AUGMENTING HOME ENVIRONMENTS WITH "SORT," AN ASSISTIVE ROBOTIC SYSTEM SUPPORTING THE DOMESTIC ORGANIZATIONAL ROUTINES OF HUMAN INHABITANTS

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AUGMENTING HOME ENVIRONMENTS WITH "SORT," AN ASSISTIVE ROBOTIC SYSTEM SUPPORTING THE DOMESTIC ORGANIZATIONAL ROUTINES OF HUMAN INHABITANTS

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Maintaining an organized lifestyle is an important domestic routine that reduces the effects of poor mental and physical health associated with clutter. While there have been many previous studies on domestic assistive robotics, a gap remains in creating a system of (wall-based) robotic organizers to understand human behaviors. This dissertation proposes a multi-robot system of wall-climbing organizers called SORT (Stuff Organizing Robot Team), aimed to help people sort, retrieve and deliver domestic items. This research contributes knowledge in four main areas: wall-climbing assistive robots, human-multi robot interaction, impact of cultural differences on HRI, and understanding people's organizational behaviors.

To explore previously under-utilized domains within the home where robots can live, SORT is proposed as a wall-climbing system that demonstrates potentials for indoor assistive uses. This dissertation presents the design and fabrication process of two prototypes, one based on vacuum suction which was successfully tested on a whiteboard wall with a tethered controller, the other based on magnets and was successfully tested on a ferrous surface controlled by a cellphone app.

To enrich the field of human-multi robot interaction, multiple user studies (online and in-person) were conducted to understand people's reactions toward SORT. The results showed users' preferences on robot group size, speed, formation shapes,

movement path, communication gestures and perceived usefulness and usability.

An additional online study was conducted to explore how cultural differences may play a role in shaping users' preferences and perceptions toward SORT with 191 participant responses from US, China and India. Our results showed significant differences that contradict prior stereotypes and reinforced the importance of considering cultural differences in HRI studies.

The qualitative results in this dissertation reveal important findings on human behaviors in sorting tasks, such as organizational logic, decision making, and perceptions of control. These findings can provide insights on how future researchers may design multi-robot assistive systems at home.

As assistive robots are becoming more ubiquitous in our everyday lives, it is important for designers, engineers and researchers to understand people's needs, preferences and perceptions toward robotic assistants, especially when the robots are embedded within a larger Internet of Things ecosystem. This dissertation shows that a multi-robot group, like SORT, can successfully enhance domestic routines to improve people's life qualities (80% participant satisfaction). We as design researchers must also take a multi-disciplinary approach, considering previously under-studied areas such as human-multi robot interaction and building cultural differences as design variables to ensure the robot group's holistic success.

BIOGRAPHICAL SKETCH

Mengni Zhang is a design researcher and practitioner working toward improving the qualities of the built environments and people’s health and life qualities. His PhD study (Human Behavior & Design, Cornell University Department of Human Centered Design, Architectural Robotics Lab) centers on the design and verification of assistive robots for helping people become more organized. He has published double blind peer reviewed articles at IEEE and ACADIA conferences, contributed to a Springer’s book chapter on Adaptive Environments, and created interactive exhibitions (Group) at the 2020 Cornell Council for the Arts biennial and the 2019 ShenZhen / HongKong bi-city biennial. Zhang is also a registered architect licensed in New York State, with several years of professional experience designing and planning hospitals in Mid, Mid-West US as well as internationally. His research and practice interests include ergonomics, human-robot interaction, healthcare architecture and human-centered design. Previously, Zhang completed a Master's degree in resilient urban planning from Harvard's GSD and a Bachelor's degree in architecture from Cornell AAP. Beyond his PhD, Zhang will continue researching and teaching in academia with a health and wellness focus, while combining tools and methods from multiple disciplines from interaction study to architecture. He will also maintain a practice presence in healthcare, collaborating with former colleague on international hospital design competitions.

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CHAPTER 1

INTRODUCTION

This dissertation is established on the basis of assistive technologies that enhance and augment domestic routines. Taking an ecological approach, context (home) is a pivotal component in this thesis, steering directions in robot designs, use case scenario constructions and user study environment setups. This concept of context, which is the place and all design elements associated with such place where interactions occur between human users and robots, has been an integral part of the field of Human-Computer Interaction (HCI) and Human-Robot Interaction (HRI). Various theories had been proposed to frame context within the realm of interaction, such as Gibson's environmental "Affordance" in 1966 [23], Weiser's "Ubiquitous Computing" in 1991 [25], Schilit's "Context-Awareness" in 1994 [27], Ishii's "Tangible Bits" in 1998 [26], and Dourish's "Embodied Interaction" in 2001 [24], who has initially linked the concept to Heidegger's 1927 comparison of "present-at-hand" and "ready-to-hand" to lay the foundation of phenomenology in context-awareness [24]. While these theories have pushed interaction beyond the human scale to consider identity and location, the author believes that designs and corresponding theories and methods pertaining to enhancing the domestic spaces and the spatial dimensions of interaction extend the discussion.

The design of the domestic environment has historically been the charge of architecture, which is a product of an iterative design process—a "middle ground"—between artistic creation (theory) and engineered code compliance (instance). This middle ground is congruent with the "intermediate level knowledge" (or "Strong concepts") proposed by Höök and Löwgren [1], which is not only characteristic of architecture but, arguably, of other much younger design fields, particularly HRI. An example of this intermediate level connection, within the academic discourse of architecture, would be when designers refer to doors as thresholds. By removing the elements' utilitarian identities through typological abstraction [28], the designers are afforded new opportunities to gauge alternative or derivative options—to expand the designer's "repertoire of partial solutions" [1]. This process echoes the "present-at-hand" (theory) and "ready-to-hand" (use of theory) relationship where oscillating between the abstract and the concrete, meaning can arise out of action.

As a confounding variable, the ambient environment may play a role in altering interaction outcomes. All human activities (including those that might be characterized by HRI) inevitably occur within some forms of context. Therefore, the study of HRI should also be contextualized to reflect and accommodate the different scales of interactivities within specific architectural spaces or against specific building elements. This type of "context-conscious interaction", which should be an integral part of the design process (Fig 1.1), can augment the impact of interaction and expand the field of HRI by exploring and integrating architectural design and corresponding theories to create site-specific robots. The purpose is to extend the current framework in ubiquitous computing and embodied interaction and explore the role of context in HCI and HRI, such that context-conscious takes a step further from context-aware in leveraging the ambient environment and architectural features to proactively cue, anticipate and guide users' needs and responses.

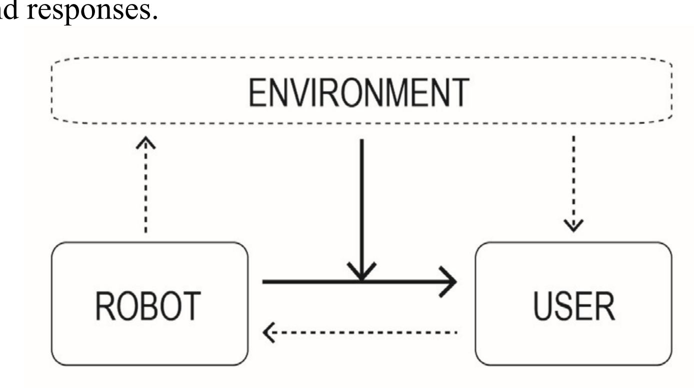

Figure 1.1. A concept model showing the environment as an additional element in the HRI process. Solid arrows represent direct impact, dashed arrows represent passive impact.

To demonstrate our phenomenological approach to embodiment—context-conscious interaction—we offer our designerly HRI process of developing a multi-robot system called "Stuff Organizing Robot Team" (SORT) supporting independent living at home and work. In so doing, we offer three scenarios corresponding to the context-conscious agenda by considering healthcare architecture principles in supportive design set by Ulrich [2] [3]. The scenarios include: (1) provide stress reduction through positive distraction, (2) provide social support via novel human-multi robot interactions [4] [5] [6], and (3) help the user become more organized to instill a sense of control. In addition, each scenario will be tailored to specific populations: 1) elderly people with mild cognitive impairment, 2) high functioning young adults with physical impairments, and 3) individuals living at home recovering from illnesses like COVID-19.

With the rise of assistive technology where context plays an important role, it has been identified that there exists a gap in health care at home that could be filled by robotic assistance or telemedicine [11]. Various robotic furniture and devices have been created that "cohabitate" with humans [7], [8]. Interactive spaces are also used to support occupational therapy [9] and to assist rehabilitation by incorporating video games [10]. Domestic assistance robots have been designed which interact with users non-intrusively, reacting only when interpreting the user's intention to initiate an interaction [12]. It has been shown that robotic controls developed to anticipate a user's needs significantly streamline HRI and help the user complete tasks faster [13]. This presents an opportunity for developing an anticipatory robotic system to promote health and wellbeing in the domestic environment.

Work in domestic robots which provide assistive care to specific groups such as children on the Autism Spectrum has seen increased interest in the HRI field [14], [15]. Moreover, it has been indicated that movement or gesturing can provide a means of socialization between a human user and a non-anthropomorphic robot, and that tuning of these gestures can successfully allow for human-robot communication [16]. In practice, the non-anthropomorphic robot Vyo has been used to successfully facilitate communication between a user and a smart home system as well as provide socialization [17]. However, it has not been determined how a user may socialize with a group of such robots.

It is clear that such interaction would vary in character based on the specific individuals involved. Studies on women living alone have shown that there is a desire for companionship that could be filled by a socially aware robot, but that it must be intelligent, problem solving, and have a distinctive personality [18]. Domestic robots supporting elderly users have been shown to require the development of a social relationship in order to be effective at providing assistive care [19], [20]. In children or young adults on the Autism Spectrum robots have been shown to provoke development of social skills. However, these are often static robots that do not move autonomously and that are designed to be introduced into the user's home only for a short, pre-determined period of time [21].

This dissertation focuses on creating a multi-robot system of organizers, that rely on altering, enhancing and augmenting the domestic environment to assist users in improving life quality. This dissertation begins with an introduction to the "Stuff-Organizing Robot Team" (SORT) concept, supporting independent living by helping people organize domestic belongings on walls rather than strewn across tables or desks, and storing items and delivering them to users as needed or wanted.

