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EnviRobots: How Human–Robot Interaction Can Facilitate Sustainable Behavior

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Abstract: Environmental psychology aims to study human behavior with regard to the environment and how psychological techniques can be used to motivate behavior change. We argue that these concepts can be applied to interactive robots designed for other tasks, which then enables them to encourage sustainability behaviors in humans. We first present a literature review on the current state of social robots that are used to encourage sustainable behaviors. We next present eight hypothetical scenarios which are informed by the progress that has already been made in social robots in sustainability, as well as notable gaps where further environmental psychological concepts could be utilized. These scenarios encompass possible robots that range from limited sensing and no manipulation capabilities, to more sophisticated sensing and no manipulation, to sophisticated sensing and manipulation capabilities. We present these scenarios in which human–robot interaction could potentially result in pro-environmental behavioral changes in humans as recommendations for robot designers interested in helping design social robots for sustainability.

Keywords: human–robot interaction; ecological psychology; sustainability robots

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1. Introduction

Sustainability has become an increasingly urgent societal challenge that must be addressed as quickly and efficiently as possible (e.g., see [1]). One line of attack has involved deploying autonomous robots for various sustainability tasks, from environmental monitoring, to picking up and sorting trash (e.g., [2–6]). Yet, the potential of autonomous robots to contribute to sustainability does not stop with autonomous machines operating independently from humans. Given that most sustainability efforts involve changing human awareness and consequently human behavior, robots, in particular, social robots, that are able to interact with humans can be utilized to encourage more sustainable behavior in people. A social robot can be defined as a physically embodied artificial system (hence, not avatars or virtual agents) that exists in a social environment, and interacts with and attends to other members of the social community [7,8]. Social robots have been shown to be able to exert social influence on humans [9,10], and various efforts have thus focused on how to utilize this influence for good, e.g., by using robots to promote positive behaviors, such as empathy in people [11], establishing healthy habits [12], and donating to charity [13].

Little research, however, has investigated how existing (1) interactive robots that are designed for other tasks, and (2) non-interactive robots designed for sustainability tasks that can be made interactive, could encourage more sustainable behaviors in humans. Such combinations would be particularly powerful because human–robot interaction research has demonstrated that embodied agents like robots are often more convincing in their messaging than virtual agents or other forms of reminder systems (e.g., [14,15]). Different from virtual agents, robots can sense their environment, and thus have the ability to detect and assess human behavior. For example, capabilities like monitoring whether a faucet or a stove is on might be desirable when developing assistive robots for people with impaired cognition or dementia, but the same capabilities could be used for supporting energy and resource conservation. Moreover, by being able to act in the environment, robots are able to effect changes themselves, and are thus able to demonstrate tasks or help humans perform them (e.g., recycling).

What is needed is a way to apply concepts from environmental psychology that were developed for instilling sustainable behavior in humans to robots, in order for robots to be able to encourage and establish sustainable behavior patterns in people. The goal of this paper is to show that such concepts can be integrated into various existing robot platforms designed for other purposes, which then allows these robots to take on additional perceptual and physical manipulation, as well as verbal educational tasks regarding sustainability and human behavior modification. By utilizing existing platforms, the entry cost for such robots is low, while the potential benefit of effecting human behavior changes could be very significant.

The rest of the paper is organized as follows. We first review applications of autonomous robots for pro-environmental tasks, as well as the basic tenets of environmental psychology, followed by a summary of the state-of-the-art of human–robot interaction for sustainability. Then, we discuss eight hypothetical scenarios where existing, as well as novel robots with interaction capabilities, can be used to apply environmental psychology concepts to encourage sustainable behavior in people. We conclude with a summary and an outlook for future research needed to evaluate the effectiveness of such robots.

2. Pro-Environmental Robots

Various robots have been developed for pro-environmental tasks over years, utilizing their ability to physically manipulate environments to perform tasks that might be dull, dirty, or dangerous for humans. One common application is recycling and waste management, where autonomous robots sort waste products and determine what can and cannot be recycled [3,16]. Wang et al. [5] developed a robot that patrols construction sites and finds, collects, and sorts material, such as discarded screws and nails, to be recycled. Another research group used two robots, the *Mobile Robot Waste Deliver System* (MRWDS) and the *Automated Waste Sorter* (AWS) to collect and sort recyclable and non-recyclable materials. The former robot collects waste bins to bring back to the AWS. The AWS then identifies and removes the steel and aluminum cans, and glass and plastic bottles that can be recycled. The researchers found that the pair of robots could collect and sort the waste with over 80% accuracy [17].

