39]. Similarly, research by Urban et al. proved that morphing advertisements to the cognitive style of the potential customer increased click-through rates by 245% [40].

Research into cognitive styles is fairly limited with few applications [41]. However, what exists can lead to important insights when designing a smart faucet to understand and adapt to the way its users think.

2.4 Research Hypotheses

We hypothesize that an active or "smart" faucet intervention that is able to control the output flow and temperature based on differences in a user's cognitive style and task could be a more effective intervention for water conservation and prolonged user-behavior change than the experiments presented in the previous section. Therefore, our hypotheses are as follows:

Hypothesis 1: The use of a smart faucet intervention decreases the water consumption of a user for a given activity.

Hypothesis 2: The interaction with a smart faucet decreases the water consumption of a user immediately after the intervention is discontinued.

3. METHOD

The user experiment described in this paper was a between-subject experiment conducted at Stanford University. Users washed 3 sets of dishes with a custom faucet to identify the water saving potential of a "smart" faucet, possible user reactions to a perceived autonomous product, and residual effects users may carry with them after (drawing of bottom here) interacting with the faucet. Users placed in the experimental group interacted with a "smart" faucet that would adjust its flow and temperature according to the task and behavior of the user. While a future implementation of this system could automate the "smart" behavior, we utilize a Wizard-of-Oz (WoZ) [42] method to remotely control the faucet. WoZ control refers to when a "wizard", a member of the experimental design team, remotely controls a robot to perform an action. This can be employed so that a human is able to control a potentially dangerous interaction, or in this case, to prototype and learn about a potential design before fully implementing the robot's behavior algorithmically. Although the wizard can control the faucet, all users can also control the faucet normally, so control over the faucet settings are shared. For the purposes of this paper, "normal" faucet operation is when the faucet only acts upon commands given to it through turning the handles by the user, and "smart" faucet operation is when both the wizard and the user can control the faucet concurrently. The following section discusses the design parameters and construction of the WoZ faucet.

3.1 Faucet Design

Since the faucet must be able to simultaneously share control of the temperature and water flow with both the participant and a wizard, a custom faucet was required. Shared control was accomplished through retrofitting the current water lines with electronic servomotors. Secondary to the simultaneous control, the water used by each participant must be tracked for each set of dishes that they washed. Since, the freestanding faucet could not be hooked up to a main drainage line, waste water was stored in a 50-qt bucket below the faucet basin. A platform with a load cell was then designed to support the waste bucket and provided real-time tracking of water consumption.

Aesthetically, the faucet was designed with the intent to blend into a typical household environment and evoke minimal initial emotions of novelty or curiousness from users. Therefore, electronics are concealed in plastic housings alongside weight monitoring devices and water collection buckets that are hidden in the cabinet below the sink. However, the servomotors that control the faucet do emit an audible noise when they turn.

As seen in Figure 2, the Raspberry Pi can control the cold and hot lines via gear trains that open each respective valve. Servos were connected to each gear train and could be individually controlled so that all usable faucet settings could be reproduced. For ease of control during experiments, a GUI (Graphical User Interface) was created for an operator to easily select the desired flow and temperature settings. Weight tracking is controlled by a separate script, which tares, measures weight at a fixed time step, and then saves the data to a text file for each phase of the experiment.