Chapter 2 introduces the design and fabrication of a working SORT prototype, the results of early lab experiments, a household belongings inventory, and two online user studies with a storyboard illustrating how SORT's group behaviors can work with the ambient environment for various interactions. Findings in this chapter suggest that SORT was positively received by both older adults (80%) and college students (70%)

and participants found SORT to be useful regardless of self-reported perception of existing domestic clutter. Design feedback include allowing robots to guide healthy user behaviors and increased customization for robots to fit into personal space. SORT was also successful in conveying messages interactive gestures and group formations.

Chapter 3 investigates how cultural differences may impact users' preferences and perceived usefulness toward the SORT system by creating and distributing an interactive online survey to 191 young adult participants from China, India, and the USA. Significant effects of culture on preferences and perceptions were found between India and China or the USA, but not between China and the USA. The findings contradict prior stereotypes in over-simplified theories, reinforcing the importance of considering cultural differences in designing domestic multi-robotic assistants.

Chapter 4 focuses on results from an in-person study with a new robot system built based on magnets and controlled via a cellphone app. The study aims to verify hypotheses constructed from prior user feedback while also providing new insights on participants' reactions and preferences toward the entire SORT concept. Results confirmed that participants (college students) were receptive to and satisfied with SORT (80%), and those who self-reported current personal rooms as messy or organized perceived the robots to be equally useful. The qualitative results also provided detailed user preference insights on robot group size, movement speed, organizational logic, decision making, and perception of control.

The final chapter explains current and envisioned future developments of SORT including summarized contributions that suggest design factors to be considered in formulating what potentially could become a design framework for creating a domestic assistive multi-robot system, and also two illustrations to imagine how SORT may work with other robots that are being developed in our lab to create an assistive suite.

For the broader fields in design, human-computer interaction, and environmental psychology, the research reported here offers a design exemplar and evaluation of a novel, robotic artifact supporting everyday activities by leveraging the home environment to provide an understanding of how people organize domestic items. This kind of artifact and understanding of people and their behaviors are especially compelling for researchers and, potentially, industry to develop domestic robot assistant, supporting populations in need such as older adults without affordable caregivers, college students living in small spaces or those with physical impairments.

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CHAPTER 2

STUFF-ORGANIZING ROBOT TEAM (SORT): A MULTI-ROBOT, WALL CLIMBING ORGANIZER-AND-DELIVERY SYSTEM FOR LIVING SPACES

Abstract

Maintaining an organized lifestyle, especially during the COVID-19 pandemic lockdown, is an important domestic routine that reduces the effects of poor mental and physical health associated with clutter. This chapter proposes a wall-climbing, multi-robot system, the "Stuff-Organizing Robot Team" (SORT), supporting independent living by 1) helping people organize domestic items on walls rather than strewn across tables or desks, and 2) storing items and delivering them to users as needed or wanted. First, the design and fabrication process of a working prototype will be reported, followed by the results of early lab experiments, a household belongings inventory, and two online user studies with a storyboard illustrating how SORT's group behaviors can work with the ambient environment for various interactions. The results provided early validation of the SORT concept and insights for future wall-based interaction designs. As interactive systems support and augment domestic routines, SORT offers a design exemplar of a multi-robot system that improves life quality by leveraging and enhancing the home environments.

Introduction

As we spend more time indoors [19], especially during the COVID-19 pandemic lockdown, maintaining an organized lifestyle by actively sorting and organizing personal belongings becomes an important daily activity. Traditionally, we rely on horizontal surfaces such as tables, desks, cabinets and shelves for storage and display. When poorly managed, domestic items can be difficult to find, causing unnecessary cluttering. This chapter introduces a multi-robot system, the "Stuff-Organizing Robot

Team" (SORT), supporting independent living at home (Fig. 2.1).

Fig. 2.1 Photo collage illustrating a SORT prototype delivering a medication bottle to user at scheduled time with prompt reminder.

A messy environment is associated with poor physical and mental health, including a reduction in working memory [16], an increase in stress [37], and difficulty in object identification [44]. When living in a disorderly space, our diminished attachment to and perception of our homes can lead to a lowered level of subjective well-being [34]. A cluttered home may also reduce a person's ability to recognize others' facial expressions [6], and significantly impact relationships by inducing negative emotions [38]. Moreover, there is evidence that clutter and its associated, perceived sense of being out-of-control can lead to overconsumption of food [42] and obesity [33]. For older adults, especially, clutter may lead to a reduction in sleep quality [7], further inhibiting mobility and potentially causing falls [36]. Clearly, an organized home environment is critical to maintaining a healthy lifestyle.

To aid in organization, SORT is designed to serve a broad range of users, such as older adults with mild cognitive or mobility impairment, college students living in confined dorm rooms for extended periods of time and ambulatory patients recovering from illness (such as COVID-19) who need medication management. The inclusion of the latter group was motived by the direct experience of a co-author of this chapter who was recovering from COVID-19 at home, managing with much frustration, and at different hours of the day, combinations of medications, inhalers and lung exercise devices that were kept on a side table (Fig. 2.2).

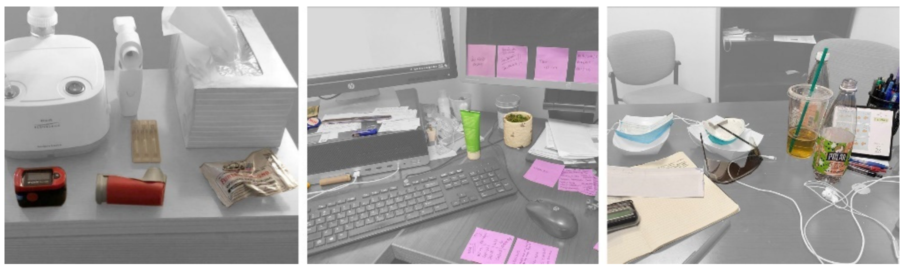

Fig. 2.2 Photographs taken by the authors: (left) an author's side table with COVID-19 treatment items; (right) authors' personal desks. Highlighted objects are candidates for sorting.

This chapter reports on the design and fabrication of various prototypes of SORT, an early lab locomotion experiment, along with an object inventory study, two interviews with older adults and college students, and a summary storyboard illustrating the potential robot group behaviors. SORT aims to help users declutter their domestic environments by arranging personal items on wall surfaces and delivering them at pre-scheduled times or when desired. When not actively delivering items to users, the system organizes itself in visually pleasing arrays, these group level behaviors may serve as novel modes of interaction and communication by activating and working with the ambient environment. We expect SORT to help users control their physical surroundings, increasing perceptions of self-control over their lives which, as already noted, are directly correlated with better quality of life [45, 29].

Related works

Robots supporting healthcare and wellbeing are an important focus in the assistive technology and interaction design community. A variety of home-based robots have been introduced to support elderly users [27, 8, 4]. Standalone robotic furnishings, surfaces, and other robotic devices are also developed to provide a range of assistive care to users [43]. However, there remains a gap in care that could be filled by robotic assistance at home, that is easy to use, practical (e.g., requiring no modifications to the home), and affordable [9] as SORT aims to be. Previous Human Robot Interaction (HRI) studies suggest that a non-anthropomorphic robot (like SORT) is a viable approach to assistive care [21]. As a means for communication, gesture can help forming social connections between a user and a non-anthropomorphic robot [35]. For example, Vyo has been used successfully to facilitate communication with a smart home system and to help form a social, human-machine connection [23]. Initial lab investigations have shown that small swarms of non-anthropomorphic robots can also communicate abstract information to a user [18]. However, it is unclear how this type of interaction may occur and contribute to a user's wellbeing, and how such interventions may fit into a person's home environment.

There are a few previous efforts in HRI more closely related to SORT in purpose. One of these studies provided valuable insights in social dynamics between users and delivery robots integrated in healthcare settings [26]. Another robot organizer system was created for homes but required the installation of tracks above the ceiling—a physically disruptive and costly implementation [14]. Also, this system was designed for able-bodied users and it lacked a reminder function for delivering important items at scheduled times such as medication. Other related research includes studies focusing on robots tasked with tidying up spaces [1,48] that specifically investigate, respectively, user preferences for sorting items and the image recognition of objects. In these cases, the robot itself tends to rely on conventional designs such as robotic arms and hence the system as a whole is immobile. These are the gaps SORT aims to fill. In addition, in order to effectively help older adults organizing their belongings at home, an ideal robotic assistant would need to be tuned to users' organizational styles [25, 30]. Simple algorithms carried out by an autonomous robot [5] suggest a way to match a user's expectation of how objects should be organized by a robot like SORT.

Various wall-climbing robots have also informed the development of SORT, including bio-inspired [15] and industrial-purposed robots [10]. Significant developments have also occurred in suction cup-based wall-climbing robots including passive suction cup climbers [47, 17] and suction cups using vacuum pressure [31, 32]. However, these robot designs are tethered and tend to rely on a steady supply of power and pneumatic vacuum air. Moreover, none of these previous examples are meant to operate in a multi-robot group for domestic use; and no suction-based wall-climbing robots have been applied to assisting users in organizing the home environment. Another major concern with wall-climbing robots is noise. SORT will be designed to operate quietly with non-continuous usage of vacuum motors. While multi-agent systems of organizing robots have been deployed across enormous industrial floors, such as the Xanthus and Pegasus system at Amazon Warehouses [2], no such system has been adapted at a smaller scale to domestic environments.

SORT is also inspired by studies on ways in which the built environment improves users' quality of life. For instance, numerous studies have shown that exposure to art and nature have positive therapeutic effects on people's mental and physical health, such as reduction of stress [22], and shortened post-operative hospitalization [39]. While music, paintings and views to outdoor green spaces have been made a part of healthcare facilities, there has emerged a range of embedded and embodied interactions that offer multi-sensory experiences allied with assistive and social robots in HRI domains. Two such cases are ScreenPlay, a contactless interactive media display installed in a hospital waiting room to provide engaging experiences among patients, family and staff [3], and LUMES, a light-emitting wood wall at Cabrini Hospital in Australia designed to improve mood [24]. The logic behind using interactive environment to promote wellness is rooted in supportive design principles of interior architecture, which include providing positive distraction, fostering social support and granting users more control over the environment [40, 41]. SORT has the potential to offer some benefits of these multi-sensory interventions at home through robot group behaviors to achieve the supportive design agenda.