Another sustainability application for robots is water clean-up, with multiple robots designed for collecting litter along the surface of rivers, ponds, and lakes. Rahmawati et al. [4], for example, developed a robot that can remove up to 20kg of surface trash in one expedition. In addition to water surface cleaning, the robot developed by Turesinin et al. [2] also monitors the state of the water by collecting information about the pH, turbidity, and temperature, and supports a live streaming feature, which allows ecologists to keep track of the water's quality. The *Amphibious Robot* by Pan et al. [18] is able to traverse land or water, and collect litter floating along the water surface. Additionally, it is able to remove water hyacinth, a highly invasive species that floats freely on the surface of many bodies of water. The *Amphibious Robot* is also solar-powered, thus giving it a sustainable energy source.

Different from ground and water vehicles, Unmanned Aerial Vehicles (UAVs) have been used for environmental monitoring tasks, such as wildlife and land monitoring. UAVs are able to collect extensive amounts of data over large expanses of land, informing ecologists of any possible changes and fluctuations in the environment [19]. They can be sent to monitor areas where human access is limited or restricted, while minimizing any potential disturbances of those places [6]. One example of this is by Koh and Wich [20], who use a UAV for tropical deforestation monitoring. With this robot, they are able to oversee a range of biodiversity, patrol for illegal forest activities, and map local land cover. UAVs have the additional benefit of being able to monitor animals who may alter their behavior in the presence of humans, such as bears [21], and thus could be particularly useful for threatened or endangered species.

3. Environmental Psychology

As demonstrated by the number of emerging environmental robotic applications, the utility of non-interactive robots performing sustainability tasks has been well established. Less established is how robots able to interact with people could be used for environmental work, e.g., how they could motivate and encourage people to engage in more sustainable behavior by demonstrating or jointly working with people on tasks. Here, not so much the robot's functional aspects, but rather its social interaction capabilities and potential for targeting messages directly at interactants take the front seat. Robots could thus benefit from methods established by *environmental psychology*, a field that aims to understand how we can encourage sustainable, pro-environmental behavior in people by taking advantage of certain psychological heuristics and patterns. Even seemingly small things, such as spending time in nature, can have profound psychological and ideological effects [22]. Much of environmental psychology research involves identifying the most effective methods for creating these behavior interventions. Successful tactics include the reinforcement of descriptive and injunctive norms, prompting, and feedback [23].

With regard to environmental conservation, descriptive norms create a sense of comparison among users, motivating a behavior change to align with the norm. The social psychology literature tells us that an addition of an injunctive message (implying that one's behavior is morally correct or not) that aligns with the descriptive norm adds an additional incentive to change behavior [24,25]. These so-called "normative messages" are particularly effective communication strategies among those who have low initial motivation to engage in "environmentally-conscious" behavior [26]. For example, an experiment conducted by Schultz [27] successfully increased participation in a residential recycling program through the use of personal and descriptive norms. Recycling efforts increased by 17% overall, and 92% by those with lower participation prior to the study, suggesting that users with low initial motivation should be the primary targets of norm-activation techniques. Additional studies conducted by Cialdini et al. [28], Jain et al. [29], and Demarque et al. [30] have employed norms to encourage recycling, reduced energy consumption, and the purchase of "green" products, respectively.

While normative messaging is effective for people who are fairly unmotivated to act pro-environmentally, feedback and prompting tend to facilitate sustainable behaviors in those with an initial care for the environment [23]. Prompting involves reminders that point people towards certain behaviors. While it has mixed effects when used alone, it has been shown to be a useful tool for affecting behavior in context-specific applications, and when used in conjuncture with other methods [31].

Feedback can be either content-based or social, with content-based feedback being factual and informative in nature, whereas social feedback typically consists of facial expressions, tone of voice, and body language to motivate a change in behavior. Factual feedback can contribute to building a foundation of knowledge regarding the environment, which can later influence pro-environmental behavior [32]. However, information as a sole form of feedback has been met with variable success, as demonstrated by Bolderdijk et al. [33]. In a series of studies directly comparing the persuasive power of factual versus social feedback, Ham and Midden [34–36] found that a robot that provided negative social feedback was the most effective at getting people to conserve water when virtually doing laundry. Therefore, bolstering information with social feedback is the key to effective behavioral interventions.

Because social robots have been shown to be able to exert social influence on humans [37–39], even to the point of the humans altering their behavior [40], it is feasible that these robots could facilitate the types of behavior changes in people discussed above. The methods that these robots use will depend on the robot's interaction capabilities and modalities (e.g., a speech-enabled robot can easily provide social or factual feedback, while a robot with an expressive face might use social signaling through facial expressions).

We thus examine next the status quo of interactive robots for eliciting pro-environmental behaviors in humans.

