Comparing Social Robot, Screen and Voice Interfaces for Smart-Home Control

Michal Luria
Media Innovation Lab
Interdisciplinary Center
Herzliya
Herzliya, Israel
michal.luria@idc.ac.il

Guy Hoffman
Sibley School of Mechanical
and Aerospace Engineering
Cornell University
Ithaca, NY
hoffman@cornell.edu

Oren Zuckerman
Media Innovation Lab
Interdisciplinary Center
Herzliya
Herzliya, Israel
orenz@idc.ac.il

ABSTRACT
With domestic technology on the rise, the quantity and complexity of smart-home devices are becoming an important interaction design challenge. We present a novel design for a home control interface in the form of a social robot, commanded via tangible icons and giving feedback through expressive gestures. We experimentally compare the robot to three common smart-home interfaces: a voice-control loudspeaker; a wall-mounted touch-screen; and a mobile application. Our findings suggest that interfaces that rate higher on flow rate lower on usability, and vice versa. Participants' sense of control is highest using familiar interfaces, and lowest using voice control. Situation awareness is highest using the robot, and also lowest using voice control. These findings raise questions about voice control as a smart-home interface, and suggest that embodied social robots could provide for an engaging interface with high situation awareness, but also that their usability remains a considerable design challenge.

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation (e.g. HCI): User Interfaces

Author Keywords
social robots; embodied interaction; human-robot interaction; interface modalities; smart-home control; domestic technology; home automation

INTRODUCTION
Two new categories of interactive technology are increasingly entering the domestic space: Home appliances with new sensing and control capabilities, collectively called *Smart-Home* or *Internet of Things* (IoT) devices [1], and expressive interactive robotic companions, also called *Social Robots* [5].

Researchers have been divided over the desired user experience in domestic spaces, ranging from high system autonomy and invisibility [55, 51, 56], to promoting the user's sense of control and engagement [29, 48]. Additionally, a wide range of interaction modalities for the home have been designed and researched, including GUI [8], voice control [58, 39], gesture input [35], and augmented reality interfaces [53].

In contrast to the above-mentioned interfaces, social robots provide for an alternative mode of interaction. Interacting with a robot is an embodied experience: Robots express their internal state and other information using gestures and nonverbal behavior (NVB) [6, 38]. Furthermore, by sharing physical space and objects with their users, they encourage interaction schemas that involve physical action on the part of the human [49, 59]. The literature suggests that embodied interaction could provide advantages over screen-based, virtual, or augmented reality interfaces. These include thinking-through-doing and higher performance [33], better learning and memory [14, 45], and higher engagement [62]. Thus, social robots are a promising new model for smart-home control, balancing autonomy and engagement, and providing the benefits of embodied interaction.

Although social robots for smart-home control are already appearing on the consumer market, the research on the topic is sparse. In the past, comparisons have been made between other non-robotic modalities for smart-home control [8, 34], while social robots and tangible interfaces were compared to screen interfaces in other contexts of the domestic space, e.g., game play [57], education [62], and weight-loss coaching [32]. However, we do not know of a comparison between a social robot and traditional interfaces in the context of smart-home control.

In this paper we present such a comparison. Using a within-subject experimental design, we compare the use of an embodied robot interface with three common interfaces for smart-home control: a voice-controlled speaker device, a wall-mounted touch screen, and a mobile application (Figure 2).

We gave participants a list of home control chores while tasking them with a cognitive-load activity. In each round they used one of the four interfaces. We measured quantitative and qualitative indicators including usability, flow, enjoyment, control, distraction, and situation awareness.

Our analysis finds the following: (1) A trade-off between perceived *usability*, and perceived *flow*. For interfaces which

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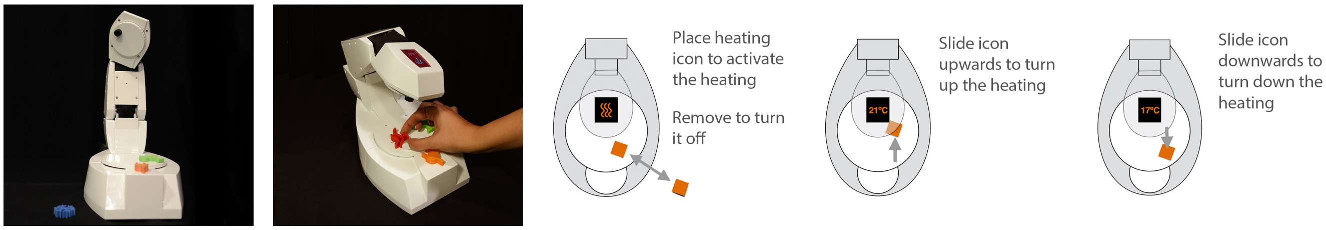


(a) (b) (c) (d) (e)

Figure 1. Vyo, the embodied social robot interface for smart-home control we designed and used in this experiment. The robot is inspired by a microscope metaphor allowing the user insight into the state of smart-home devices, each represented by a tangible icon. Vyo doubles as a social agent when it rises to express face-to-face gestures (a) and becomes an examination tool when it is facing down (b). The robot is commanded by placing the device icons onto its turntable (c) and moving them as physical sliders to adjust settings (d-e).

rated high on perceived *flow*, the rated *usability* was low, and vice versa; (2) the robot was rated with the highest *situation awareness*, and voice control was rated lowest; (3) participants' *sense of control* was rated highest using familiar interfaces (wall-mounted screen and mobile application). However, voice control was perceived with particularly low sense of control in the interaction; (4) although unfamiliar interfaces were said to be somewhat *distracting*, the most familiar one, the mobile application, was described as a highly distracting interface.