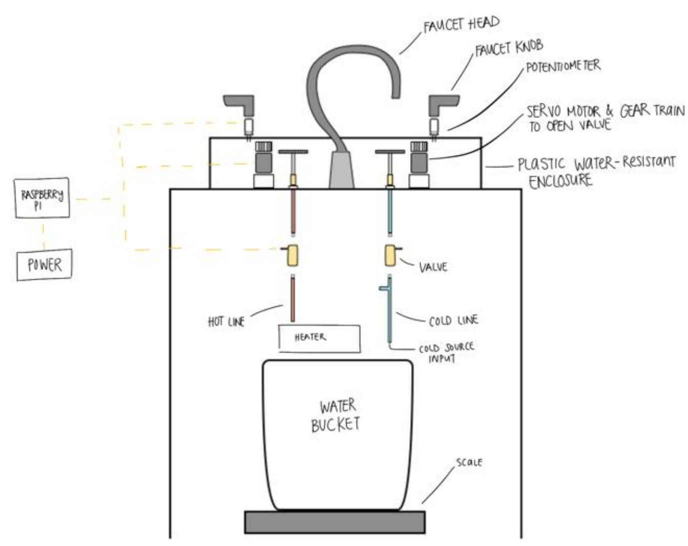

FIGURE 2 FAUCET SETUP FOR WOZ CONTROL

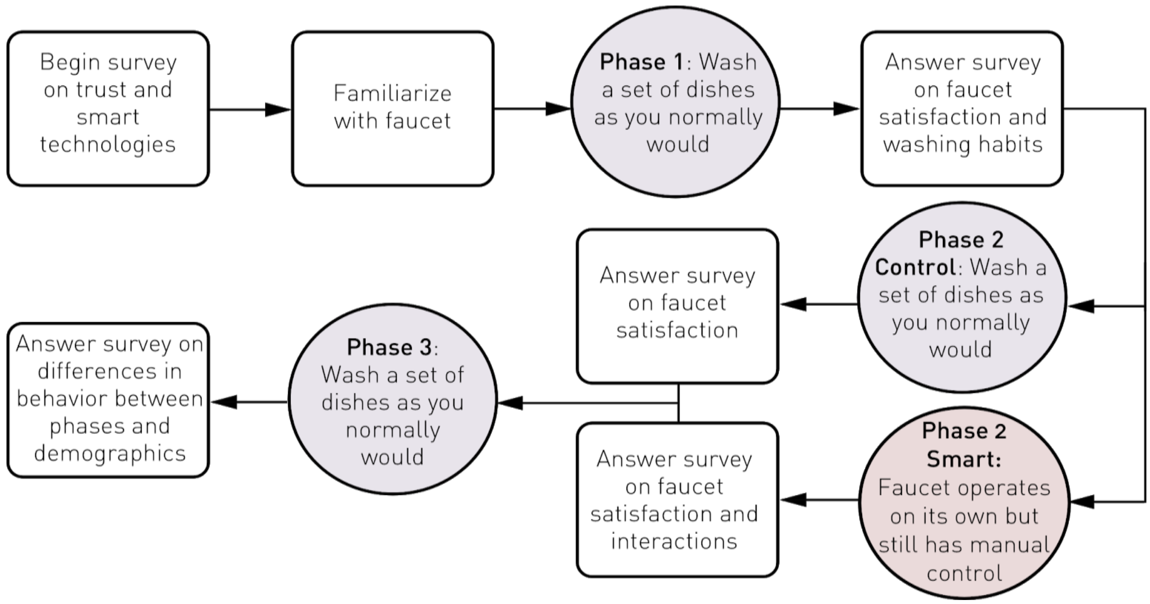

FIGURE 3 FLOW CHART DIAGRAM OF EXPERIMENT SETUP

3.2 Experimental Set-up

A three phase set up, with a baseline phase, treatment phase, and discontinued treatment phase, has previously been successful in comparing use between experimental and control groups during a treatment and after a treatment [34]. Studies have shown that efforts to improve water consumption using feedback and cognitive dissonance in the short term have proved successful during both the treatment phase and the following discontinued treatment phase [22]. Therefore, we modeled our experiment so that we can test for hypothesis 1 and hypothesis 2 with this 3 phase setup as shown in Figure 3.

Both the control group and the experimental, or "smart" group have 3 distinct phases where they are asked to wash a set of dishes. For all phases except for the 2nd phase of the experimental group, the custom faucet operates in manual mode. The experimental group is informed through a computer survey that the faucet will now "function as an interactive smart faucet" in phase 2. To explore hypothesis 1, the effect of the treatment phase (phase 2) versus the baseline phase (phase 1) will be compared between the control and experimental groups to see what impact the smart faucet has on users. The effect of the discontinued treatment phase (phase 3) will then be compared to the baseline phase (phase 1) to test for hypothesis 2: to identify if interaction with the smart faucet changes the behavior and resource consumption of participants.

3.3 Experimental Procedure

The experiments were performed in the Interdisciplinary Research in Sustainable Design Lab (IRIS) at Stanford University. Participants - whose demographics are discussed at the end of the section - were recruited from both on campus flyers, university email lists, as well as from flyers at a local grocery store plaza.

The experiment begins with a proctor, otherwise referred to as a host, who welcomes the participants and informs that the purpose of the study is to investigate faucets, as the research propositions regarding water conservation cannot directly be revealed (IRB approved). There were 3 different lab members who would serve as the proctor, but the wizard was kept consistent throughout all experiments. The proctor then leads the participants to a laptop next to the faucet, which guides them through the rest of the experiment. The wizard is hidden from the participants behind an opaque screen throughout the experiment. Participants are pre-assigned to the control or experimental condition randomly prior to the start of the experiment

The computer then asks the participants a series of questions about their demographics before asking them to wash their hands in the faucet. This activity was designed so that the participants gain familiarity with how the faucet operates like a normal faucet.

FIGURE 4 THE 3 SETS OF DISHES AFTER BEING WASHED BY PARTICIPANTS

3.3.1 Experimental Procedure: Phase 1 Following the hand washing activity, Phase 1 begins and the proctor(s) (varying from one to two proctors depending on lab member availability) bring out one set of dirtied dishes as shown in Figure 4. The dishes were dirtied with a mixture of cornstarch, water, and food dye that formed a sticky goo. Pilot studies found that the cornstarch mixture was easy to identify, typically required a sponge to remove, and would not spoil or become rancid throughout the course of multiple experiments. The ratio of cornstarch to water (3:2) was maintained across all experiments for consistency in washing difficulty.

Phase 1 is the baseline phase in which participants of both the control and experimental group are asked to use the faucet as they normally would to wash the set of dirty dishes provided to them. They are instructed to wash and then place the dishes in the drying rack provided next to them. When completed, they complete a survey on their satisfaction with how the faucet operated and their dishwashing habits–whether they wash by hand or by automatic dishwashers–as well as how often they wash the dishes themselves. Upon completion of the survey questions, the computer instructs the participants to leave the room for the hosts to prepare the next phase. Once participants leave the experiment room, the clean dishes are removed, a new set of dirty dishes are placed next to the faucet, and the waste bucket is emptied.