Inventory Study

To better understand what objects can be organized by SORT, an inventory study was conducted on various domestic items, which were gathered and weighed on a tabletop scale. They were then built as 3D models where a bounding box was fitted on each to record the dimension. The longest side was noted as the critical dimension that needed to be satisfied when designing container receptables. For items that the authors did not have at hand, specification information was obtained from similar products found on Amazon. The inventory list is summarized in Table 2.1, and the corresponding objects' weight to critical dimension relationships are shown in Fig 2.3. Based on items assembled so far, the critical length needed to be satisfied by the robot and container ranged from 5.2cm to 20.5cm. While the final design may not accommodate the entire list, it will be designed for the majority of the objects identified.

Robot Design and Fabrication

To conceptualize the SORT robot, a morphological chart was first created to document potential candidates for each of the robot's components (Fig. 2.4). Because the robots are expected to move on walls while holding various items, a circular body shape was selected to minimize accidental corner collision and maximize the container volume. As mentioned, current wall-climbing robots that focus on heavy industrial use

Table 2.1 Initial inventory list of potential household objects for sorting.

	Item	**Weight (g)**	**Boundary dimension (cm)**
1	Eye glass	30	13.8 x 4.4 x 3.7
2	Cell phone	150	16.8 x 9 x 1.2
3	Wallet	75*	12 x 10.6 x 2
4	Keys	90*	19.8 x 5 x 2.6
5	Remote	110	20 x 6 x 2.5
6	Inhaler	50	8.5 x 6 x 3
7	Nebulizer med.	5*	10 x 9 x 5
8	Cough drop	85*	12.5 x 10 x 3.5
9	Ibuprofen	30*	7.5 x 4 x 4
10	Thermometer	25	10 x 1.5 x 0.5
11	Oxygen monitor	60	6 x 4 x 4
12	Pen / pencil	8(x6)*	10 x 4 x 1.2
13	Digital screen	73	10 x 6 x 0.5
14	Med. bottle	20	10 x 5 x 5
15	Med. organizer	70	20.5 x 3.4 x 2.2
16	Picture frame	113*	15 x 10 x 10
17	Alert device	56	8.1 x 5.5 x 5.5
18	Sticker note	60*	9.4 x 9.4 x 8.4
19	Paper clip	34*	5.2 x 5.2 x 3.2
20	Deodorant	130*	14.6 x 5.4 x 5.4
21	Nail clipper	45	7 x 4 x 1.6
22	Breathing device	100	9.5 x 5 x 3.6

* Items have greater weight variability

Note: list to be expanded with new item feedback from user studies.

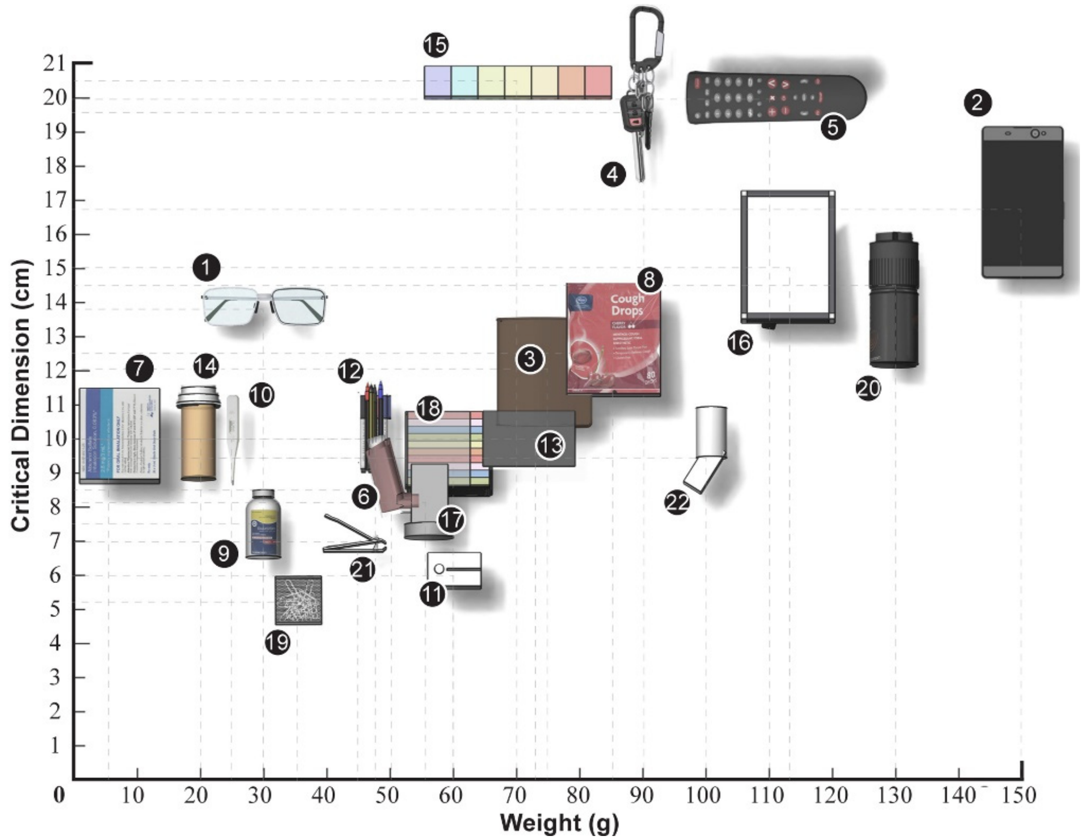

Fig. 2.3 Plotting of the inventory study, showing relationship between object weight and critical length. Object identification number corresponds to list in Table 2.1

tend to require high levels of steady supply in power and vacuum air. Since the household items SORT aims to organize have lighter weights, a different design was created with simpler hardware by linking two cylindrical units together with a fulcrum arm. Locomotion can then be achieved by having the two units swing around each other in a path pattern similar to that described in a self-contained wall-climbing robot [46]. For SORT, the suction cup option was selected for its availability and low cost.

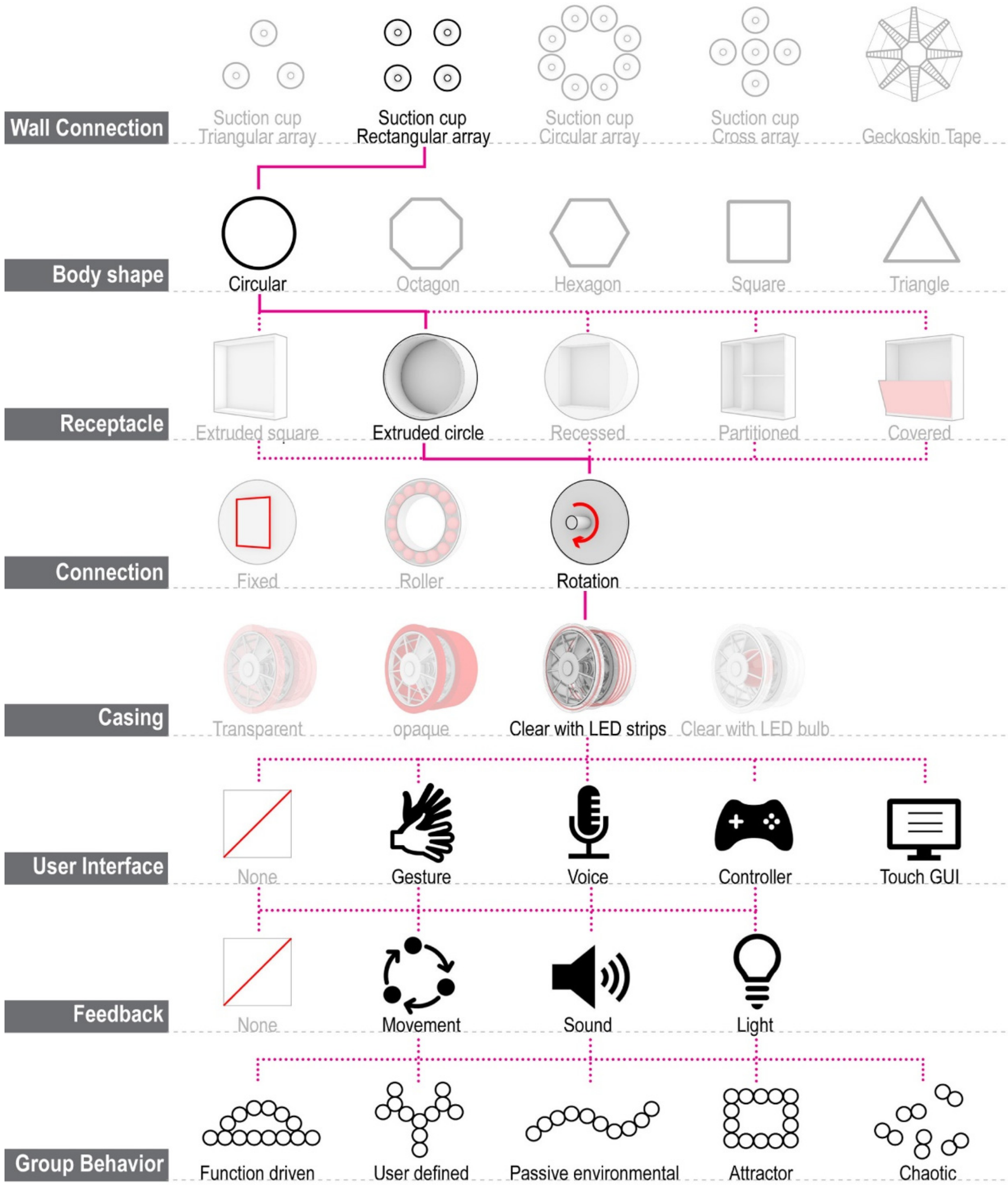

Fig. 2.4 Morphological chart documenting component variations for designing the SORT robots. Solid magenta lines indicate options included for prototyping. Dotted magenta lines indicate potential alternatives to be explored.