These results raise questions about voice control and mobile application interfaces for domestic environments. They also suggest that social robots are good candidates for embodied interfaces in automated homes, promising to be highly engaging, visible, and encouraging thinking-through-doing. Nevertheless, when designing robots as home interfaces there is a need to overcome outstanding issues concerning usability.

RELATED WORK

Smart-Home Interfaces: Invisible or Engaging?

Researchers are divided if domestic technology should blend into the background or engage users. Striving to support Weiser's original vision of calm computing [55], automated, transparent, and seamlessly integrated smart-home technologies have been developed [13, 60, 47]. The downside in this approach is that home automation could become unpredictable—users lack feedback on events in their domestic environment and therefore lose sense of control over the state of their home [34, 44].

This led others to argue that technology should empower users by allowing them to make decisions for themselves, rather than having the home make decisions for them [29]. Home technology should therefore be designed for involvement and engagement [48], and with affordances for the status of their homes [19]. This could help restore users' sense of control [29] and allow for flexibility [17].

Embodied Interaction

Research on embodied interaction focuses on interfaces that incorporate a growing range of human capacities, in contrast to textual and graphical interfaces [18]. The literature points out the advantages embodiment brings to interaction design: It promises an opportunity to bring social and human values back in balance and to create meaning in interaction [28]. It also allows expert users to maximize interaction efficiency through motor memory and simultaneous action [33]. The visibility and persistence of embodied interfaces serve as reminders [61], and can help coordinate between co-workers and house members. Finally, gesturing can promote users' thinking and communication skills, play a role in lightening cognitive load [22] and communicating complex thoughts [2]. Thus, embodied interaction using gestures encourages "thinking-through-doing" [33].

Robots constitute an embodied interface in two ways. They communicate their intentions using gestures and other nonverbal behavior, and they encourage users to physically engage in interaction with them by sharing the same physical space and physical objects.

Smart-Homes and Social Robots

In fact, embodied social robots have been suggested as candidates for an increasing number of applications integrated in our daily lives, including service providers [31], delivery robots [36], therapeutic assistants [54] and tour guides [9]. Furthermore, robots are intended for deployment in homes for a variety of purposes, such as assistants for the elderly [4, 43], security robots [10], entertainment devices [23], and personal companions [25, 46].

Research suggests that social robots are perceived and interacted with differently that other forms of technology. Intentions are attributed to abstract robots that use simple 2D-movement [50], and owners of robotic vacuum cleaners define their robots' personality traits and the social relationships with them [20, 52]. This suggests that social robots could have unique interaction potential and novel effects when used as interfaces to technology in people's homes.

OVERVIEW

In order to study the benefits and drawbacks of social robotics in the context of domestic interaction, we designed an expressive social robot, Vyo, as an embodied interface for smart-home control [37]. In this study, we evaluate Vyo's design by comparing it to other common smart-home interfaces: a voice-controlled speaker device, a wall-mounted touch-screen, and a mobile device application (Figure 2).

(a) Embodied Social Robot (b) Voice-Controlled Speaker (c) Wall-Mounted Screen (d) Mobile Application

Figure 2. The four smart-home control interfaces compared in this study.

Embodied Robot Interface

Vyo is a social robot that serves as a central interface for smart-home control [37] (Figure 1). Building on the notions of ubiquitous computing [55] and engaging interfaces [48], we designed Vyo as a new interaction paradigm that combines expressive robotics and tangible user interfaces. The robot uses tangible icons as a means of user input, and a combination of physical gestures and low-fidelity screen icons for output. This design suggests an alternative to the commonly used interaction modalities of most social robots, which highlight bidirectional speech, touch screens, and high-resolution informational displays.

The design process is provided in detail in [37] and summarized below. It was driven by five design goals: engaging, unobtrusive, device-like, respectful and reassuring:

Engaging — A smart-home interface should promote the user's sense of control and raise their awareness to the status of their home. One of the ways to do so is to evoke engagement and bring back "excitement of interaction" by designing a tangible interface [48].

Unobtrusive — Domestic technology should be at least partially automated and strive not to disturb house members [56]. We therefore aimed to design a robot that would stay in the periphery of attention, and would come to the foreground only when necessary [27].

Device-like — Based on the notion of designing non-anthropomorphic robots [26] and supported by [16]'s finding that people prefer their home robot to be device-like or butler-like, our third goal was for the robot to resemble a device rather than a human or a pet.

Respectful — As also described in [16], users expect their robots to be polite and show awareness of social situations. We therefore defined 'Respectful' as one of our design goals.

Reassuring — According to previously conducted interviews [37], home technology should be reliable and trustworthy. The robot should therefore express reliability and reassure the user throughout the interaction using gestures and nonverbal behavior.