Leaving the room between phases was implemented after the discovery that some participants would use enough water to overflow the waste bucket- 21 participants were not asked to leave the room, but there was no significant difference in the data collected between the two groups of participants. To not give indication about the purpose of the study, or to influence participant behavior in between phases, they were asked to leave during the emptying and resetting of the waste bucket.

3.3.2 Experimental Procedure: Phase 2 Phase 2 is the treatment phase where faucet behavior differs between the control and the experimental condition. Participants in the control group are given the same instructions that they received in Phase 1 and another identical set of dishes. The participants of the experimental group are told through a statement in the survey that, “The faucet will now function as an interactive smart faucet. It will operate on its own, but can still be controlled manually like in phase 1.” Beyond the survey statement, participants had no exposure to how the “smart” faucet would behave. Afterwards, both sets of participants are asked to answer questions on their satisfaction with the faucet and the experimental group has an additional set of questions concerning their interactions with the self-operating faucet. The participants are asked once again to leave the room as the proctor resets the waste bucket and dishes.

3.3.3 Experimental Procedure: Phase 3 Phase 3 is the discontinued treatment phase, in which participants in both the control and experimental groups are given the same instructions that they received in Phase 1. Both groups will operate the faucet manually to wash a third set of dishes. Upon completion, they are asked to answer questions regarding the differences they perceived throughout the experiment, as well as to gauge how much water they thought they used in each phase of the experiment. Once the participants completed all of the questions on the survey, the experiment concludes and participants are given their compensation via an email code.

It should be noted that the change for asking participants to leave the room occurred after a participant had overflowed our collection bucket. That data was not used, and statistical tests conducted after the study had completed showed no difference between the users who had stayed in the room prior to the change, and users asked to leave between phases.

3.4 Wizard Control Scheme

Building upon the work of Ramaswamy and MacDonald, the dishwashing activity was broken into the same 4 categories of Preparation, Unsoiling, Soaping, and Rinsing. Preparation refers to initial wetting of the dish and soaping of the sponge; Unsoiling refers to the removal of material from the dish via hands or sponges; Soaping refers to the usage of soap to clean the dish - and may be commonly performed simultaneously with Unsoiling; and finally, Rinsing refers to using water to wash away remaining soap and debris. The state chart below is formatted as a state chart according to Unified Modeling Language (UML) and provides the wizard a model by which to know how to act when it is presented with different scenarios.

The wizard has two methods to observe what is occurring during the experiment. In phase 1, the wizard can use the GUI to see exactly what settings the user selects for each of the dishwashing categories. These settings for both the cold and hot handles are recorded so the wizard has a reference for the user’s preferred baseline settings. Throughout the experiment, the wizard also is able to view the sink area of the faucet via camera relay, so they can tie the preferred settings to the item that is currently being washed.

During phase 2, the wizard then follows the logic shown above in Figure 5. The UML state chart above depicts how the wizard is analyzing each individual item that the user is washing. UML notation indicates that a solid circle is the starting point for each state. The wizard begins if logic in the Flow Off state initially for each particular item. If the wizard detects an item underneath the faucet, it then enters the Flow On state and the ‘H’ denotes that the Flow On state has history. This means the wizard will remember what state within the Flow On state it was last in if it ever must transition to the Flow Off state.

Whenever the wizard is in the Flow On state, it will refer to the baseline desired setting for each item from Phase 1, as well as what the experiment designers have designated as Sustainable Usage (SU) settings. SU settings for each item were defined through pilot testing as the lowest acceptable flow and temperature reported by users - approximately 70ml/s and 37 degrees Celsius [14]. These settings were calibrated through measurements of collected water over a set amount of time for defined servomotor angles.

3.4.1 Water Flow Control Settings are determined by 9 preset servo rotation settings, from 0 to 8 (with 0 being off and 8 being maximum flow).

- If the user prefers temperature or flow rates that are greater than the SU settings by a value of 2 for either category, the wizard will set the faucet at a setting that is 2 lower for each category, but still above the SU settings.
- If the user prefers temperature of flow rates above the SU settings by less than a value of 2, the wizard will set the faucet at the SU settings
- Else, the wizard will set the faucet at the users baseline desired settings if they are below the SU settings
- If the user manually overrides the settings provided by the wizard at any point of the experiment, the wizard will attempt the procedure of lowering the flow or temperature once more on the next transition between Flow Off to Flow On. If the user overrides the wizard again, the wizard will then refer to the user's baseline desired settings for the remainder of the experiment.

Preparation, Unsoiling, Soaping, and Rinsing each have their set of SU settings, and transitions between each state are controlled by the wizard via the observations available to the wizard as described in section 3.4. The logic of the Wizard of Oz State Chart was designed to be objective and consistent across all participants, but human error during the control process is inevitable. To alleviate the concerns addressed by [5][14], the same wizard controlled each experimental phase for consistency, and performed multiple trials before the study began.