4. State of the Art in Human–Robot Interaction Sustainable Social Robot Work

While the intersection of human–robot interaction (HRI) and sustainability is a rather understudied field, there is existing research that has begun to examine social robots' capability to encourage behaviors such as energy conservation, water conservation, recycling, and sustainable use of shared living spaces. In early summer 2021, we conducted a comprehensive literature search using the following search terms in Google Scholar with the following search terms: "human-robot interaction behavior change", "human-robot interaction water conservation", "human-robot interaction", "energy conservation", "autonomous recycling robot" "environmental robots", and "pro-environmental behavior robots" (which lead to a conjunctive search) and collated the relevant papers from these searches. In addition to the papers found via these search terms, we checked the references of each of the identified papers to see if they could lead us to any additional relevant work. This resulted in eleven papers from six different research groups, which we will briefly summarize below, broken down by sustainability area.

4.1. Energy Conservation

Over a series of multiple studies, Ham et al. and Midden et al. used the *iCat* robot to incentivize energy conservation in people [34–36,41]. They sought to determine whether social or factual feedback, positive or negative feedback, and higher or lower perceived agency was most effective when delivered by a social robot. In each of the studies, participants were instructed to complete trials with a washing machine, in which they were able to choose the energy setting of the wash cycle. The *iCat* robot responded to the participants' choices with happy or sad facial expressions, colored lights, and phrases to provide various forms of feedback. Overall, the studies found that negative social feedback was the most effective in encouraging behavior change. In the factual feedback conditions, positive vs. negative feedback did not make a significant difference, and agency had no significant effect on behavior change.

4.2. Water Conservation

Water conservation has also been a target of pro-environmental behavior in HRI, particularly in households and hotels. One study used an extensive survey to gather opinions about the use of robot companions and virtual assistants in hotel rooms to encourage pro-environmental behavior (e.g., towel reuse, reduced energy/water consumption, etc.) among hotel guests [42]. There were four conditions (virtual assistant vs. robot and absence vs. presence of social feedback). The social feedback condition involved statements announced by the agent that were voiced in happy or sad tones based on the behavior of the subject.

The study resulted in the following four main findings:

1. People's behavior after the attempted behavioral intervention was not significantly different when the robot or the virtual agent attempted the intervention.
2. When social feedback was used to encourage pro-environmental behavior, it was found to be significantly effective when used by the virtual agent, but not by the robot.
3. The consumers' attitude towards the behavior intervention or prompt had a major effect on the intervention's success.
4. There was an effect of automated social presence—or the idea that the subject perceived the presence of the agent as a form of surveillance—which encouraged normative behavior (i.e., the watching eyes effect [43]).

4.3. Recycling

Beyond energy and water consumption, waste management in the form of recycling has been studied in HRI. Castellano et al. [44,45] and De Carolis et al. [46] used *Pepper*, a social robot, to teach children recycling via a recycling game. Developed over a series of studies, the game was displayed on Pepper's tablet, and children were instructed to identify the correct bin in which to place the object that they were holding. Real objects were used, and Pepper was programmed with a waste recognition system, in order to identify glass, paper/cardboard, plastic, metal, and trash items.

Overall, the researchers found that Pepper was successful in improving children's recycling accuracy and engagement. More generally, these studies point to the value of social robots in educational contexts, and the study pioneered the combination of a social robot with a semi-autonomous waste-sorting capability, rather than studying the two separately. Important to note is that Pepper's believability and positive user experience was crucial for the efficacy of its interactions with the children.

Similarly, Arnett et al. designed the *Smart Trash Junior*, a social robot with vision recognition and dialogue capabilities, to teach children to recycle properly. The robot had a sensor on it that detected recyclable items, and the *Smart Trash Junior* was then programmed to instruct the children to "feed" the robots its recycling [47]. The study revealed the need for a social robot that is designed to not only motivate children to be receptive to the new recycling information, but also to carry out the new information learned, in the form of proper recycling behavior.

4.4. Sustainable Living Spaces

Sustainable living is an all-encompassing term that describes an ecologically, economically, and socially sound way of life. Behesthian et al. [48] aimed to promote environmental and social sustainability in a housing community. To do so, they conducted a three-phase study to evaluate the potential for social robots and other persuasive technologies to incentivize sustainable behavior in shared living spaces. The first phase involved focus groups, which were used to gauge people's interest and openness to various sustainability initiatives, as well as to assess people's perceptions of sustainability. The second phase consisted of the design of *GreenLife*, an application based on the results from phase one, that was implemented in a social robot for the purpose of encouraging sustainable behavior. Lastly, the third phase involved the assessment of *GreenLife* with the help of an online survey.

The study found that social robots can be used to persuade people to live more sustainably through the use of

1. social feedback
2. reliable data
3. personalized information
4. rewards
5. social influence strategies (i.e., comparison and creating competition)

5. Recommendations for Social Robots and Sustainable Behavior

The summaries of the status quo in HRI for sustainability show the first steps of utilizing environmental psychology for developing interactive robots for sustainability. However, more research is needed to stake out the potential territory of interactive robotic applications, followed by systematic HRI evaluations to determine the effectiveness of the robots. Currently, we see a noticeable lack of interactive robots that actually take advantage of their embodied form and the fact that they exist in, and can therefore manipulate, the physical world. An opportunity lies in combining these two capabilities—autonomously sensing and interacting with the physical environment, and social functions—to facilitate sustainable behavior. Furthermore, new robots do not necessarily need to be built for the sole purpose of encouraging sustainable behavior. Rather, sustainability applications can piggy-back on other existing robot platforms (e.g., household robots, education robots, industrial/logistical robots, etc.) to increase the prevalence of sustainability interventions.