After setting these goals, the design process was along two interleaved paths in the spirit of [26]. One was the design of the robot's morphology, including its scale, shape and materials. The other was the design of the robot's nonverbal behavior (NVB). 3D character animations were used to explore movement patterns for the robot; improvisation studies with professional actors were conducted to inspire NVB; and puppet designers assisted in developing the robot's gestures. These two paths ultimately shaped an interaction schema that was then evaluated in an early-stage user study, together with the robot's size and NVB. The findings helped us make design decisions that shaped the robot's final size, gestures, and interaction schemas.

The robot uses embodied and physical interaction modalities for both input and output, and is inspired by a microscope metaphor. Supporting the design goal of *engaging* and *reassuring*, physical icons are used as an input communication channel with the robot. Each icon is designed to represent a smart-home device, controlled by placing it on the robot's turntable (Figure 1c). When an icon is placed, the robot responds with expressive physical gestures and a screen icon, indicating it has turned on the device. By sliding an icon the user can adjust control parameters (Figure 1d–e). For example, sliding the heating icon upwards will increase the home temperature. When the icon is removed from the turntable, the robot turns off the device and acknowledges this action with an expressive gesture. This interaction design choice supports both the visibility and the thinking-through-doing principles of embodied interaction.

The microscope metaphor suggests a mental model of "examining" devices in the home and supports the *device-like* and *engaging* design goals. While one could argue that a microscope is more of a scientific tool than a domestic device, it also relates to the excitement and sense of discovery of educational microscopes. Importantly, it is a familiar device capable of supporting a predictable mental model.

The robot, however, is not just a passive tool, but straddles the boundary between device and social agent. For example, it rises to face the user in a conversational front-facing pose (Figure 1a), and a rotating lens-like feature on the robot's face enables minimalistic, but also surprisingly expressive, facial gestures. When the robot detects problems in the smart-home environment, it uses peripheral gestures indicating nervousness instead of sound or LED notifications. This supports the *unobtrusive* design goal.

The integrated low-fidelity screen on the back of the robot's head measures 1.8 inches in the diagonal, and is exposed when the robot performs a bowing gesture. The gesture moves Vyo back from its conversational stance as a social agent to that of an examination device (Figure 1b). This bowing gesture is aligned with the design goal of *respectful*, while the action of hiding the screen when in conversation also relates to the design goal of being *unobtrusive*.

The robot's hardware and software are built on a Raspberry Pi 2 PC-on-board system, running a combination of Python and Java code. The robot moves using 5 Robotis Dynamixel motors, and integrates a TFT display and a loudspeaker. Its internal frame is laser-cut from 6-mm acrylic and its shell is made out of sanded and painted 3D-printed acrylonitrile butadiene styrene (ABS).

In our experiment, the robot was introduced to participants as "a robot interface for smart-home management, controlled by placing physical icons on its turntable", making sure not to expose participants to descriptions that might influence their perception of the robot. During the experiment it was controlled using a Wizard-of-Oz (WoZ) desktop application [24].

Voice-Control Speaker

The voice control interface is a small speaker with an LED indicating when it is on (Figure 2b). The interface was designed to highlight and support advantages of voice-controlled interfaces: intuitive, by using spoken language as its input, ubiquitous, in that it can be activated from anywhere in the room, and "hand free, eyes free" [11].

To dismiss potential technical problems in speech analysis and to ensure full comprehension of the participants' spoken language, we also used a WoZ method for feedback. This allowed us to focus on the user experience of a voice interface regardless of technical issues.

We designed the feedback of the system according to the design guidelines of [30]. The system would give auditory feedback to user input using slightly altered wording to indicate the correct recognition has taken place. The main disadvantage of auditory feedback is in the disruption of other auditory information held in the memory of an individual [30]. However, since vocal feedback is prominent in existing commercial voice control interfaces, we implemented this feedback in our system as well.

In this study participants would be instructed to say "Smart-Home" to activate the interface before giving it a command. We prerecorded audio clip sentences for feedback, manually voiced by a commercially available voice-control device (Amazon Echo), for example: "The heating is set to 29 degrees". We also recorded several responses for scenarios in which participants might say something unclear or unrelated to their task, such as: "Sorry, I did not understand the question I heard. Could you repeat that?". The prerecorded audio clips would be manually played in real time according to participants' actions and a WoZ script written in advance.

Wall-Mounted Touch Screen

We designed a smart-home control application optimized for an Android tablet device (Figure 2c). The tablet would be fixed to a wall for the experiment, representing common wall-mounted touch screen interfaces in smart-homes today. The user interface of the application was designed based on existing smart-home control applications by commercial companies. The interface is divided into four sections, one for each device. We also added a representative icon and background color for each section according to the physical icons used by the robot in form and color to eliminate confounding differences between the designed systems.

For each device, the interface had an on/off toggle button that could be changed by either touching or swiping it, with immediate visual feedback. For temperature control (heating, cooling) we placed a slider with a number representing the current temperature to its right. When a user would move the slider, the temperature would immediately adjust. The interface was designed based on interaction design guidelines, considering affordances, signifiers and feedback [41], but also according to contemporary user interface (UI) conventions (toggle buttons, sliders). In addition, we made sure the UI elements would be large enough for easy control using an average-sized finger [12]. During the experiment the screen would always stay on.