Prototyping

Utilizing the morphological chart, a series of prototypes were developed. The first prototype was built to test the suction cups with tubes. Running a 3.3V micro vacuum pump for only one second with a check valve to prevent backflow was enough to have the prototype successfully adhere to a glass window and a smooth white board wall. The pumps can remain off so the whole system is quiet. A cardboard shell was then added with a receptacle container clipped on via magnets. Engaging the release valve will allow air into the tubing and the prototype can be detached from the wall. These steps are shown in Fig 2.5. There were some limitations, such as leakage, an unstable connection bridge, and a bulky shell chamber. A servo was installed but did not successfully create locomotion and the suction cups work only on smooth surfaces.

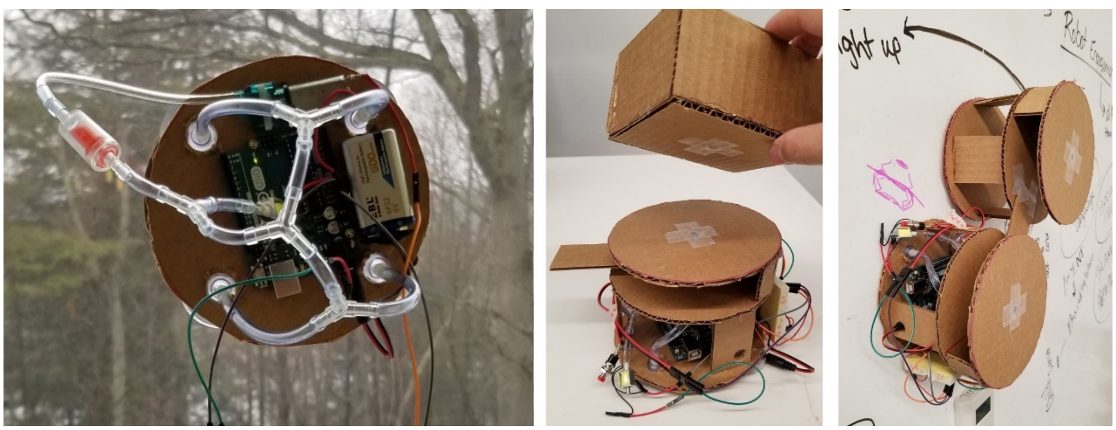

Fig 2.5 Left: the first prototype's base adhered to a window with 4 suction cups controlled by a micro vacuum pump connected to a check valve and release valve. Center: one robot unit with detachable container via magnets. Right: prototype adhered to a whiteboard wall.

Improvements were made for the second prototype. integrated channels were created in lieu of plastic tubing to connect the vacuum pump, check valve, and release valve. A new base was 3D-printed to better organize the components inside. The new robot successfully adhered to a white board on the wall via Bluetooth controlled by a cellphone; but due to power and torque issue, the servo provided limited range of motion. As a result, a tethered controller with external power was used for testing (Fig 2.6).

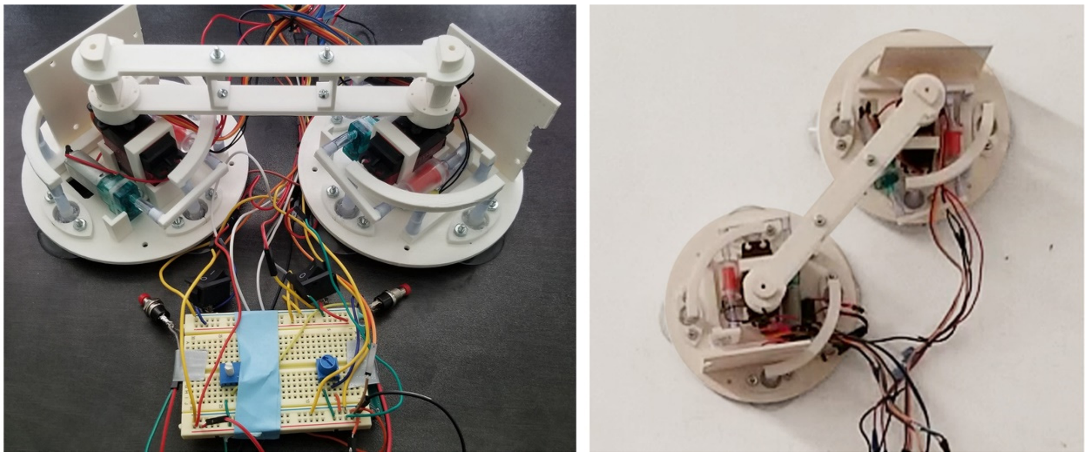

Fig. 2.6 Photos of the second prototype. Left: 3D-printed base with air channels that connect release valves, check valves and vacuum pumps. Right: one SORT robot on a white board.

An experiment on locomotion with the second prototype served as early proof-of-concept. As mentioned earlier, the robot moves on the wall by having one cylindrical unit ("unit-A") swing the other cylindrical unit ("unit-B") around it, following the sequence shown in Fig. 2.7.

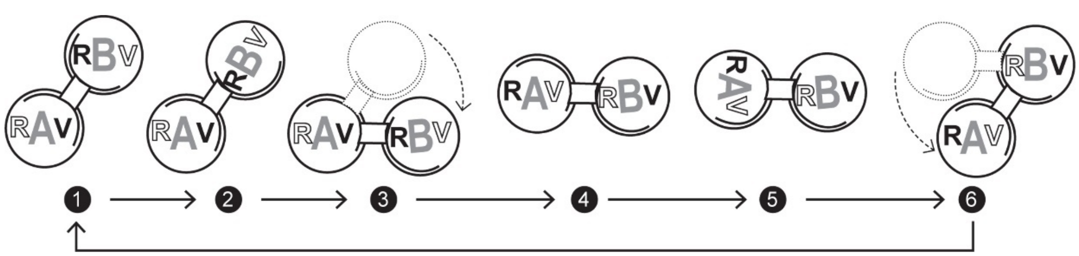

Fig. 2.7 Locomotion sequence: 1) Unit-A's vacuum engages; unit-B's release valve activated. 2) Unit-B self-rotates. 3) Unit-A swings unit-B to position. 4) Unit-B's vacuum engages; unit-A's release valve activated. 5) Unit-A self-rotates. 6) Unit-B swings unit-A to position. Then the sequence repeats. Note: V represents vacuum on, V represents vacuum off, R represents release valve on, R represents release valve off.

A tethered controller was used for the above process with two switches for the vacuum pumps, two buttons for release valves, and two knobs for the servos. The locomotion test was performed manually on a whiteboard wall. In 3 minutes, 30 seconds, the robot moved 40 inches horizontally (Fig. 2.8) – the distance from an armchair to a table in a studio apartment.

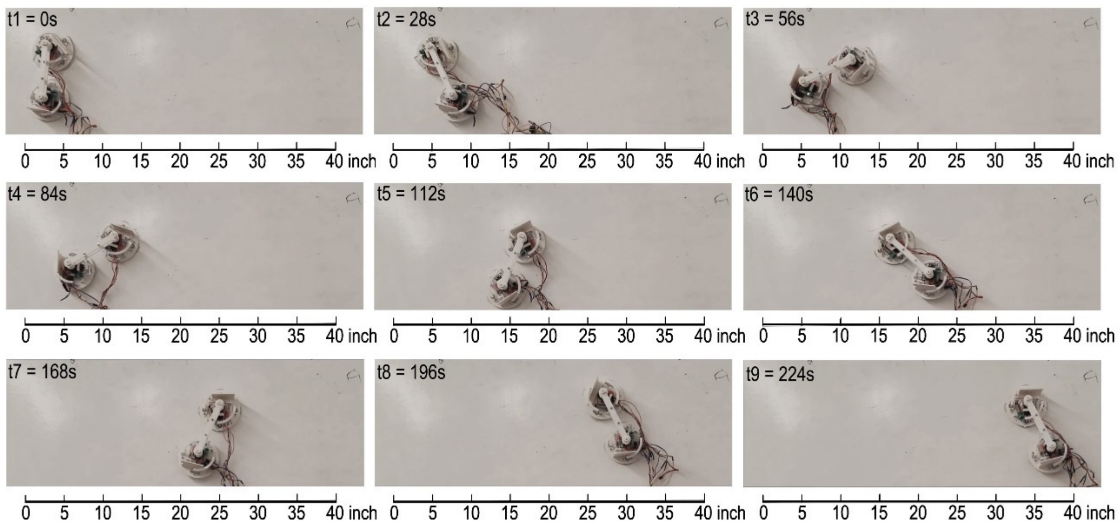

Fig. 2.8 Image captures from recorded video showing the manually controlled movement of the second prototype on a white board wall.

The third prototype (Fig. 2.9, 2.10) included a base with integrated channels connecting vacuum pumps with suction cups to further eliminate leaks. An inner-frame structure was created with non-rigid connection bridges accommodating vertical slippage. A ball bearing was inserted at the top center of each cylinder unit's frame, supporting a magnet connector. The receptacle container and display disk can be snapped onto or easily pulled off from the base via the magnet connections. In addition, a semi-circular rail was introduced at the base where the bridges can slide along anchor points; this will prevent the rotation from swinging the other cylinder unit out of plane. The vacuum pumps and valves had not been installed and only one prototype was fabricated. This iteration was instead used during the user studies for Wizard of Oz demonstrations.

Fig. 2.9. Left: exploded isometric showing the robot components: 1) Receptacle container, 2) Display, 3) Magnetic connector with ball bearing, 4) Interior frame, 5) Connector bridge, 6) Micro-controller, 7) High torque servo, 8) Check valve + release valve, 9) Micro vacuum pump, 10) Base with integrated channels, 11) Bridge rails, 12) Suction cup anchor, 13) Suction cup. Right: 3D printed parts for constructing the prototype.