The literature review presented above showcased the current limited state of sustainability and social robots; there is great potential for further combining these fields. For the remainder of this paper, we present recommendations in the form of scenarios to paint a small picture of what the future of this field, and the interactions with these robots, could look like. The creation of these scenarios involved choosing a pro-environmental behavior that we would like to see encouraged in people (i.e., energy conservation), and then imagining how robots could be used make these encouragements. The roles of the robots were strongly influenced by what the literature review showed us was and was not effective in how social robots persuaded people's behavior, particularly towards sustainable behavior, as well as by broader environmental psychology concepts that were lacking in the studies found in the literature review. Through the presentation of these scenarios, and the description of how these robots could be designed to achieve the effect seen in the scenarios, we provide recommendations to researchers on possible directions for social robots in sustainability.

For each scenario, we describe which environmental psychology principles are at play in each scenario, how the robot involved can be connected to the broader field of HRI, what other similar potential applications and iterations these robots might have, and what potential limitations stand in the way of implementing this robot now. As some robots are more advanced than others, we divide the following recommendations based on robot capability. The first section proposes sustainability applications for robots with limited sensing and no actuation. The second section discusses robots with better sensing abilities, but with no physical manipulation. The third and final section details scenarios for which a robot requires both sensing and manipulation capabilities. Additionally, in Table 1, we break down additional factors for each scenario, such as the target age group of the robot (an important consideration for robot designers, for designing a robot toy for children likely involves different interfaces and interaction abilities than a household assistant robot for adults), the robot's possible communication methods, the robot's general sophistication level, and whether the robot in the scenario would be uniquely designed for sustainability purposes, or could be added onto a different system.

Table 1. A summary of the robots discussed in the scenarios.

Robot Scenario	Sustainability Topic	Enviro. Psych. Method Used	Feasible Communication Method	Target Age Group	Robot Sophistication Level	Unique Robot or Add on to Existing System?
Litterbot	Pollution	Prompting, injunctive norms	Natural language, non-verbal noise, lights, colors	All ages	Low	Unique
Sunflower robot	Outdoor time	Factual & social feedback	Natural language, colors, non-verbal noise, facial expressions	Children	Low	Unique
Household robot I	Energy & water conservation	Prompting, social feedback	Natural language, colors, facial expressions	All ages	Medium	Add on
Corporate sustainability robot	Energy conservation & waste management	Comparison & competition, descriptive norms	Natural language	Adults	Medium	Add on
Household robot II	Waste management	Factual & social feedback	Natural language	All ages	Medium	Add on
Laundromat robot	Water conservation	Factual & social feedback, incentive	Natural language	Adults	High	Add on
Cafeteria robot	Waste management	Factual & social feedback, demonstration	Natural language, gestures	Children	High	Unique or add on
Grocery store robot	Eco-friendly consumerism	Factual feedback, normative, descriptive & injunctive norms	Natural language	Adults	High	Add on

5.1. Limited Sensing, No Manipulation

The first robots that we will discuss have a limited understanding of the world, due to having only one or two types of sensors providing them information. Additionally, while they may be able to move or respond in some way to the limited information they are receiving, they do not have the means to manipulate their environment in any great way.

Scenario 1: *Litterbot*

A parks and recreation department purchased a small solar-powered robot that they can deploy on non-rainy days to find litter that needs to be cleaned up in a park. The robot is low to the ground, and has a simple camera for object-detection. When it detects an anomaly on the ground, it says "Excuse me, I may have found a piece of litter on the ground. If anyone is around, will you please help me and throw it out if it is litter? Thank you!"

The above scenario provides an example of a sustainability application for a robot with limited sensing capabilities. The robot relies on its detection capability to identify potential litter; because the robot is unable to physically manipulate its surroundings, it relies on human assistance to pick up the objects that it detects. This is similar to a delivery robot designed by Booth et al. [49] which relied on people to open doors to facilitate its deliveries. The *Litterbot* has the benefit of being low-cost and easy to implement. While the primary goal of the robot is to help pick up litter directly, the robot also serves to raise awareness of the topic of pollution more generally.