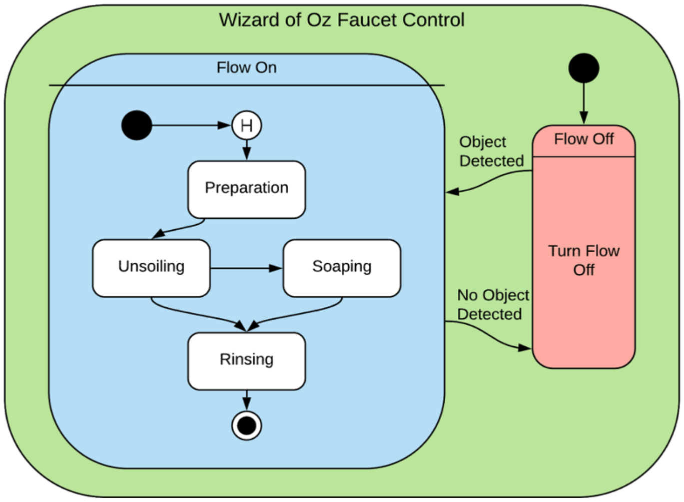

FIGURE 5 WIZARD OF OZ CONTROL STATE CHART

3.5 Participants

In order to conduct the proposed experiment, we recruited individuals in the Stanford-Palo Alto area to voluntarily participate. Flyers and email listings offered a $15 Amazon gift card upon completing the experiment. In total, 52 participants were recruited, with 26 participants in pre-assigned in each group.

As seen in Table 1, in total we recruited 19 male participants and 33 female participants. Of the 52 participants, 44 were age 18-29, 3 were age 30-49, 3 were age 50-64, and 2 were age 65+.

TABLE 1 DEMOGRAPHICS

		Control	Smart	Total
Age	18-29	23	21	44
	30-49	1	2	3
	50-64	1	2	3
	65+	1	1	2
Education	Highschool Diploma/ GED	1	1	2
	Associate's	0	0	0
	Some college	19	17	36
	Bachelor's	3	2	5
	Master's	2	5	7
	PhD	1	1	2
	Professional	0	0	0
Gender	Male	10	9	19
	Female	16	17	33
	Other	0	0	0
Race	Asian	11	11	22
	Black	1	0	1
	Caucasian	9	10	19
	American Indian	0	0	0
	Native Hawaiian/ Pacific Islander	0	0	0
	Mixed Race	3	3	6
	Other	0	0	0
	Prefer not to say	2	2	4

3.6 Data Collection

During the experiments, we recorded videos of the users' hands and the sink. While the experiments were being conducted, we watched participants through the camera to record data, such as number of handle touches. Videos were also reviewed post-experiment to record total time per phase. We decided to measure the number of handle touches to serve as a proxy for good behavior, where good behavior would mean turning the faucet on and off more frequently to conserve water. We hypothesized that more handle touches would correspond to more water conservation, as users would be turning the faucet off more frequently while soaping dishes. Since the video recordings included time duration, we decided to analyze the total time per phase after the experiments to see if there was any correlation between amount of water used and total time duration. We also measured the amount of water used, using a scale and a large bucket under the sink. Due to limitations of sensors, were unable to measure the real-time temperature and flow being used by participants.

Data was also collected in a survey, administered via Qualtrics and previously mentioned in Section 3.3.1. This survey collected data on water conservation views, dishwashing frequency, satisfaction ratings for flow-rate and temperature, as well as fill-in forms for participants to share what they thought the experiment concerned. Questions were spaced throughout the different phases to increase participant engagement.

4. RESULTS AND FIGURES

As shown in Figure 6 and Table 2, we compared the percent reduction in water (by weights) used between phases 1 and 2 and phases 1 and 3 for each group. From here, we will refer to percent decrease between phases 1 and 2 as %Δ1-2 and the percent decrease between phases 1 and 3 as %Δ1-3. The average %Δ1-3 for the control group was -4.42%, compared to an average of 10.10% for the experimental group. A positive %Δ indicates a decrease of water use because 'water used in phase 1' - 'water used in phase 2' is positive. The standard error for the control group was 8.97 for %Δ1-2 and 6.53 for %Δ1-3. The standard error for the experimental group was 5.85 for %Δ1-2 and 4.45 for %Δ1-3. The average %Δ1-2 for the control group was -12.5%, compared to an average of 26.5% for the experimental group.

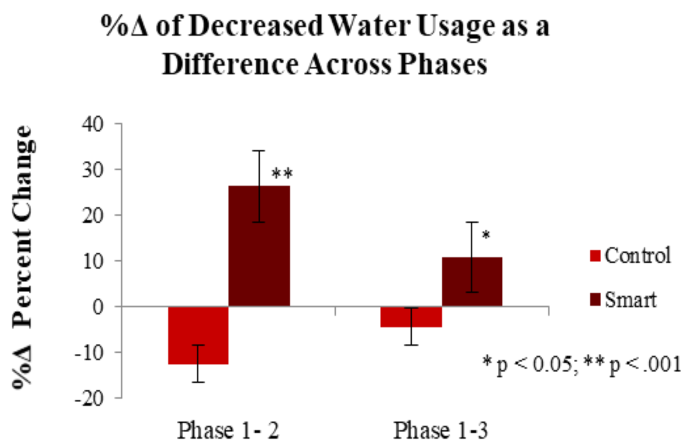

FIGURE 6 PERCENT DECREASE IN WATER USE AS A DIFFERENCE ACROSS PHASES

TABLE 2 PERCENT DECREASE IN AMOUNT OF WATER USED BETWEEN PHASES

	Control Avg	Experimental Avg	*p-value
%Δ1-2	-12.5	26.5	0.0003
%Δ1-3	-4.42	10.9	0.0290

After conducting a two-sample t-test, we found a corresponding p-value < 0.0005 for %1-2 and p < 0.05 for %1-3 when comparing the experimental group to the control group, as summarized in Table 2. The average water used per phase recorded in gallons is displayed above in Table 3. We collected this data in order to verify our original hypotheses. Meanwhile, the following data results attempt to find correlations between different habits and water usage, which could aid in grouping the participants as having different cognitive styles while at the sink.