Mobile Application

The mobile device application interface was the same interface as the wall-mounted one, but adapted for a Samsung Galaxy J5 personal mobile device running Android (Figure 2d). It was adapted by scaling the interface down to fit the mobile device properly, and the buttons were repositioned accordingly. The button size, however, was maintained in order to enable easy touch interaction. Throughout the experiment participants would be asked to lock the mobile device screen between interactions and hold onto it or place it in their pocket, to better simulate the way we interact with mobile devices in casual day-to-day operation.

STUDY

We conducted an exploratory controlled experimental study comparing the four interfaces described above and investigating the following research questions:

- Whether and how the choice of interface affects users' **perceived flow** of using the interface.
- Whether and how the choice of interface affects users' **perceived usability** of the interface.
- Whether and how the choice of interface affects users' **distraction** and **cognitive load**.
- Which interface users **prefer**, find the most **comfortable**, most **enjoyable**, and most **natural**.
- Which interface gives users the best **situation awareness** of the state of the home.

Participants

We recruited 42 undergraduate students who received extra credit for their participation (25 female, age $M = 22.07, SD = 2.58$). The students were recruited from the university's international school. This allowed us to include participants from 19 different countries and to examine multicultural perspectives (USA = 9, France = 9, Israel = 4, Germany = 2, Canada = 2, Panama = 2, Other = 14). We ran the experiment in English, and while English was not the native language for most participants, their lectures and homework all require college-level English. Nevertheless, we used simple vocabulary in the experiment materials, questionnaires, and interviews, and have no reason to believe that any English language barrier played a major confounding role.

Method

The experiment was conducted within-subjects, with one independent variable—the interface used to perform a series of smart-home control tasks. This variable included four conditions: embodied robot (ROB), voice control (VOC), wall-mounted touch screen (WAL), and mobile application (APP).

In the experiment, participants were asked to simulate a situation where they control several devices in a smart-home environment while being loaded with a cognitive task to simulate the distractions in the home (the "Copying Task" described below). The experiment included four rounds for each participant. In each round participants were asked to use a different interface for the smart-home control tasks (four conditions), counterbalanced for order.

The Copying Task

Throughout the experiment participants had a cognitive load task of copying words from a list to a whiteboard in the room (Figure 3). The task of short-term memorizing random words was found to require high concentration, and was previously used to evaluate external disruptions—when participants were disrupted, more time was required to recall words [21]. Thus, counting the number of words participants manage to copy for each round would serve as a measure of disruption and cognitive load for each interface. We also wanted to keep participants physically busy to simulate the occasionally demanding home environment. For this reason we placed the list of words on one wall, and the whiteboard on another.

Procedure

Each round of the experiment started with participants doing the main copying task. In each round the task was interrupted five times by a knock on the door. With every interruption, participants were instructed to stop the copying task, approach the smart-home control task list in the room and execute the next task on the list. The tasks were control tasks for four devices in the home (e.g. "Turn on the dishwasher", "Change the heating temperature to 29 degrees"). All tasks were to be executed using the interface introduced at the beginning of the round. The interfaces and smart-home control tasks were counterbalanced for order. Furthermore, the experimenter interrupted the copying task at fixed time points in each condition, ensuring the number of words copied in each round would be a valid quantitative measure.

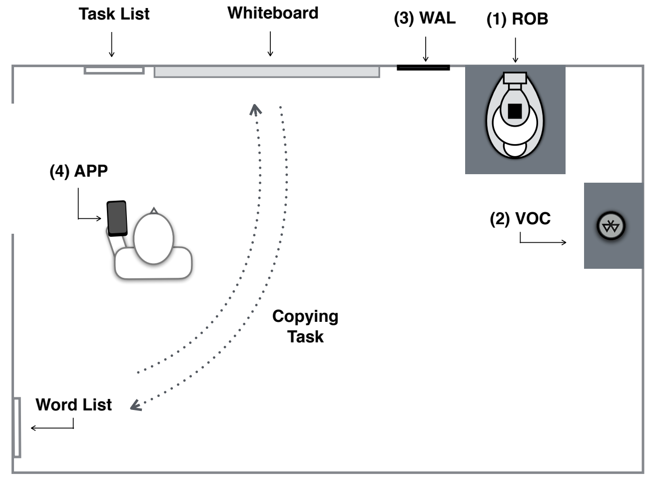


Figure 3. Diagram of the experimental setup. Participants were asked to copy words from the word list to the whiteboard. When interrupted by a knock on the door, they performed the next task on the Task List using one of four interfaces (1)–(4).

After each round, participants answered a short questionnaire regarding their experience. They were also asked what devices were on and what the home temperature was. We did not intend to measure if their answers were accurate, but to trigger their ability to recall the home status after using a specific interface. At the end of all four rounds, the participants were interviewed using a semi-structured interview script written in advance.

Measures

We used quantitative and qualitative measures. We collected data from written questionnaires and verbally asked categorical questions for subjective quantitative measures. As an objective measure, we counted the number of words participants were able to copy with each interface. Finally, we conducted qualitative semi-structured interviews.

Questionnaires

The questionnaires evaluated each interface according to two scales. In the first scale participants rated the *flow* they had experienced using an interface on an 8 item scale. The notion of *flow*, frequently used in the field of HCI, expresses focus, deep involvement and enjoyment one experiences when performing an activity [15]. The scale was adapted from [62], removing 3 items that were irrelevant to our interfaces. The second scale in the questionnaire measured *usability*, taken in its full form from [7] (SUS). All measures were on a scale of 1–7.