By making people aware of nearby litter, the robot is using the environmental psychology tool of prompting. Prompting was met with success when used by social robots to encourage water savings in hotel guests [42]. Moreover, the Litterbot exerts social pressure onto nearby humans by asking directly for help, which can lead to moral normative behavior. Research in HRI points to the efficacy of this social pressure; a mobile trashcan robot with similar robotic capabilities to the *Litterbot* was attributed social agency, and participants thought that the robot was "intrinsically motivated to collect trash" [50]. By assigning social agency to the robot, subjects felt more obliged to dispose of their waste in the robot's trashcan. Interactions with the *Litterbot* will hopefully aid the immediate pick-up of trash, while also reminding people to look for litter in the future.

The idea behind the *Litterbot* scenario above is not unique; in fact, a similar robot has been deployed in select grocery stores, such as *Stop & Shop*, which utilizes limited sensing and natural language to identify and alert employees to areas that need to be cleaned [51]. Furthermore, the implementation methods chosen are not exhaustive. While natural language can make a direct social connection with people, lights [52], movement [53], and non-verbal noise [54] on robots have also been used to successfully convey various "emotions" and messages to humans. The *Litterbot* could employ one of these communication methods, rather than natural language. For example, in a study by Robinette et al. [55], lights and pointers were implemented in an emergency guide robot to aid people in evacuating a building. The robot was able to use these signals to properly communicate direction information. A challenge that has to be addressed for this robot to become available is the vision processing algorithms needed to identify litter off the ground.

Scenario 2: *Sunflower Robot*

A child has a robot toy sunflower, which has a cartoon face in the center. The sunflower's leaves are made of solar panels. When the robot is exposed to sunlight, it grows. As it grows, it tells the child "I'm so glad to be outside! Did you know that flowers like me need sunlight to grow? Flowers play an important role in keeping the environment happy and healthy! I hope that you enjoy spending time outside like I do!" While outside, the robot provides the child with more educational fun facts about plant life and pollination.

Research in environmental studies suggests that a child's experience in nature greatly impacts their future ideology and behavior regarding the environment as an adult [22]. With the rise of television and video games, children have spent less time outdoors recently than they have historically [56], threatening their perception of nature. Therefore, it is crucial to invest in technologies that enable children to engage in adequate outdoor play.

The sunflower robot mentioned above was inspired by, and expands on the abilities of, the *Floffy* robot. *Floffy* was created with the same goal of increasing outdoor playtime in children, but without a social component [57]. The sunflower bot utilizes both factual and social feedback to encourage children to spend time outdoors. Regarding factual feedback, the sunflower bot can educate children directly through its use of natural language on the psychological benefits of exposure to natural light, biological processes of pollination, and more through interesting fun facts. In terms of social feedback, the sunflower bot can utilize facial expressions (smiling or frowning), celebratory movements, and positive phrases such as “Good job! Now I’m happy” to motivate the child to spend more time in nature. For this robot, designing the mechanical “growing” would likely be more difficult than coding the software. The biggest limitation for deploying such a robot would likely be the additional cost of developing this children’s toy.

Another similar idea to the sunflower bot presented here is *PlantBot*, a robot potted plant designed to help young adults with depression re-engage in simple daily activities via behavioral activation therapy [58]. *PlantBot* uses an LED screen on its pot to display simple task requests to the user, and provides social feedback in the form of happy or sad emoticon faces when the tasks are or are not completed. The visual displays are accompanied by happy or sad sounding beeps. Similar to our sunflower idea, the goal of *PlantBot* is to use this type of feedback to establish positive behavioral changes in the user. *PlantBot* shows that our robot could potentially use non-verbal signals as well to convey its intentions.

5.2. Better Sensing, No Manipulation

In these scenarios, the robots discussed have more comprehensive sensors that give them a broader sense of the world. For example, many of these robots use cameras to get a sense of what is happening in their surrounding environments (and not only detect a few specific objects like the *Litterbot*); this provides them with more information than if they were only using simple infrared or light sensors, which paint a very narrow informational picture. However, the robots in these scenarios still have limited means of manipulating the world themselves, and therefore rely on humans to change the world around them.

Scenario 3: Household robot I

A mobile household robot enters the kitchen, where a person is washing dishes. A phone rings, and the person rushes to another room without turning off the faucet. The robot is able to watch all of this happen via its camera; however, it has no arms, and is therefore unable to turn off the water itself. After a few seconds pass without the person returning, the robot is triggered to go find them to alert them of the running water. When it does, it tells the person “Hi there. I noticed that you left the faucet on in the kitchen. It is important to conserve water, so please turn it off as soon as possible. Thank you!”

Scenario 3 involves a potential sustainability application for a household robot. The robot can use its monitoring capabilities to ensure that water is turned off when appliances are not in use, helping residents to save energy. Household monitoring capabilities are desirable features for assistive robots that are designed to help people with cognitive impairment and dementia. In a caregiving context, such monitoring capabilities are deployed for safety reasons [59]. However, the same robot functionalities can be re-purposed for energy conservation and helping promote behaviors relevant to helping the environment. While re-purposing these robots for sustainability would not be too difficult, the limitation with this robot lies more in getting it into people’s homes, as currently very few people have robotic home assistants (the cost barrier to buying such robot assistants will likely have to be lowered first if these were to become the norm).