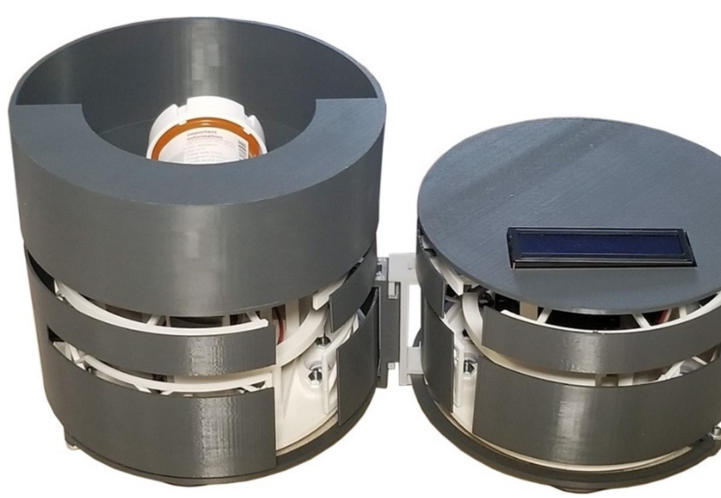

Fig. 2.10 Prototype-3 configured with a container on the left and a display screen on the right.

User Studies

A previous study [13] has shown correlations between procrastination and clutter, where such relationship tends to strengthen as the population age increases. For older adults, clutter may lead to a reduction in sleep quality [7], further inhibiting mobility and potentially causing falls [36]. According to research on the impact of visual clutter, both young and older adults were found to be negatively affected by on-screen clutter, with older adults being affected more [28]. Another study on young adults and college students found that indecision or decisional procrastination was related to self-reported clutteredness [12]. For our user studies, older adults and college students, whom tend to live in small spaces such as nursing home rooms and college dorms were first identified as potential participants. Due to the on-going pandemic lockdown, user studies were conducted online via Zoom.

Study one with older adults

We conducted the first user study to determine if older adults were receptive to the SORT concept and how they would envision themselves or someone close to them using it at home. Nine individuals who currently use or have used a walker completed our study. The participants (seven females and two males) ranged in age from 51 to 80 years with a mean of 64.8 years (SD = 8.2 years). All participants live in their own home and have access to a computer. eight of the participants had used a web-based video conferencing program or Facetime, and all have cell phones. Ethical approval was obtained through the university review board.

A semi-structured user interview was conducted via Zoom with participants in their own home. The participants were given an overview of the concept while viewing a rendered image of SORT (Fig 2.11). Four questions pertaining to SORT were asked: 1. "What do you think about this idea?"; 2. "How do you think you could potentially use this?”, and 3. “Can you think of friends or loved ones who would benefit from something like this? How? Why?”. Each session lasted a maximum of ten minutes.

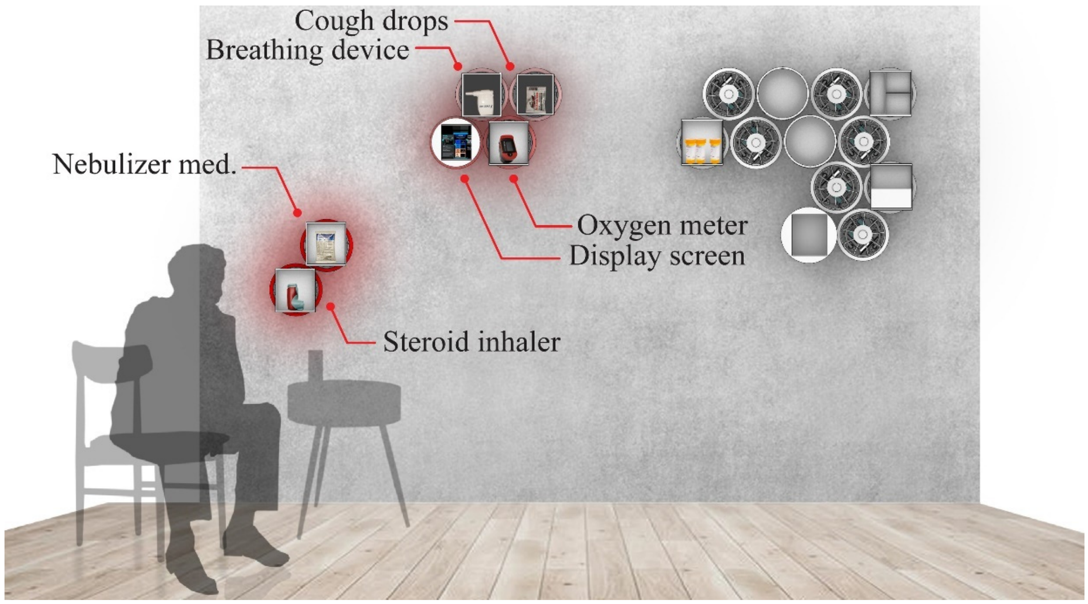

Fig. 2.11 Concept rendering used during the interviews to show SORT managing a user's COVID-19 treatments by delivering an inhaler and nebulizer medicine

For the first question, “What do you think about this idea?”, two individuals had unfavorable comments including “I don’t see much use for that” and “We don’t have any open wall so no way to get from one place to the next, (moving) tables would work better”. Seven participants had favorable responses to the concept of SORT, with comments such as “Very helpful”, “It’s a good idea”, “I would give it an 8 out of 10” and “…like the idea for people to remember medications”. The feedback also contained suggestions for items to store that the team had not previously considered including sewing needles and decks of playing cards. Participants wanted to know how they would “call” it to them and who would program it. The greatest concern was a lack of open walls due to pictures and artwork or an open floorplan; this was mentioned by three of our nine participants.

For the second question, “How do you think you could potentially use this?”, four expressed interest in using SORT for medications, with one individual in specific need for organizing various eye drops after cataract surgery. That individual also suggested having pictures of each medication with reminder alarms when it is time to use them. One participant would use SORT for a variety of important personal belongings, such as holy cards, jewelry and “special things”. Novel items to store include lip balm, a mirror, dental floss and ointments. One participant commented on potentially using another robotic arm to retrieve items from SORT.

When asked, “Can you think of friends or loved ones who would benefit from this?”, all participants responded favorably. The suggested potential users include: someone who was paraplegic, people with poor eyesight, people with arthritis, parents of small kids, anyone who has confusion using medications or someone who takes medication infrequently, patients recovering from surgery, family members with special personal belongings and specific instances such as “when my mom had MS (Multiple Sclerosis) she would have greatly benefited from this and it would give more independence”.

When asked “How?” or “Why” as a follow up question, the responses varied from gaining more independence, feeling more self-reliant, to serving as a reminder for medication or other tasks, to feeling less overwhelmed. One person asked if the user would need one “good hand to use the system”. Another who used to work in long term care felt “if people could just do a few things for themselves, it could be super!”. Some others commented SORT could be used for daily calendars and care plans, goal setting, and declutter over-the-bed tables.

Study two with college students

After receiving positive reactions from the first study, a second online user study was conducted with 10 college students (six females and four males) ranging in age from 20 to 27 years with a mean age of 22.9 years (SD=2.1). All participants live in their own rooms either in a house or an apartment. When asked to rate the clutteredness of their personal spaces from 1(tidy) to 5(cluttered), participants' responses were neutral with a mean of 3.05 (SD=0.76). A four-part semi-structured interview was conducted via Zoom. First, participants were shown images and videos of how SORT works (as presented earlier), followed by nine open-ended questions. Then six robot demonstrations were performed to better understand user preferences and reactions. The researchers then walked the participants through eight Likert scale questions. Finally, renderings and animations of robot group behaviors were shown followed by open ended questions. Each interview session lasted one hour. Each participant was compensated with a $15 Amazon gift card. Ethical approval was obtained through university review board.

Open ended questions

The first question "What do you think SORT is trying to do?", and the second question "Can you describe to others what SORT does?" aim to understand if participants' perceptions of the robots align with the design intention. All participants were able to describe SORT both in functional goals and physical appearances. Some interesting reactions include, "SORT moves like a toddler or penguin.", "They are very cute.", and "My cat would like watching it move."

For the third question, "Would you have SORT in your home?", seven participants responded positively, three would use SORT but under certain conditions. Some participants feedback include, "My concern is that it is hard to reach (over furniture).", "The sound level would have an impact on whether I would want it.", and "I wonder if there will be some damage to the wall."

For the fourth question, "Do you have an empty wall at home for SORT?", nine participants responded positively.

For the fifth question, “Where would you put SORT in your home?”, the spaces mentioned include (Figure 2.12): kitchen (six times), bedroom (five times), laundry room (once), living room (four times), bathroom (four times), workspace (once).

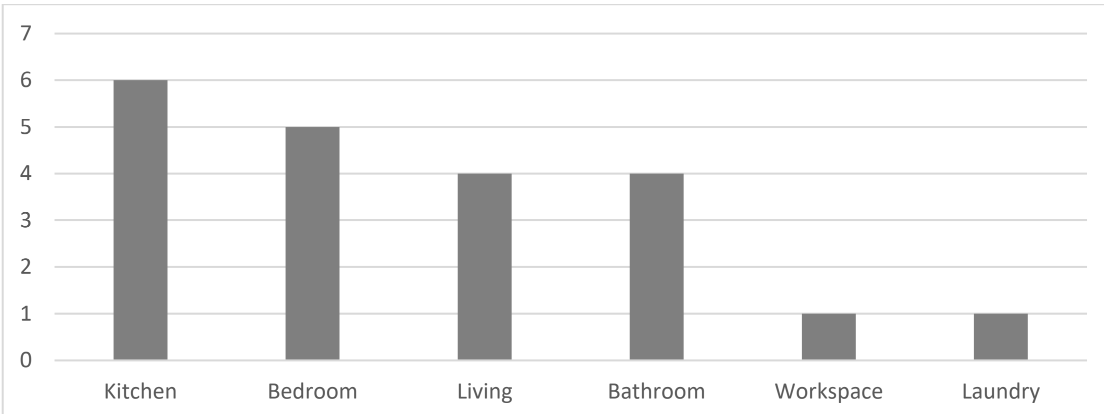

Fig. 2.12 Results of preferred SORT usage location by room types.

When asked “How many SORTbots would you have?”, the overall preferred robot numbers range from 1 to 20, with additional maximum tolerance up to 30. The preference ranges were also room specific (Figure 2.13) - bedroom: 1-6, kitchen: 5-15, bathroom: 2-5, living room: 4-15, workspace: 10-20.