We recorded the number of total touches per participant per phase per group. As shown in Figure 7 and Table 3 below, the correlation between the number of total touches and weight is weakly negative, meaning the more times the participant interacted with the sink, the less water was used, for every phase except for Experimental phase 2, where there is no correlation. A t-test of the number of touches in Phase 1 (the baseline phase) between the experimental and control groups revealed a p-value > 0.5, showing that our groups do not significantly differ.

TABLE 3 AVERAGE HANDLE TOUCHES AND VOLUME OF WATER USED PER PHASE

		Avg Touches	Avg Water Used (gal)	Correlation
Experimental	Phase 1	8.9	2.38	-0.36
	Phase 2	3.3	1.61	0.00
	Phase 3	9	2.04	-0.54
Control	Phase 1	8.5	2.25	-0.30
	Phase 2	8.9	2.37	-0.25
	Phase 3	8	2.33	-0.30

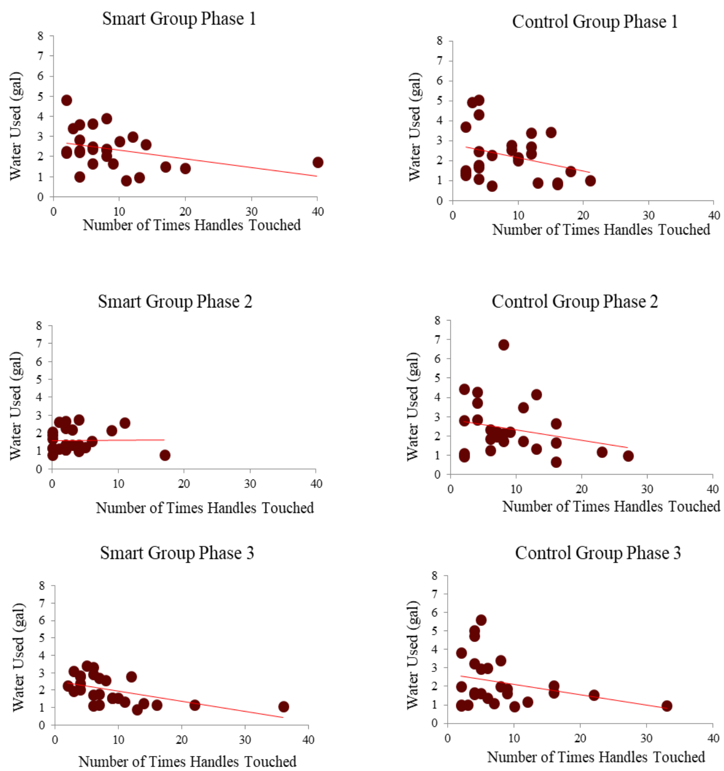

FIGURE 7 CORRELATION BETWEEN AVERAGE HANDLE TOUCHES AND VOLUME OF WATER USED PER PHASE

In a survey before beginning the experiment, all participants were posed the phrase, "I am likely to trust a machine even when I have little knowledge about it," and asked to rate agreement on a scale from 1 (not trusting at all) to 5 (extremely trusting). We used this data to compare how trusting the participants were of smart technologies to how much water they used per phase. As shown in Table 5, there is no correlation between trust score and %Δ1-2 or %Δ1-3, as calculated with the Pearson Test with the Holm adjustment method [43]. However, for the experimental group, the correlation between trust and water usage for %Δ1-2 was slightly higher than the other groups, at 0.21. Between the experimental and control groups, the trust scores were not significantly different. A t-test between the two groups revealed p > 0.1, showing that our groups did not significantly differ in their pre-faucet trust ratings.

TABLE 4 TRUST SCORE AND PERCENT DECREASE IN WATER USED BETWEEN PHASES

	Average Trust Value	1-3 Correlation	1-2 Correlation
Experimental	3.27	0.04	0.21
Control	3.54	0.05	0.08

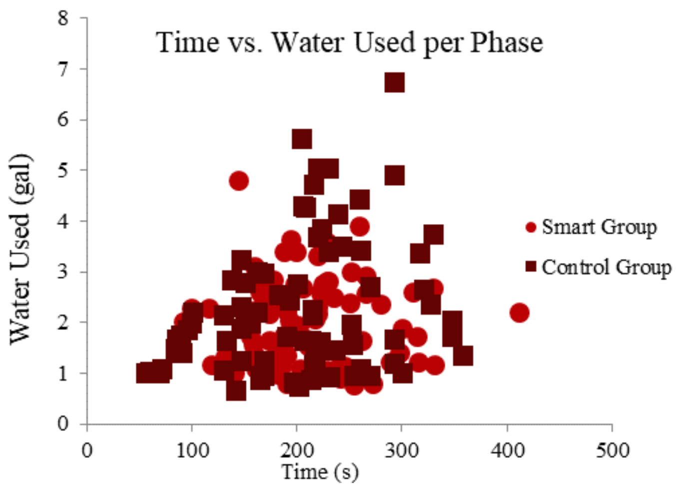

FIGURE 8 CORRELATION BETWEEN TIME SPENT WASHING DISHES AND TOTAL WATER USAGE

Next, we recorded the total time needed to complete each phase of the experiment, plotted in Figure 8. From this figure, we determine that there is not a strong correlation between time taken and water used for either the control or experimental group. Table 6 shows the average time used per phase across all participants in their given groups. A t-test of the time duration in phase 1 between the control and experimental groups revealed $p > 0.5$, showing that our groups did not differ significantly.