Similar to Scenario 1, the household robot described above does not have actuation capabilities, and therefore cannot physically turn the water off itself. Therefore, the robot relies on prompting to encourage the human to turn off the faucet. As mentioned earlier, prompting has been successful in motivating eco-friendly behavior, particularly when used with people who are receptive to potential interventions [11].

Even more effective would be to follow up the behavior with social feedback, either positive or negative, depending on the human’s response to the prompt. If the human turns off the faucet, the robot could light up yellow to symbolize happiness. If the human decides to ignore the robot’s request and leave the faucet on, the robot could light up red for anger, or blue for sadness. Research has demonstrated the efficacy of colors in expressing certain emotions [60], so the robot could show color as a form of social feedback. The robot could also be programmed to display happy or sad facial expressions or dictate phrases such as

"Good job!" or "You're wasting water by leaving the faucet on" to provide the human with social feedback.

The sustainability application presented in Scenario 3 can be used in other household contexts as well. For example, the robot could be connected to the residential air conditioning or heat system, which would allow it to monitor the temperature of the house. If the robot is aware of the air conditioning or heat running and sees a window open, the robot could notify the human and prompt them to shut the window, with a similar approach to the aforementioned scenario. Additionally, the robot could use light detection to observe lights turned on in rooms where there is no human. Similar to Scenario 3, the robot could approach the human and remind them to turn off the lights. All of the robots' nudges can be followed up with social feedback, as mentioned above.

Scenario 4: Corporate sustainability robot

A company based out of a multistory building is committed to corporate sustainability. The company has an office robot deployed on each floor of its building. The robots are equipped with motion detection sensors in front of the trash and recycling bins, and light sensors to be able to tell when the lights are on in the room. The robots on each floor collect data on the employees' sustainability habits. They are able to share the data between robots to compare the overall energy consumption and sustainability trajectory of each floor, given the goals outlined by the company. When a certain floor is lagging behind, that floor's robot says to the employees "The other floors have been better about meeting their sustainability goals than you. Remember to turn off the lights when you leave a room, and recycle the appropriate items. Thank you for helping our company reach our goals!" Additionally, the robots report to the corporate sustainability officer each week to update them on the company's progress.

In this scenario, the office robot is purposed as a sustainability aid, likely working under the sustainability officer of a corporation. However, the robot could also be a general reception-type robot that has these sustainability monitoring features as well. In either case, the robot described relies on motion and light detection to collect data about the behaviors of the employees in the building. As in the previous scenarios, this robot has no manipulation capabilities, and can therefore not manipulate its surroundings, although it can use various psychological tools to encourage the employees to make the behavior changes themselves. In Scenario 4, the robot uses social influence strategies known as comparison and competition. By comparing one floor's progress to another, the robot is creating a sense of competition between floors, which can be a motivating factor for pro-environmental behavior change [23,61]. Other HRI work has found that robots can be effective social agents for creating competition [48], and when competition with a robot has been invoked, people work harder [62]. Moreover, the robot could use descriptive norms to notify employees of what other companies are achieving in the sustainability realm, encouraging the employees to meet or surpass the goals of other corporations.

The robot in Scenario 4 could also be adapted for residential purposes. A home robot could compare household energy or water usage to that of other neighbors, particularly if those other homes have robots as well. The robot could also have a database of energy consumption information provided by the energy company, which it could use to draw comparisons with. Similar to how the robot reports to the corporate sustainability officer of the company in Scenario 4, the home robot could provide homeowner's associations with updates about a household's consumption. Furthermore, the same idea could be applied to school districts or any other large unit of buildings where friendly competition can exist. To achieve these goals, companies and organizations need to commit to investing in sustainability, which currently presents a monetary barrier to realizing these robots.

Scenario 5: Household robot II

A household robot is in the kitchen while a person cleans up after preparing a meal. Using its camera, the robot detects food scraps and says "I noticed that there are bell pepper scraps on the cutting board. Did you know that those are compostable?" The person thanks the robot and puts the pepper in the composting bin. She then brings over a food-soiled napkin to show the robot and asks if it is compostable as well. The robot tells her that it is, and she adds it to the composting bin. The robot says, "Good job! You diverted X pounds of waste from the landfill by composting today!"

The following scenario involves another household robot that acts as a cooking aid. The robot is equipped with a camera that allows it to observe the human's behavior as well as its surrounding environment. As mentioned above, the robot uses its camera to detect compostable items, which it confirms by running through a database of acceptable items. Ideally, the list would be based on the specific composting program that a person is enrolled in, as different programs accept different types of food waste. Because people are often unsure of which items are compostable, this robot has the opportunity to not only reduce contamination of the composting stream, but also to reinforce long-term composting habits in the people it works with.