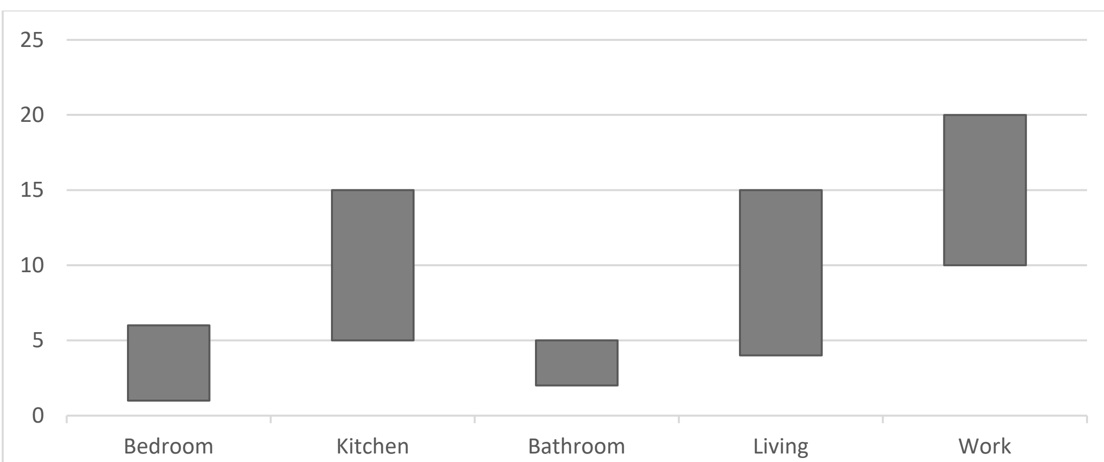

Fig. 2.13 Results for preferred robot numbers per room types.

For the next question, “What other items would you want SORT to carry or deliver?”, the responses include: toothbrush, cooking utensil, cups, sanitizer, spices, masks, small plants, electronic parts. Larger items, that cannot fit in current prototypes, include books, cloth, shoes, laptop, camera, hairdryer, speaker, bag, yoga mat. There were also some interesting user feedback: “(it) would be great if SORT could function as a library.”, and “(put) valuables if it has a lock.”

When asked “Would you use SORT for some other purposes?”, the responses range from interactive art with different shapes and lights, sending items to others in the room, a mobile video conferencing platform, to toys for pets, using SORT itself as a pet and as a cooking assistant.

For the last question, “Can you think of friends or loved ones who would benefit from SORT? How and why?”, all participants responded favorably. The suggestions include elderly grandparents, people with disabilities, those living in tiny spaces, people who are forgetful. Some interesting comments are: “I want to have a healthier life...have chocolate inside the robot, it will run away from me if I try to take (the chocolate).”, and “If there are things you don’t want children to get into, raising (SORT) almost to the ceiling level...would be a smart use.”

Scenario demonstrations

Six scenarios were demonstrated to understand users’ preferences on robot group location, movement speed, movement path, interaction mode, feedback mode and meanings of communication gestures. To expedite the process, two cardboard robot mock-ups (Fig. 2.14) were created and operated via a Wizard of Oz method.

During the first scenario demonstration, three different height options, measured off of the floor level, were shown by the researcher with the cardboard model group on a wall. The options include 100 cm (at around the standing waist level of the researcher who is 180cm tall), 140 cm (at around the chest level) and 180cm (above head level). The participants were asked to select a preferred option where they would locate SORT at home. Seven participants preferred the middle location (140cm). One favored the higher location. Two expressed no preferences but mentioned that the robot location would depend on specific use cases.

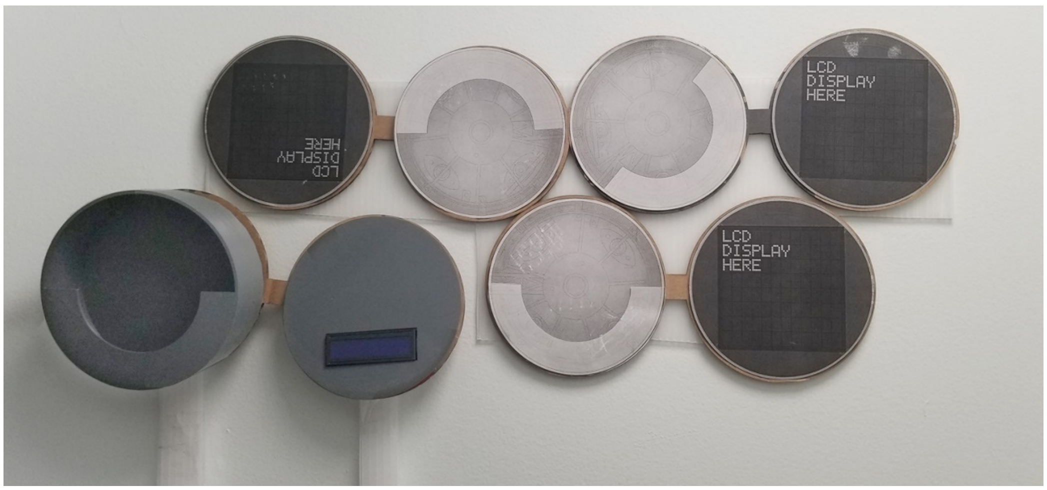

Fig. 2.14 Robot mock-up models used during the scenario demonstrations. Photo print outs on cardboard base representing the actual robots were mounted together on a sheet of plastic to be moved quickly as a group. One set of the robot container and display screen were mounted on cardboard bases controlled by plastic dowels for Wizard of Oz demonstration.

For the second scenario demonstration, three different robot movement speeds were shown by the researcher using the container model on plastic dowels to simulate the swinging locomotion. The manually operated speeds, across a distance of approximately 60cm, include a slow option (approximately 6cm/second), a medium option (approximately 10cm/second), and a fast option (approximately 20cm/second). Participants' preferences were varied depending on robot tasks. In general, the fast speed was associated with efficiency and the slow speed was associated with low obtrusiveness. Some interesting feedback include, "I want SORT to mirror my own pace.", "It would be good if you could choose the speed.", and "Fast speed makes me scared...slow speed makes me feel impatient.”

Next, two types of robot paths were demonstrated with the container model on plastic dowels moving either in a straight line or a curved path. Five participants preferred the straight path for efficiency, two chose the non-straight one for it being “lively” and “animated.”

Then five types of robot interaction modes were explained and demonstrated to the participants, including hand gesture, voice, a remote controller, a touch screen app and no interaction (Figure 2.15). Five participants favored using voices to communicate with SORT for convenience and familiarity, two preferred gesture for its “friendliness,” one preferred touch screen, one wanted no interactions where robots simply carry out tasks as scheduled, and one chose the controller. Each participant could choose more than one option.

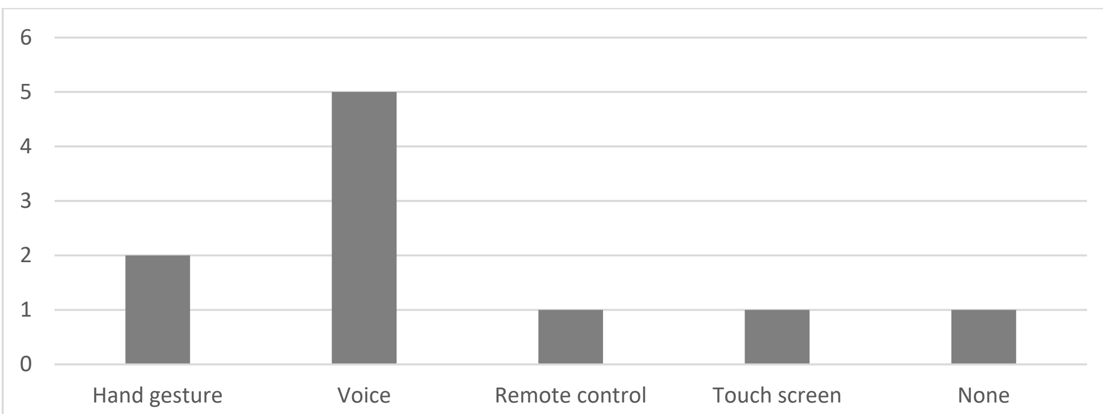

Fig. 2.15 Preferred interaction modalities.

Four types of robot feedback modes were also explained and demonstrated (Figure 2.16), including a swinging motion as gesture feedback, a bird chirping noise as sound feedback, a pulsing LED as light feedback, and a last option of no feedback. Four participants chose movement, four picked the light, three preferred sound, and one chose no feedback where robots would directly proceed to carry out the task without acknowledging user input. Similarly, each participant could choose more than one option.

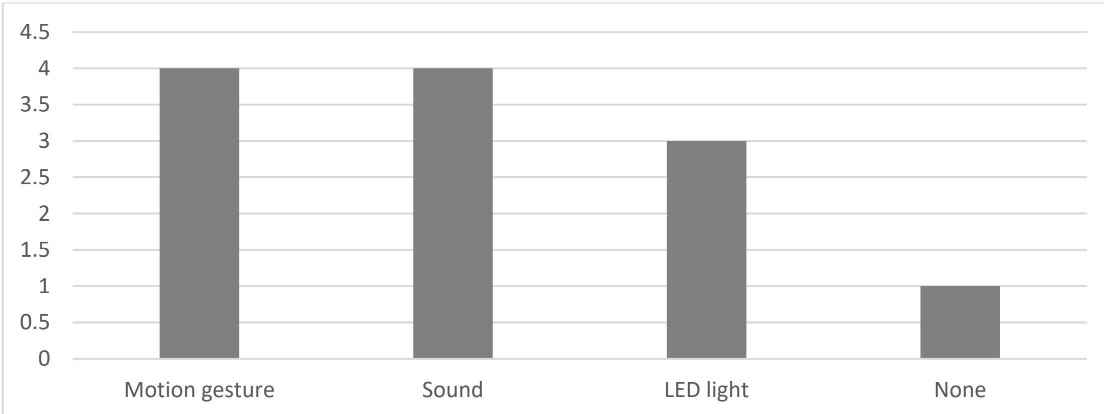

Fig. 2.16 Preferred feedback modalities.