Quantified User Preferences

The post-experimental interview included asking participants to choose their top interface in different categories: which interface they liked most, which they liked least, which was most comfortable, most natural, most enjoyable, and using what interfaces was it easiest and hardest to recall the status of the home at the end of the round. We then counted the answers that expressed a preference for a particular interface in each category.

Table 1. Quantitative measures from questionnaires and word transfer count. Each cell shows mean±std. Bold indicates conditions with means significantly higher ($p < 0.05$) than one or more other conditions in corrected pairwise comparisons.

Measure	ROB	VOC	WAL	APP
Flow	**5.40±0.67**	4.95±1.05	4.82±0.96	4.65±1.13
Usability	5.30±1.21	5.69±0.88	**6.22±0.60**	**6.23±0.59**
Word Count	28.36 ±7.46	29.93±9.24	**33.02±8.84**	29.45±9.37

Word Count in the Copying Task

At the end of each round the experimenter counted and noted the number of words participants were able to copy, before erasing the words from the whiteboard for the next round.

Interviews

Semi-structured interviews were conducted at the end of the study. Participants were asked to elaborate on their experience with each interface, including what they liked, disliked, what difficulties they encountered and so on. The interview transcriptions were read and analyzed separately by two research assistants. The analysis was driven by key aspects and research questions defined in advance, but allowed space for discovery of additional patterns if indicated by both research assistants. If a disagreement regarding a specific aspect or pattern emerged, it was resolved by discussion with reference to the transcripts.

FINDINGS

We first present the main findings along two main themes: (a) Flow and Enjoyment, and (b) Comfort and Usability, using quantitative and qualitative measures. We analyze the questionnaires using a one-way repeated measures ANOVA with pairwise comparison post-hoc t-tests. For effect size, we report the generalized η^2 measure, which is recommended for repeated measures analysis [42, 3]. We then report on the objective word count measure, and add notable insights we recognized when analyzing the qualitative interviews.

Flow and Enjoyment

Questionnaires

Self reported questionnaires that measure perceived *flow* were administered after each round. A one-way repeated measures ANOVA shows that the interface modality has a significant effect on reported flow, $F(3,123) = 6.42, p < 0.001, \eta^2 = 0.08$ (Figure 4(a)). Pairwise comparisons using repeated measures t-tests with a Bonferroni correction show that ROB is significantly higher on perceived flow than WAL ($p < 0.05$) and APP ($p < 0.01$), with no other comparisons resulting in significant differences. Table 1 shows full descriptive statistics for all questionnaire scales.

Interviews

Interviews supported these quantitative results by pointing out that when participants interacted with the robot, they felt intrigued and excited to continue the interaction:

> "It [ROB] gives you more associations... it develops such amazing imagination"

> "I wanted to try it [ROB] more. You can play with it, which creates this excitement. You just want to use it again"

Table 2. Quantified User Preferences: Participants chose which interface they liked most and least, which was most comfortable, natural and enjoyable, and with which interface was it easiest and hardest to recall. *Negative preference.

Measure	ROB	VOC	WAL	APP
Most Enjoyable	**68%**	25%	3.5%	3.5%
Liked Best	**38%**	**34%**	16%	12%
Liked Least*	**33%**	**33%**	17%	17%
Most Comfortable	0%	17%	24%	**59%**
Most Natural	0%	21%	15%	**64%**
Easy to Recall State	**61%**	21%	9%	9%
Hard to Recall State*	4.5%	**61%**	9.5%	19%

In contrast, the screen-based interfaces (WAL, APP) were described as mundane, common, and automatic:

> "It [APP] did not urge me to explore it more... just doing what I do every day."

> "It [WAL] is good. But it's not interesting. It didn't develop curiosity."

Quantified User Preferences

Table 2 shows the quantified user preferences. When participants were asked what interface was most enjoyable, a majority (67.8%) chose ROB. Participants were also asked what interface they liked most and least, taking all of the interface qualities into consideration. 37.5% liked ROB most, and 34.3% preferred VOC. However, when participants were asked to select their least favorite interface, the results were surprisingly similar: 33.3% selected ROB, and 33.3% selected VOC. The full results are presented in Table 2.

Usability and Comfort

Questionnaires

We measured the perceived *usability* of each interface using the 10-item SUS scale [7]. A one-way repeated measures ANOVA shows that the interface modality has a significant effect on reported usability, $F(3,123) = 15.67, p < 0.001, \eta^2 = 0.17$ (Figure 4(b)). Pairwise comparisons using repeated measures t-tests with a Bonferroni correction show that both the WAL and APP conditions are significantly higher on perceived usability than ROB ($p < 0.001$) and VOC ($p < 0.01$), with no other comparisons resulting in significant differences. Table 1 shows full descriptive statistics for all questionnaire scales.