TABLE 5 AVERAGE TIMES RECORDED PER PHASE IN MINUTES

	Phase 1	Phase 2	Phase 3
Experimental	3:33	3:46	3:15
Control	3:27	3:20	3:16

During the final stage of the survey, after completing all faucet activities, the participants answered the question, “Would you consider purchasing the faucet you interacted with in phase 2?” Note that for the control group, this was exactly the same faucet, with no smart interaction, as in Phase 1. For the control group, 9 participants said “Yes,” 11 participants said “No,” and the remaining 6 participants selected “N/A.” For the experimental group, 18 participants selected “Yes,” 7 participants selected “No,” and the remaining 1 participant said “N/A.” We grouped these answers into “Yes” and “Not yes” by combining the “No” and “N/A” options. By assigning an answer of “Yes” to be 1 and an answer of “No” or “N/A” to be 0, we formed the null hypothesis that the difference between the means of the two groups would be 0 with the alternative hypothesis that the difference between the means of the two groups would be greater than 0. This resulted in a significant p-value of $p < 0.01$. When we grouped these answers into “Yes” and “No,” by ignoring the “N/A” data, and ran the same test, we ended up with a significant p-value of $p < 0.05$, shown in Table 6 below. Therefore, we can confidently reject the null hypothesis that the two groups have the same preference for the faucet. Similarly, 25 out of 26 participants in the smart interaction group answered “Yes” to “Do you think a smart faucet like you interacted with in phase 2 could help you save water?”

TABLE 6 RESPONSES ABOUT PURCHASING FAUCET FOR EACH GROUP AND P-VALUE

	Yes	Not Yes
Experimental	18	8
Control	9	17
P-Value*	0.006	

Finally, we needed to ensure that the procedure change of asking participants to leave the room between phases to empty out the bucket did not affect participant behavior. Therefore, we conducted four more T-Tests with the following null hypotheses. The difference between the %Δ1-2 for the smart group where the bucket was emptied between phases and the smart group where the bucket was not emptied is 0, the difference between the %Δ1-3 for the smart group where the bucket was emptied between phases and the smart group where the bucket was not emptied is 0, the difference between the %Δ1-2 for the control group where the bucket was emptied between phases and the control group where the bucket was not emptied is 0, and the difference between the %Δ1-3 for the control group where the bucket was emptied between phases and the control group where the bucket was not emptied is 0. We set $p < 0.05$ to be significant. Table 7 below shows the results of these tests, none of which were significant.

TABLE 7 DIFFERENCES BETWEEN GROUPS BEFORE AND AFTER PROCEDURE CHANGE

	P-value
%Δ1-2 smart	0.157
%Δ1-3 smart	0.170
%Δ1-2 control	0.0513
%Δ1-3 control	0.149

5. DISCUSSION

Subjects in the experimental group used considerably less water in phase 2 as compared to phase 1, as compared to the control, affirming hypothesis 1: a wizard-of-oz "algorithm" saves water over manual dish washing. Subjects also used considerably less water in phase 3 as compared to phase 1 in the experimental group as compared to control group, affirming hypothesis 2: this savings continues when manual washes resumes.

Observing faucet touches (adjustments of the knobs) shows that smart phase 2 not only conserves significant water, but does so primarily via its own control. Minimal user touches in this phase by users show that they were willing to let the faucet perform on its own and suggests acceptance of the technology. The faucet confirmed hypothesis 2, that interacting with the faucet reduced water consumption in future interactions; however, it did not affect the number of touches between phase 1 and 3. This suggests that the learning is not via the on-off behavior of the faucet, but rather lowering overall faucet flow rate. Once people try a lower flow and learn that it adequately washes dishes, they will use it again in immediate interactions. This leads us to wonder if systems of this design could be employed elsewhere in the home (or car), and how design could encourage less water consumption. For example, using such a faucet at work may encourage people to try a lower flow lever at home, but such a conclusion would require further research.

The positive correlation of users with higher trust scores having a higher value for percent decrease in water used between phase 1 and phase 2 indicates that a user's baseline trust of the technology is correlated with the effectiveness of the intervention.

From the text box responses on the survey regarding "Do you think a smart faucet like you interacted with in phase 2 could help you save water", many participants mention that "It definitely cut down on the amount of time the water was running, and therefore conserved significant amounts of water" and "The automatic feature of turning off the water is something I would never do by hand in order to save time…" In general, participants found the smart faucet to provide a convenient solution to something that they might not necessarily pay attention to in their daily lives. Certain individuals even remarked about the potential for the faucet to "…to slowly force me to change habits, or make marginal impacts on consumption that would lead to huge savings in the long run." With 96% of participants in the smart intervention believing that there is potential for a smart faucet to save water and a statistically significant increase in purchase consideration over the control group, the study shows consumers can see the benefit of such devices. When compared to the devices studied by Hopp and Geller, this study incorporates an active intervention that not only can be used in a long-term fashion to save water, but also to encourage users to be active and conscious about their energy and water usage habits [23][25].