For the final scenario, six robot gestures (Fig 2.17) were demonstrated with the container robot on plastic dowels. The gestures include a small wave, a quick jitter, a pacing back-and-forth movement, a large wave, a rotation from up to down position, and a rotation from down to up position. Participants were then asked what they thought SORT was communicating. For the first gesture – small wave, six participants associated the movement with attention seeking; two felt it was a greeting; two thought the robot was in trouble. For the second gesture – quick jitter, five participants perceived the gesture as urgent reminder; two said attention; three thought the robot was in trouble (such as being stuck). For the third gesture – pacing back-and-forth, the responses were diverse: the robot was "bored," "antsy," or "pending," in a "holding pattern." For the fourth gesture – large wave, five participants were unsure; three mentioned attention; one said waiting; one thought it was sleeping. For the fifth gesture – moving from up to down, three participants were unsure; four said the robot was powering off; two said task completion; one said charging. For the last gesture – moving from down to up, four participants were unsure; three said the robot was powering on; three said task completion. Based on the responses, it appeared larger robot movements tend to produce more ambiguous gestures that are difficult for users to interpret.

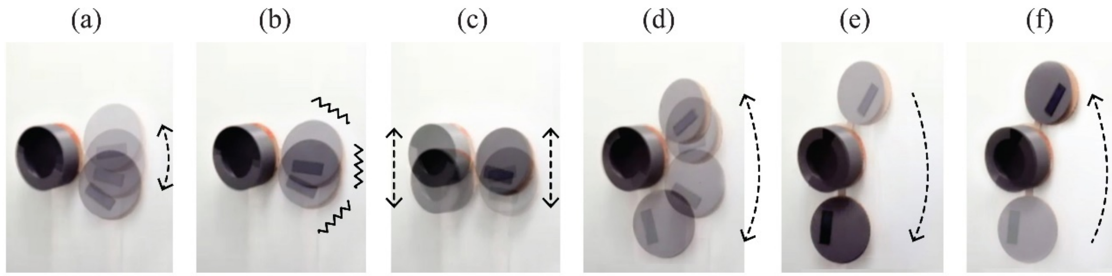

Fig. 2.17 Robot gesture demonstrations. (a) Small wave, (b) Quick jitter, (c) Pacing back-and-forth, (d) Large wave, (e) Moving from up to down, (f) Moving from down to up.

Scaled questions

In this section of the interview, the researchers walked the participants through eight questions based on a 5-point Likert scale with 1 being strongly disagree and 5 being strongly agree.

For the first question, "I think I would like to use SORT.", the mean response score was 4.35 (SD=0.67). Participants responded positively toward SORT. Some concerns include container size limitations and a need to have SORT match existing interior design.

For the second question, "I think it is helpful that SORT can move and transport, fetch and deliver things to me.", the mean response was 4.7 (SD=0.48). Participants' responses were very positive. The main concern was that SORT cannot move between rooms.

When asked "I think it is helpful that SORT can remind me of tasks.", the mean response was 4.85 (SD=0.34). Participants' responses were very positive. One asked to pair SORT's reminder with personal cell phone.

For the next question, “I think it is helpful to have more than one SORT robot unit.”, the mean score was 3.7 (SD=1.2). Responses were varied. Participants had favorable views toward the different functionalities of SORT as a group. Others who preferred fewer robots wanted to test out the product before acquiring more.

For the fifth question, “I think I will feel very confident using SORT.”, the mean response was 4.1 (SD=0.74). The responses were generally positive with a moderate spread. Some concerns include the robustness of the system, the types of surfaces SORT can work on, the weight of items, pets jumping on the robot and a need to provide clear instructions.

For questions six, seven and eight, three photographs (Fig. 2.18) depicting various item organizations on a desk were shown, the participants were then asked to answer a question: “For the following scenes, how organized do they appear to you? (1-least organized, 5-most organized)”, same household belongings were used in each scene. For question six, the mean was 1.85 (SD=0.7). Some judging criteria mentioned were: inability to identify object quickly, presence of unnecessary items and misalignment. For question seven, the mean was 4.35 (SD=0.6), which was significantly higher than the previous question. Some judging criteria mentioned were: grouping of similar items, more open work space and presence of unnecessary items. For question eight, the mean was 4.8 (SD=0.4), slightly higher than the previous one. Some judging criteria mentioned for the score increase were: smaller items were moved into SORT and out of sight, more work space. Overall, participants did not find the SORT presence obtrusive.

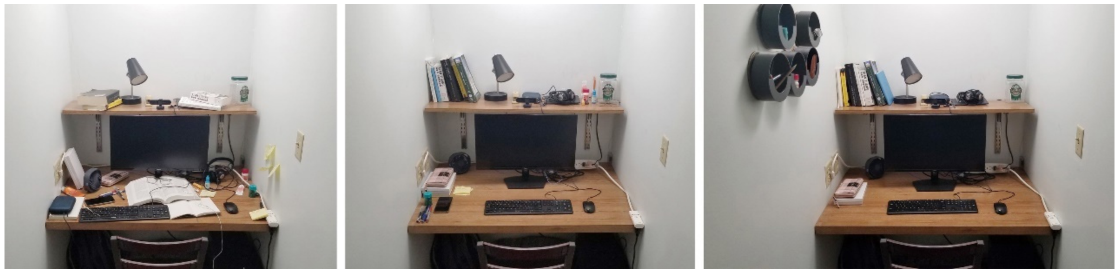

Fig. 2.18 Photographs shown to participants depicting three different scenes of item organizations. Left: photo used for question six, showing a disorganized desk. Center: photo used for question seven, showing an organized desk. Right: photo used for question eight, showing an organized desk with SORT on the wall.

Robot group behavior

Aside from its functional goal of fetching and sorting household belongings, SORT also considers various group configurations as important means to improve the effects of interaction and augment the ambient environment. These were achieved by creating interactive experiences through human-swarm interaction [20], where the system can form various geometries, such as a user defined tree shape or imitating a sunrise above horizon, combined with lighting effects to convey meaning (Fig. 2.19). For this section of the interview, participants were asked to rank these images (1-most favorite, 5-least favorite) when using SORT as a decorative element at home.

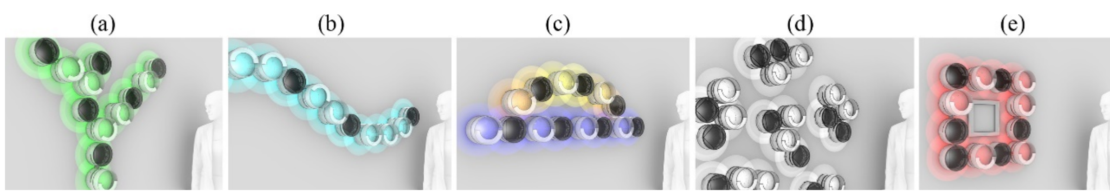

Fig. 2.19 Concept renderings of possible robot group behaviors. (a) tree: a user defined tree shape, (b) wave: an ocean wave, (c) sunrise: imitation of sun rising above horizon, (d) random: robot pairs moving around without a pre-defined pattern, (e) frame: robots surrounding a family photo. These design intentions were not disclosed to participants during interviews.

For the user defined tree shape, the mean score was 2.2 (SD=1.0), it was selected as the most favorite for four times and none chose it as the least favorite. For the wave pattern, the mean score was 2.7 (SD=1.2), it was selected as the most favorite once and least favorite also once. For the sunrise imitation, the mean score was 3.2 (SD=1.3), it ranked as most favorite twice and least favorite once. For the random pattern, the mean score was 3.1 (SD=1.5), it was selected as the most favorite for two times and least favorite for three times. Lastly, the photo frame formation received a mean score of 3.8 (SD=1.4), it was selected only once as the most favorite but five times as the least favorite.

Next, three of the five group behaviors (wave, sunrise and frame) were animated to demonstrate how various lighting effects work and can reinforce the interaction process (Fig. 2.20). After seeing the animations, participants were asked what they thought the robots were trying to communicate (the design intentions were not disclosed).

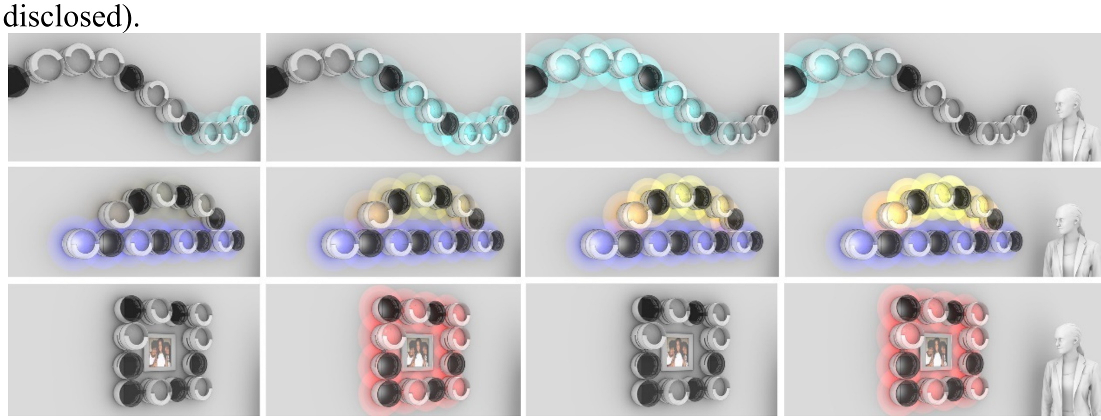

Fig. 2.20 Image capture from animations showing various lighting effects of robot group formations. Top row: light moving in a linear direction to depict wave movement. Center row: lights gradually increase intensity to imitate a sunrise. Bottom row: a blinking light pattern to draw user attention to the framed photo.

For the wave animation, participants' reactions were varied. Five participants felt the behavior made them want to look or move toward the light direction. Three felt "relaxed" or in a "standby" mode. For the sunrise pattern, five participants guessed this group behavior was imitating a sunrise as a way to say "good morning". One thought it was a weather indicator. One said the robots were charging. For the frame pattern, participants' reactions were negative. Six participants felt the red color and blinking pattern indicated danger and was not pleasant. Three mentioned phone calls from family.