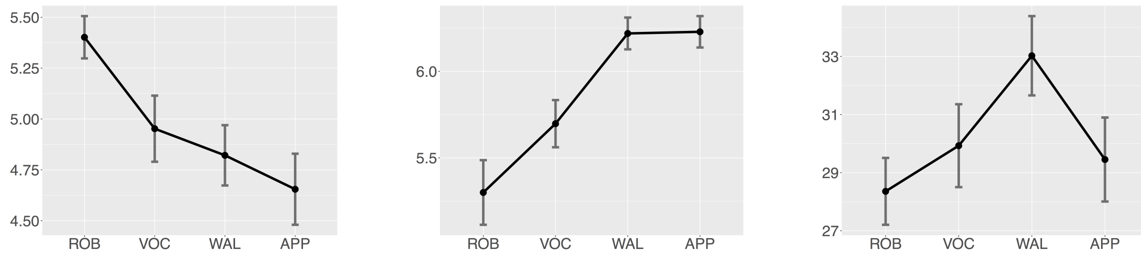
Quantified Findings

Participants were asked which interface they perceived as most *comfortable* and most *natural*. In line with the above findings, 58.6% of participants indicated APP was most *comfortable*. APP was also selected as the most *natural* interface, with a 63.6% selection rate. Table 2 shows the complete quantified data.

Interviews

During the interviews, WAL and APP were also described as interfaces participants generally felt very comfortable and familiar with:

> "It [APP] is very easy to use. People carry it in their backpacks, go to school, go to work. People have it



(a) Flow by Condition (b) Usability by Condition (c) Word Count by Condition

Figure 4. Quantitative measures: Self-reported mean *flow* (left) and *usability* (center), and the mean number of copied words per interface (right). Error bars indicate standard error of mean ($n = 42$)

wherever they are going, next to their bed. It is very convenient”

“The tablet [WAL] is the most safe and secure thing to have for me... I feel it is reliable...it is there always, it is always going to work.”

ROB, however, was described as an interface difficult to use:

“I would not want to use it [ROB] all the time because it takes more time.... If you are in your house you want it to be quick... I do not want to wait for it. The robot takes more time”

“I guess specifically for me, if [you are] not technologically inclined, that [ROB] was the most difficult to use”

With regards to VOC, participants generally liked being able to give a vocal command. It allowed them to do it from anywhere in the room and without the use of hands. However, at times they perceived the interaction as confusing:

“I really liked the voice [interface]. I really liked the option to be anywhere in the room and still be able to talk and that it recognized it.”

“[Using] the voice [interface] you had to stop, you had to think what you need to say”

Word Count in Copying Task

We measured the number of words participants were able to copy with each interface in their main copying task. A one-way repeated measures ANOVA shows that the interface modality has a significant effect on the word count, $F(3,123) = 5.53, p < 0.01, \eta^2 = 0.04$ (Figure 4(c)) Pairwise comparisons using repeated measures t-tests with a Bonferroni correction show that WAL condition had significantly more words copied than ROB ($p < 0.01$) condition, with no other comparisons resulting in significant differences. Table 1 shows full descriptive statistics for all questionnaire scales.

Insights from Qualitative Interviews

In addition to our main findings, we identified three notable themes in our qualitative interviews: Sense of Control, Situation Awareness and Distraction.

Sense of Control

When using familiar interfaces (WAL, APP), participants expressed feeling very confident and in control:

“[What interface felt most comfortable?]” — “Tablet [WAL]. Because you feel fully in control with it. You are ultimately the one touching the screen and deciding what to do”

“It [APP] is part of us, like a third hand”

We expected the interaction using physical icons with ROB to also encourage participants’ perceived sense of control, but this was not found to be true:

“This [ROB] is kind of scary: it is smart, it is intelligent. I would not like having it in my house controlling the most important things”

“In the end you don’t have much control over what it does, it can do its own thing”

Participants felt even more strongly about VOC—not only did they mention lack of control over the interface, they also felt substantial discomfort:

“I didn’t like it [VOC] because I feel like it was always listening to me, and I have to be very careful [about] how I speak to him”

“[Using VOC] it kind of feels like you are deciding, but someone else is also deciding for you. On that one [WAL] it feels like you have full control, but here [VOC] it is like you are waiting for them to accept what you are saying... The disadvantage is that you do not feel 100% in control like with other interfaces. It feels like you are requesting something from your home and then you have to wait for it to be approved”

“I don’t like it [VOC]. I don’t like talking to myself in a room with myself, it feels very awkward and weird... I don’t know it’s weird having a voice talk back to you. It is a little bit creepy.”

Some expressed a more ambivalent relationship with the voice interface, that evoked both positive and negative emotions simultaneously:

“It [VOC] seems to be really cool. You can talk to your home. I don’t know - I can’t really explain why but I

> didn't feel comfortable with it. Because it's a machine and it was answering me. I just felt uncomfortable"

> "It [VOC] would become kind of your friend after a while, like the voice. You would feel very comfortable with it, almost like you were not alone? Maybe that is a little bit scary".

In conclusion, the touch-screen interfaces elicited a sense that users were in control, were alone in the room and in charge, and using the interfaces as tools. In contrast, both ROB and VOC elicited a sense of an additional "presence" that might make decision on its own. In the case of VOC, there was an added sentiment of discomfort talking to a machine.

Situation Awareness

In our study, participants were asked to recall what smart-home devices are turned on, and what is the current home temperature at the end of each round. They were later asked using which interfaces was this information easiest and hardest to recall. 61% of participants claimed it was easiest to recall using ROB. 67% claimed the hardest to recall was using VOC (See Table 2).