Some potential sources of bias from our study include: (1) age, as most participants were between the ages of 18 and 29; (2) gender, as many more females than males signed up to participate, and (3) education, as the participants were predominately students at Stanford University. There are a number of other limitations. Participants enjoyed the novelty of the dyed cornstarch during pilot testing, however some participants mentioned they did not wash the dishes as they normally would as there were no fats and oils that accompany normal meals. To test for consistency of washing behavior, additional questions were added in the survey regarding their dish-washing frequency per week as well as their water conservation views, but the data was not significant. Additionally, the study took place over a short period of time. An extended study that can evaluate participant's usage in their homes before and after the intervention would be a stronger method of quantifying the long-term effects of this intervention.

Furthermore, in rare scenarios participants would adjust the faucet simultaneously with the wizard. The faucet would then execute the commands in the order that they were received, potentially leading to a jarring experience for the participant. Ideally, over time the system would be able to better understand the needs of the user and such instances would be rare. Although the data showed that participants were interested in purchasing the smart faucet, the question did not assign a price to this faucet nor explain how installation would occur, and it is likely that these two factors would negatively influence purchase intentions. Thus, more work is needed in examining willingness-to-purchase a smart faucet.

6. CONCLUSION

Our study confirmed Hypotheses 1 and 2: that a smart faucet, controlled by Wizard of Oz method, could save water during interactions with users, as well as train a user to save water in a non-smart interaction that immediately followed the smart one. Significant water savings in "smart" mode demonstrates promise for developing these systems in areas of high traffic as well as in homes. Slight water savings during non-smart following interactions reveals an area for future study in which in-home studies could be conducted over time to track human behavior. In this study, we could not track long term behavior changes after repeated sink use since our study was completed in one hour time slots. Further study would include tracking long term behavior by installing a faucet in people's homes or monitoring continuous user interaction with the smart faucet over a period of time. The participant pool and study locations would also need to be expanded, to gather data from users beyond the Stanford community and surrounding areas. Additionally, it would be useful to test if a one-time intervention or faucet training session could make a long-term impact on non-smart faucet usage.

Building upon our specific study, it would be interesting to see how a truly autonomous system would adapt to user behavior. Research could be conducted on exploring how to introduce different human behaviors to the system before any interactions occur to prime the system, or to see how the system tries to categorize the user. Different arrays of sensors from computer vision to inductive metal sensors could also greatly affect system performance. Ultimately, not only does this study show that brief training to conserve water can potentially provide lasting effects, but that there is a rich opportunity to design products to better suit our users and protect our planet's natural resources.

ACKNOWLEDGMENTS

We thank Hala Al-Khalil, Ufuoma Ovienmhada, and Naren Ramaswamy for their help with creation of the faucet, as well as Ting Liao for her considerable contributions to the experiment analysis. This research is based upon work supported by the National Science Foundation under Grant No. 1548234. Any opinions, findings, and conclusions or

recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] "Table 2.1 Energy Consumption by Sector." U.S. Energy Information Administration. U.S. Government. 19 Feb. 2019 <https://www.eia.gov/totalenergy/data/monthly/pdf/sec2_3.pdf >.

[2] "Costanzo, Mark, et al. "Energy conservation behavior: The difficult path from information to action." American psychologist 41.5 (1986): 521.

[3] Corral-Verdugo, Víctor, Robert B. Bechtel, and Blanca Fraijo-Sing. "Environmental beliefs and water conservation: An empirical study." Journal of Environmental Psychology 23.3 (2003): 247-257.

[4] Geller, E. Scott. "Evaluating energy conservation programs: Is verbal report enough?." Journal of Consumer research 8.3 (1981): 331-335.

[5] Nietzel, Michael T., and Richard A. Winett. "Demographics, attitudes, and behavioral responses to important environmental events." American Journal of Community Psychology 5.2 (1977): 195-206.

[6] Karjalainen, Sami. "Consumer preferences for feedback on household electricity consumption." Energy and buildings43.2-3 (2011): 458-467.

[7] Mayer, Peter W., et al. "Residential end uses of water." (1999).

[8] Willis, Rachelle M., et al. "Alarming visual display monitors affecting shower end use water and energy conservation in Australian residential households." Resources, Conservation and Recycling 54.12 (2010): 1117-1127.

[9] Gauley, B., and J. Koeller. "Sensor-operated plumbing fixtures: do they save water." California Energy Commission DOCKETED (2010).

[10] Yang, Rayoung, and Mark W. Newman. "Learning from a learning thermostat: lessons for intelligent systems for the home." Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing. ACM, 2013.

[11] Riding, Richard, and Stephen Rayner. Cognitive styles and learning strategies: Understanding style differences in learning and behavior. David Fulton Publishers, 2013.

[12] Mayer, Peter W., et al. "Residential end uses of water." (1999).

[13] Gauley, B., and J. Koeller. "Sensor-operated plumbing fixtures: do they save water." California Energy Commission DOCKETED (2010).