In order to do so, the robot uses a combination of positive social and factual feedback to reinforce the composting behavior in the human. By congratulating the human and providing a statistic related to the pounds of food waste saved, the robot is demonstrating to the human that their actions have positive consequences. Lastly, the robot could provide a progress report detailing a person's composting achievements, which could be compared to that of other households or neighborhood averages, serving as an additional form of social influence. This robot is limited by the same financial barriers as the previously discussed household robot. Additionally, new software would likely need to be developed for the robot to be able to identify different types of food products, in order to check if they are or are not compostable.

5.3. Sensing and Manipulation Capabilities

In this section, we propose scenarios for social robots with both sensing and manipulation capabilities. Therefore, these robots could carry out any of the tasks outlined in Sections 5.1 and 5.2 with added manipulation. For example, in Scenario 3, a robot with the ability to physically manipulate the environment can turn off the faucet, turn off the lights, or turn down the air conditioning itself. This provides an added benefit, as the robot can demonstrate the sustainable behaviors to the human. Similarly, following the ideas proposed in Scenario 1, 2, and 4, robots with actuation could physically carry out the tasks that they are asking the human to do (e.g., pick up litter, recycle, etc.). The previous scenarios are by no means exhaustive; below we provide three additional scenarios that are unique to robots with manipulation capabilities.

Scenario 6: Laundromat robot

A laundromat robot is helping a customer load their laundry into a washer. Part of this process involves assessing the different wash settings on the washing machine, each of which has a different water footprint. The robot briefly explains each setting's footprint to the customer, and says "This last setting is the most eco-friendly. If you were to use this setting today, you would be saving X gallons of water. If you were to use it every time you did laundry for a year, you would save about X gallons." The robot then provides a fun comparison as to how much water is saved. When the person agrees to this, the robot sets the dials appropriately and tells the person "Great job, thanks for helping us conserve water today!"

In this scenario, a laundromat robot is programmed with a sustainability application that helps customers to save water. The robot is able to physically manipulate the environment, so it has the ability to set the washing machine to an eco-setting. In the above scenario, the robot utilizes factual feedback to inform the customer of the gallons of water needed for each of the washer's settings. If the person agrees to use the eco setting, the robot follows up with positive social feedback through friendly phrases such as "Great job!". Building on this example, the robot could also provide a small monetary incentive in the form of a discount for the customer's pro-environmental behavior. Incentives have been proven to be successful in increasing eco-friendly behaviors, particularly when initial motivation is low [23,63].

The laundromat robot could also use negative social feedback to produce a response in the customer. In fact, Ham et al. [35] pioneered this in the aforementioned paper involving the *iCat* robot. The *iCat* produced an unhappy facial expression, as well as negative phrases, to encourage participants to change their behavior. The laundromat robot presented in Scenario 6 could use the same approach to motivate the customer to reconsider their decision of avoiding the eco setting.

The personal nature of the feedback provided by an embodied robot is extremely powerful. Despite the fact that similar information could be conveyed through an infographic or a virtual character, people tend to prefer receiving feedback from a robot. This was demonstrated in a study where robots and virtual characters provided feedback to participants on communication style [15]. However, this scenario would again involve businesses choosing to invest in robots, which could limit how many businesses make that choice.

Scenario 7: Cafeteria robot

At an elementary school cafeteria, a Pepper robot moves around the room. When it notices that a student has finished their meal, it goes up to them and says "I see that you're finished with your lunch! I can help you throw it away if you want. But first let's play a quick game – do you think this item should be put in the black trash can or the blue recycling bin? Touch the button on my screen that you think is the right answer!" When the child incorrectly chooses the trashcan, the robot says "Actually, what's cool about this bottle is that since it's made of plastic, we can put it in the recycling! Do you want to come with me to see it get recycled?" The robot then picks up the bottle, and the child goes with Pepper to watch it recycle the bottle.

In this scenario, a *Pepper* robot has both social and autonomous capabilities. This is an extension of the PeppeRecycle robot [44] that was developed with semi-autonomous waste sorting abilities for the purpose of teaching children how to recycle in classrooms. The cafeteria robot introduced above primarily educates the child on proper recycling through a brief game. Depending on the child's responses in the game, the robot can provide different types of social feedback. Previous HRI results have found that games are an effective way to capture people's attention and engage them in ways that are beneficial for those involved [64].