One way in which this insight was explained in the interviews was because of the *visibility* of the robot's physical icons, as opposed to the VOC, where there was no visible indication regarding the home status, only immediate voice feedback:

> "Here [ROB] when you are out of your house and you leave the A/C on you can see that it's on, you go out and you see the icon there. Here [VOC] you see nothing."

> "At the end I didn't know anything [with VOC]. It was so easy to do the commands, but at the end you didn't know what was going on."

WAL was also described as an interface with high visibility:

> "It's kind of like a computer board where you can see everything that is going on in your house. Very simple, very straightforward, you can see a clear display of what is working and what is not"

Other participants attributed their ability to recall the status of the home, as well as their inability do to so, to the existence or lack of *physical interaction*:

> "With the robot I was holding the tangible icons, so it registered"

> "I think that the robot is easy [to remember what is on], because you are moving [phicons], you are actually thinking of what you are doing"

> "[With] the voice [VOC] it was harder for me to remember. You are just speaking, you do not have to look or do a physical action, you just have to speak. For me it is harder to remember when you are just talking."

In conclusion, while ROB was recognized for both giving visual feedback and enabling participants to think-through-doing, VOC was described as an interface that lacks these qualities. WAL, although described with high visibility, was not perceived as an interface that encourages thinking-through-doing. Neither of these qualities were attributed to APP.

Distraction

One of the qualities we seek in a home control system is for it to disturb the user only when it is necessary, preferably in a non-disruptive way. This was our motivation for the copying task—we wanted to evaluate how disruptive each one of the interfaces was.

Using unfamiliar interfaces (VOC, ROB), participants felt completing the home control tasks was distracting:

> "The robot [ROB], the disadvantage is that it moves around and it reacts to whatever you are doing so it throws you off a little bit. Same with the speaker [VOC]"

> "It [VOC] is kind of like when you are in a middle of a task and someone interrupts you... Every time I had to say something I quickly forgot what I was doing."

> "The minute you speak you immediately forget what you are doing"

This could be due to the novelty of the interfaces. However, several participants thought ROB suggests a unique, "silent" interaction:

> "I liked the robot most"—"Why?"—"Because you are taking something and you are putting [it]. There is no noise, it is silent."

Surprisingly, the unfamiliar interfaces were not the only ones perceived as distracting. The most familiar interface, APP, was described as a highly disruptive one:

> "Not everything has to be in one device. Sometimes it is distracting. It is kind of like when you have a bedroom where you sleep, sometimes you can not study there, because you rest there... Or [the] kitchen, you can not study in the kitchen, because you think about food... The same with the phone... immediately someone sends me an email or someone calls you, it is distracting."

> "I didn't like that because it reminds me a lot of driving and texting at the same time... That experience for me reminds me of trying to get too many things done at once."

WAL was not mentioned as a distracting interface during the interviews. Moreover, the quantitative finding of the number of copied words in the copying task supports that WAL was the least distracting interface in the experiment (see Figure 4(c) and Table 1).

DISCUSSION

The interfaces we compared represent different levels of familiarity for users. The mobile application is the most familiar interface, as most people use it on a daily basis. Wall-mounted screens, voice-controlled speaker devices, and social robots are less familiar, in this order.

Our findings align with this gradation; they show that the more familiar an interface was, the more usable, comfortable, and natural participants felt using it. A notable exception is that VOC was rated slightly more natural than WAL. On the other hand, participants perceived interactions with familiar interfaces as mundane and predicable. This is reflected by lower perception of flow, lower situation awareness and less attention when using familiar interfaces. Our strongest finding is thus a trade-off between flow and usability, following the gradient of familiarity.

Embodied Robot vs Voice Control

The two most unfamiliar interfaces are VOC and ROB; at time of writing, most users would have little experience using them. But while they are similar in familiarity, they present two contrasting interaction paradigms: out-loud voice control on the one hand (VOC), and peripheral, tangible, and silent interaction through physical icons and expressive gestures on the other (ROB).

According to our qualitative findings, the main perceived advantage of the voice interface lies in the user's ability to control the home from any location in the room, and free of using their hands.

However, VOC seemed to have evoked more negative feelings: Participants described the interaction as intimidating and as one that causes unease.

In addition, ROB was perceived with significantly better flow than WAL and APP. whereas the interaction with VOC, also novel, did not show similar results. ROB was also by far the popular pick for most enjoyable interface, chosen almost three times more often than VOC.

Familiarity, Situation Awareness, and Sense of Control

Another interesting findings is in the relationship between familiarity, flow, and sense of control. The most familiar (and thus low-flow) interfaces (WAL and APP) gave participants a better sense of control than less familiar, high-flow ones (VOC and ROB). However, the inverse relation between flow and sense of control was not fully inverse—participants described feeling more in control with ROB than with VOC, although ROB's flow was also rated higher. This speaks in support of the design choice of a tangible embodied interface, suggesting it might maintain both a high perceived sense of control and high perceived flow.

Situation awareness could partially explain ROB's higher sense of control. Participants had the highest situation awareness using ROB, and the lowest of all four interfaces using VOC, i.e—it was easiest to recall the status of the home using ROB, and hardest using VOC. The interviews explained these results in two ways.