[14] Ramaswamy, N. and MacDonald, E. (2017). Telepathic product design for water conservation. In DS 87-1 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 1: Resource Sensitive Design, Design Research Applications and Case Studies, Vancouver, Canada, 21-25.08. 2017.

[15] Gilg, Andrew, and Stewart Barr. "Behavioural attitudes towards water saving? Evidence from a study of environmental actions." Ecological Economics 57.3 (2006): 400-414.

[16] MacDonald, Erin F., and Jinjuan She. "Seven cognitive concepts for successful eco-design." Journal of Cleaner Production 92 (2015): 23-36.

[17] Fogg, Brian J. "Persuasive technology: using computers to change what we think and do." Ubiquity 2002.December (2002): 5.

[18] Flack, J. Ernest, and Joanne Greenberg. "Public attitudes toward water conservation." Journal of American Water Works Association 79.3 (1987): 46-51.

[19] Kappel, Karin, and Thomas Grechenig. "Show-me: water consumption at a glance to promote water conservation in the shower." Proceedings of the 4th international conference on persuasive technology. ACM, 2009.

[20] Chetty, Marshini, David Tran, and Rebecca E. Grinter. "Getting to green: understanding resource consumption in the home." Proceedings of the 10th international conference on Ubiquitous computing. ACM, 2008.

[21] Kuznetsov, Stacey, and Eric Paulos. "UpStream: motivating water conservation with low-cost water flow sensing and persuasive displays." Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, 2010.

[22] Aitken, Campbell K., et al. "Residential Water Use: Predicting and Reducing Consumption" Journal of Applied Social Psychology 24.2 (1994): 136-158.

[23] Hopp, Wallace J., and William P. Darby. "Household water conservation: the role of indirect energy savings." Energy 5.12 (1980): 1183-1192.

[24] Willis, Rachelle, et al. "Revealing the impact of socio-demographic factors and efficient devices on end use water consumption: case of Gold Coast Australia." Proceedings of the 5th IWA Specialist Conference Efficient 2009. 2009.

[25] Geller, E. Scott, Jeff B. Erickson, and Brenda A. Buttram. "Attempts to promote residential water conservation with educational, behavioral and engineering strategies." Population and Environment 6, no. 2 (1983): 96-112.

[26] Han, D. M., & Lim, J. H. (2010). Design and implementation of smart home energy management systems based on zigbee. IEEE Transactions on Consumer Electronics, 56(3), 1417-1425.

[27] Gupta, Manu, Stephen S. Intille, and Kent Larson. "Adding gps-control to traditional thermostats: An exploration of potential energy savings and design challenges." International Conference on Pervasive Computing. Springer, Berlin, Heidelberg, 2009.

[28] Scott, James, et al. "PreHeat: controlling home heating using occupancy prediction." Proceedings of the 13th international conference on Ubiquitous computing. ACM, 2011.

[29] Capone, Antonio, et al. "A new architecture for reduction of energy consumption of home appliances." TOWARDS

ENVIRONMENT, European conference of the Czech Presidency of the Council of the EU. 2009.
[30] Hazas, Mike, A. J. Brush, and James Scott. "Sustainability does not begin with the individual." Interactions 19 (2012).
[31] Pierce, James, Diane J. Schiano, and Eric Paulos. "Home, habits, and energy: examining domestic interactions and energy consumption." Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, 2010.
[32] Jahn, Marco, et al. "The energy aware smart home." 2010 5th international conference on future information technology. IEEE, 2010.
[33] Froehlich, Jon, Leah Findlater, and James Landay. "The design of eco-feedback technology." In Proceedings of the SIGCHI conference on human factors in computing systems, pp. 1999-2008. ACM, 2010.
[34] Lynham, John, et al. "Why does real-time information reduce energy consumption?." Energy Economics 54 (2016): 173-181.
[35] Abrahamse, Wokje, et al. "A review of intervention studies aimed at household energy conservation." Journal of environmental psychology 25.3 (2005): 273-291.
[36] McClelland, L., & Cook, S. W. (1979). Energy conservation effects of continuous in-home feedback in all-electric homes. Journal of Environmental Systems, 9(2).
[37] Rayner, Stephen, and Richard Riding. "Towards a categorisation of cognitive styles and learning styles." Educational psychology 17.1-2 (1997): 5-27.
[38] Witkin, Herman A., et al. "Field-dependent and field-independent cognitive styles and their educational implications." ETS Research Bulletin Series 1975.2 (1975): 1-64.
[39] Hauser, John R., et al. "Website morphing." Marketing Science 28.2 (2009): 202-223.
[40] Urban, Glen L., et al. "Morphing banner advertising." Marketing Science 33.1 (2013): 27-46.
[41] Cassidy, Simon. "Learning styles: An overview of theories, models, and measures." Educational psychology 24, no. 4 (2004): 419-444.
[42] Kelley, J. F. (1984). An iterative design methodology for user-friendly natural language office information applications. ACM Transactions on Information Systems, 2(1), 26–41. http://dx.doi.org/10.1145/357417.357420
[43] Holm, Sture. "A Simple Sequentially Rejective Multiple Test Procedure." *Scandinavian Journal of Statistics* 6, no. 2 (1979): 65-70.