In the example above, the child answered *Pepper*'s question incorrectly and was therefore met with factual feedback, as the robot explained why the item was recyclable and not meant to be disposed of in the trash. The cafeteria bot could also deliver additional social feedback in the form of affectively appropriate noises or gestures. A study conducted by Nakagawa et al. showed that people are able to recognize emotion in robot gestures [65]. With the use of both factual and social feedback, repetitive interactions with the cafeteria robot will reinforce proper recycling behavior in students, and hopefully facilitate long-term habits. In addition, after having the social interaction with the student, the robot offers to take the child to the recycling station to actively demonstrate the action of throwing the plastic bottle in the blue recycling bin. Once again, this reinforces the recycling behavior in the student.

The basic concept of the cafeteria robot can be modified for use in other contexts as well; middle schools, high schools, or other large-scale events that require waste management assistance serve as potential environments. The robot has the benefit of being able to take on the role of human-surveillance of waste management, which is time-consuming and repetitive. The robot can have countless interactions with humans, both teaching and directly helping them to sort their waste. This robot is limited by the sensing and cost barriers discussed in previous scenarios. Additionally, because this robot is targeted to work with children autonomously, designers would need to be confident that the robot can both operate safely around children and tolerate any physical interactions the children may have with the robot (i.e., hitting it, pulling on it, hugging it, etc.).

Scenario 8: Grocery store robot

At a local grocery store, customers can send in their shopping lists, and store robots will move around the store and gather the items and bring them to the delivery people. An order comes in containing a request for various cleaning supplies. When gathering these supplies, the robot sends a message to the customer offering similarly priced, eco-friendly alternatives to their shopping list. The robot waits for the person to confirm that they would rather use these eco-friendly products, and then packages them up with the rest of the groceries. The robot sends a follow-up message to the customer stating "Your eco-conscious purchases saved X amount of CO2 emissions today. Thank you for helping to support sustainable companies!"

In Scenario 8, a robot is employed at a grocery store to aid in the gathering of products for online orders. The robot is equipped with a sustainability feature that allows it to offer environmentally-conscious product alternatives to the customer via a messaging system while it is collecting groceries. This is an extremely useful feature, as most people lack the motivation and/or time to research information about each of the products that they are purchasing. Presenting reliable, accessible, and easily understandable data to humans is a beneficial property of robots, particularly in environmental contexts [48].

The robot has access to a database of all of the store's products, along with their attributes. One of the attributes contains information about the carbon footprint of the product, or the environmental impact related to the item's production. This allows the robot to compare various products and suggest those with lower carbon scores. These could include plant-based meat alternatives, cleaning products made with less harmful chemicals, paper products made from recycled paper, and more. Because economic viability often acts as a hindrance to sustainable purchases, the robot can be programmed to suggest products within a similar price range to those initially chosen by the customer. A limitation of this robot is that it would need to have a comprehensive list of the alternatives to every product in the store, and keep that list updated on new products that come in, as well as products that might be out of stock. Additionally, having the ability to physically manipulate the environment in order to pick up a variety of products requires sufficient mechanical sophistication and control.

After locating alternatives, the robot can follow up with a combination of positive, factual feedback, and normative messaging. As mentioned in the scenario above, the robot informs the customer of the amount of carbon dioxide saved through their purchases, which serves as the non-social feedback component. The robot could also use descriptive norms to inform the customer of the percentage of others who purchased a specific product. For an even stronger follow-up, the robot could insert an injunctive norm describing the moral implications of the customer's purchase. For example, if the customer chooses the less eco-conscious version of a product, the robot could send a message saying, "Choosing to support sustainable companies is an important step that you can take to fight climate change at the individual level." This sentence implies that purchasing the eco-friendly product is the right thing to do. Through this method and the others described in the scenarios outlined above, we demonstrated various ways for which robots can be utilized to encourage pro-environmental behavior in people.

6. Conclusions

In this paper, we presented the idea that interactive robots that can sense and manipulate the world combined with the utilization of social influence factors derived from environmental psychology can be a powerful method for designing robots that can encourage sustainable behaviors and patterns in people. Past research in HRI has shown that people are susceptible to robotic social influence, and environmental psychology as a field can point us to what influence strategies can be most poignant for developing sustainable habits. Additionally, because robots exist in the physical world, they can access knowledge about the state of the environment they are in, act upon that information, and potentially demonstrate and correct specific behavior in people. These sustainable interactive robot aspects further have the advantage of being combinable with a robotic platform designed specifically for encouraging pro-environmental behavior, or they can be added to already existing systems, eliminating the need to spend time and money developing completely new robots. To illustrate our argument, we presented eight different hypothetical scenarios designed around promising uses of robots, as well as noticeable gaps in the current social robots in sustainability literature in regard to potentially relevant environmental psychology concepts. These scenarios represent the recommendations that we make for how and where to use interactive robots for sustainability tasks. We analyzed each scenario with respect to the environmental psychology tools being used, similar robots already seen in HRI, and other similar iterations of the given scenario possible. We hope that our analysis and proposals will be of use to robot designers, human–robot interaction researchers, and environmental engineers alike for developing the next generation of EnviRobots.

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