One explanation was the visibility of ROB's physical icons, whereas VOC had no visual feedback. According to Nielsen [40], visual indication on the interface's current state is critical and should be given to the user at all times. The second explanation to the high situation awareness using ROB can be attributed to the physical action required to control it. Participants were thinking-through-doing, while VOC is controlled using solely vocal commands. Previous work [33] discusses the importance of physical interaction using interactive systems, and claims it encourages thinking and learning. Although WAL was also described with high visibility, participants did not mention it as an interface in which they were thinking-through-doing. APP evoked neither of these traits.

A final surprising finding relates to distraction. APP, arguably the most familiar interface to participants, was perceived as the most distracting interface, while WAL seems to be the least distracting one, as reflected in the high word-copying rates using it.

Tying our findings to the interface's differences in familiarity, visibility, and embodiment is clearly only one possible interpretation. We did not directly test these hypotheses or measure our participants' familiarity or sense of visibility and embodiment with each of the interfaces. This experimental evaluation is left for future work.

LIMITATIONS

An important limitation of our study is the possibility of a "novelty effect" when interacting with interfaces unfamiliar to participants. The novelty effect could explain the high perceived flow and enjoyment using ROB and VOC. However, given the differences between ROB and VOC, both novel interfaces, the novelty effect can explain these results only to a certain extent. In addition, some of the results cannot be explained by the novelty effect at all, for example the high situation awareness for ROB, low situation awareness and negative perception of VOC, the low distraction for WAL, but high distraction for APP. To fully address the "novelty effect" issue, future long-term studies deploying these technologies in peoples' homes are required.

An additional limitation of the study is that we could not isolate the differences that are inherent in the nature of each interface (for example the range of locations from which one can use the device and the response time of visual vs. auditory feedback). These trade-offs should be kept in mind when designing for a specific interaction modality.

Furthermore, the robot combines two separate interaction modalities which differentiate it from the other interfaces in this experiment: physical input (tangible icons) and physical output (gestures). Our experiment did not tease apart these two variables. In this work, our goal was to evaluate the new robot design as a whole. Studying its various interaction aspects in isolation is left for future work.

Finally, there is a clear difference between a device that is designed specifically for the purpose of smart-home control (ROB, WAL) and devices designed for more than one purpose (VOC, APP). Single-purpose devices take away the added complication of selecting the particular application a user wants to use. There is also a consideration that some technologies reuse devices that people might already own and toward which they have a personal long-term relation. This is most obvious with respect to the mobile application.

CONCLUSION

As the popularity of smart-home and IoT devices grows, an increasing number of technologies are entering our domestic spaces. To control these devices, diverse interfaces and interaction modalities are introduced to users, including voice control, screen-based interfaces, embodied interactions, and most recently, social robots.

We suggest a unique design approach to the social robot paradigm. The interaction with Vyo, the robot used in this experiment, differs from the common wisdom of how users wish to interact with most domestic social robots today. Vyo suggests a quiet, peripheral, and tangible interaction through physical icons, gestures unaccompanied by notification sounds, and only intermittent use of a low-fidelity display. This is in contrast to the almost ubiquitous social robot design approach which includes high-resolution information-rich displays, bidirectional human-robot voice interaction, and touch-screen input.

In this paper we compared this social robot to common home control interfaces in an experimental exploratory study. Our findings from the comparison between robot, voice controlled, wall-mounted and mobile application interfaces show clear advantages and disadvantages for each interface.

The advantages of the embodied robot were flow, engagement, enjoyment, and high situation awareness regarding the state of the home. Its disadvantages were low perceived usability and low perceived sense of control. Further research should be conducted to better understand the low perceived usability finding. Usability is linked to familiarity with an interface, and a certain learning curve is expected to form new interaction habits. We recommend evaluating how long-term interaction with such an embodied interface would evolve over time and how it might influence perceived usability. In addition, usability issues may be addressed by improving performance using sensing and providing feedback with better accuracy and clarity.

The hands-free and ubiquitous control offered by the voice interface were its clear advantage. However, our findings shed light on critical disadvantages of this interface that raise questions on the appropriateness of such an interface for smart-home management. Participants felt out of control, showed low situation awareness, and expressed discomfort and aversion towards the voice interface. We recommend that designers of voice interfaces address these issues by providing better vocal feedback, and perhaps by adding visual indication for information that is critical to the user's sense of control.

The main advantage of the wall-mounted screen interface was its usability: It was perceived as efficient, comfortable and straightforward. It was also found to be the least distracting interface. The disadvantages were low perceived flow, and low enjoyment. There are interesting differences between this interface and the second screen-based interface, the mobile application. Further research is required to better understand the qualities that make the wall-mounted interface less disruptive, a highly desirable aspect in the design of smart-home interfaces.

The obvious advantages of the mobile application—the fact that everyone already has one—is also a major disadvantage. Participants felt highly distracted using the mobile device, although it was not their own personal device but one given to them for the experiment. None of the participants received incoming messages, calls, or other notifications. This suggests that even though mobile devices are a simple and usable solution for remote control of automated homes, they might not be the ideal interface for control inside one's domestic space.

In sum, despite the usability shortcomings of the social robot interface, we conclude that it holds promise as a new interaction paradigm for smart-home control, where engagement, enjoyment, and situation awareness are critical aspects for a successful user experience.

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