Storyboard

In developing the interactive scenarios, a storyboard was created (Fig 2.21) as informed by the design outcomes and user studies thus far. The persona, John, is a college student living alone in a one-bedroom dorm room. He is recovering from illness such as COVID-19 with non-critical symptoms. Different from the flu, John finds it difficult to manage an assortment of items including various medications, each has a

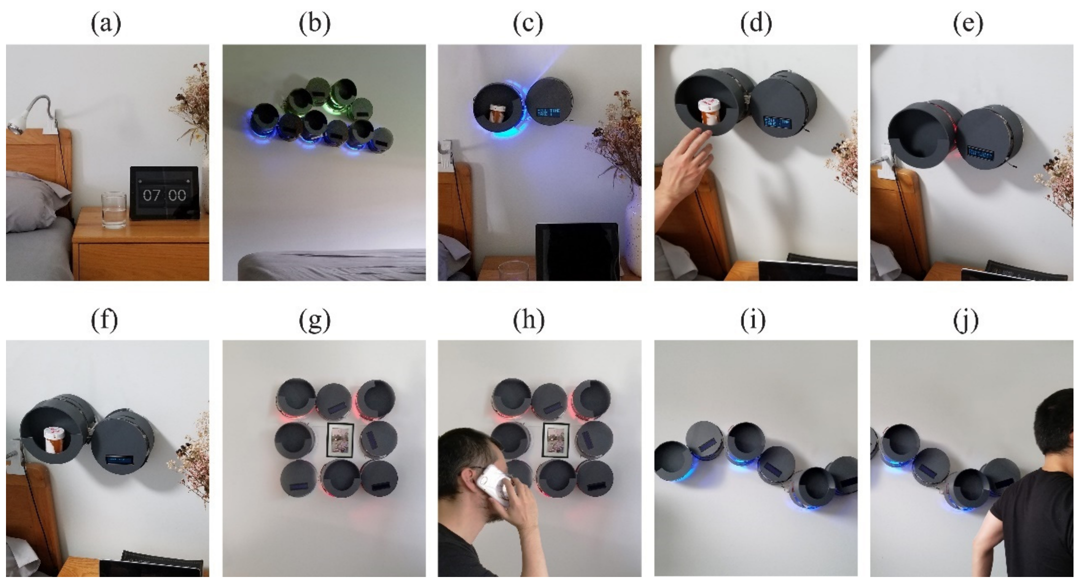

Fig. 2.21 Collaged photos showing the storyboard of how SORT interacts with John and provides assistance through the day. (a) It is 7:00 in the morning. (b) In lieu of conventional alarm, SORT forms and imitates a sunrise coupled with lighting and sound effects to wake up John. (c) One SORT robot that holds the morning medication moves down towards the bed, the screen displays "Pill time, take one." (d) John reaches into the container and takes the medicine. (e) After a while, the robot emits a red color and vibrates, the screen displays "Please return pill bottle." (f) John puts the bottle back into the container, the robot moves back to the upper corner of the wall. (g) Later in the morning, SORT moves to frame around John's family photo. (h) John later notices the robot groups and proceeds to phone home to update family on his conditions. (i) After working for an hour, SORT next to John's desk starts to form a wave pattern with blue lights. (j) John decides to stand up and take a short walk.

different dosage and use time. In addition, John is trying to stay mentally positive by being productive and is relying on SORT to help him through the recovery. This storyboard served as a recollection moment on the research activities accomplished to date and to capture this reflection in a vision, in pictures and written notations, of what SORT might do for a likely user. This process will aid the authors in designing and structuring future in-person user studies.

Discussion and Implications

Collectively, the robot design iterations, the locomotion lab experiment, the inventory and configuration summaries, and the potential user interviews have captured the design and evaluation agenda, suggesting the promise of SORT. With roughly an 80% favorable interview response to the concept, it is encouraging to imagine ways in which SORT may improve the life quality for a broad range of users. Participants helped us, as well, identify household items needing organization in addition to what we had envisioned in the inventory study.

Given the intensive focus on assistive technology and smart robots aimed at supporting independent living, there are some interesting findings and lessons learned from SORT. Based on the second user study, participants' willingness to use SORT was unrelated to the self-reported clutteredness of personal spaces. As mentioned during the interviews, robot designs need to fit into user's existing interior architecture style, or the users need to be provided with the option to change robot exteriors, such as color, to fit into personal environments. Compared to older adults, who worried about lack of wall surfaces for the robots, college students were more concerned with the robustness of the system.

One interesting benefit of conducting the online interviews during the pandemic lock-down was the opportunity to let participants answer questions in the room where the robots are meant to be deployed. This, instead of conducting in lab studies, helped participants better imagine and visualize how the robots may work and provide assistance while answering questions such as robots' preferred locations.

As suggested by one participant, in addition to the basic sorting and delivery functions, SORT can also be programmed to help guiding user behaviors. For example, the robot that stores chocolate can "run away" or discourage users from over-eating sweet food.

During the interviews, one concern the researchers had was whether the SORT robots themselves, which declutter the horizontal surfaces, may introduce a new type of clutter on wall surfaces. Based on the results, participants rated item organizations with and without the assistance of SORT almost equally, implying that perceived organization may be less affected by the quantitative presence of objects than on groupings of similar items and placement logic (e.g., long slender objects should be placed pointing in the same direction). Hence, the introduction of organizer robots on walls may not negatively impact users' perceived clutteredness of the space. This finding will need to be further studied.

Furthermore, participants' reactions toward robot group formations were quite varied. For the group behavior where SORT frames around a family photo with blinking red lights, participants reacted negatively. This implies that for multi-robot systems, the group shapes, coupled with lighting effects, may negatively impact participants' mood and perception. Also meaning may be conveyed successfully via robot group behaviors to some participants. For example, without explaining the design intentions, participants were able to identify the tree shape SORT created in the rendering, others viewing the wave pattern mentioned the desire to move toward where the light is pointing, and half of the participants identified the sunrise formation. Lastly, participants in general preferred design options that allow personalization where the robot group can fit better into their existing environment (e.g., container size, robot color, speed, feedback sound and group shape and size).

There are also some limitations. The current robot suction cups work only on smooth wall surfaces and the carrying capacities of the servos have not been tested. There are potential breaking points at the magnetic connectors and the rotating arm bridge. The robot base may also swing out of plane, requiring manual adjustment for adhesion.

Conclusion and Future Works

This chapter introduced a multi-robot, wall-climbing system called SORT, embedded within the home environment to aid users in organizing personal belongings, an activity associated with improved quality of life. The ideation process was reported here, along with design iterations of the robots, a lab experiment with a working prototype, an inventory study and results from a preliminary user interview on receptivity. Finally, a storyboard was illustrated to summarize the collected vision for SORT based on the activities presented here.

As an on-going project, SORT will be improved in many areas. The robots first need to become un-tethered and fully autonomous. A more systematic investigation will be conducted to understand the carrying capacities and potential failures of suction cups. A similar study is also needed for designing the receptacle containers. Insulation materials must be added to further reduce noise from vacuum pumps. We also intend to embed on-board sensors in SORT units and design an associated control algorithm to allow localization and communication between robots and permit the system to orient itself on the wall, assemble in orderly configurations, and locate users. A centralized docking station also needs to be created for recharging batteries. Based on our initial interview feedback, interaction modes need to be further studied to answer questions such as “How should I call SORT for help” and “Should I use gesture or a remote controller to talk to SORT.” As a follow up, an in-person study is planned once three robots are fabricated to understand SORT’s usability, performance and efficacy.

As demonstrated in this chapter, SORT offers inspiration for designing multi-robot systems fulfilling a wellness agenda while leveraging the ambient home environment. For researchers working in the domain of domestic assistive technology, the user study results presented here may provide insights into how people perceive and understand their personal spaces in terms of clutter and item organization. We understand that artifacts like SORT must be designed to adapt to user groups of wide-ranging capabilities to ensure beneficial human-robot interactions. Incorporating principles from fields such as interior architecture and environmental psychology can lead to advancements in interaction design. We encourage future designers and roboticists to consider unconventional domains where robots can live and interactions can occur, such as wall surfaces. Interaction researchers also have a tremendous opportunity to improve users’ health and quality of life – a goal that should be in the foreground of the design process.

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CHAPTER 3

HOW MANY ROBOTS DO YOU WANT? A CROSS-CULTURAL EXPLORATION ON USER PREFERENCE AND PERCEPTION OF AN ASSISTIVE MULTI-ROBOT SYSTEM

Abstract

There has been increased development of assistive robots for the home, along with empirical studies assessing cultural differences on user perception. However, little attention has been paid to cultural differences with respect to non-humanoid, multi-robot interactions in homes or otherwise. This chapter investigate how cultural differences may impact users' preferences and perceived usefulness of a multi-robot system by creating an interactive online survey and considering variables often absent in HRI studies. The multi-robot design is briefly introduced here again with survey construction, and report on results evaluated across 191 young adult participants from China, India, and the USA. The findings show significant effects of culture on both participants' preferences and perceived usefulness of the system between India and China or the USA, but not between China and the USA. This chapter also finds effects of culture on perceived usefulness to be partially mediated by participant preferences. The results here reinforce the importance of considering cultural differences in designing domestic multi-robotic assistants.

Introduction

As mentioned in the previous chapter, assistive technology for the home has long been a focus for Human Robot Interaction (HRI) researchers, who are developing both humanoid (e.g., [1]) and non-humanoid robots (e.g., a robotic walker [2]). Studies have also investigated reactions of users, such as elderly people with mild cognitive impairment [3], toward robotic assistants. While there have been efforts in developing multi-robot system (MRS) across various scales, such as [4] and [5], there is a lack of studies investigating user perceptions when assisted by a MRS. Such exploration needs to consider novel parameters not commonly included in single robot interaction studies, such as robot group shape and size. In addition, user's cultural background is also an important factor to consider when studying HRI in domestic settings. There have been many investigations on the relationship between cultural differences and user behaviors and preferences (e.g., [6]). However, it is not known how cultural differences may play a role in influencing user preferences and perceptions when interacting with a MRS.

The aim of this chapter is to explore the relationship between cultural differences and user preferences and perceived usefulness of SORT ("Stuff-Organizing Robot Team"), a multi-robot, domestic "organizer" system we are developing. Each robot is composed of two cylindrical units connected by a rotation arm with containers and display disks snapped on via magnets. The robots adhere to smooth wall surfaces by vacuum suction and achieve locomotion by having each unit swing the other one around. The robots can form a larger group to organize, retrieve and deliver items to a user at scheduled times or as wanted. This chapter investigated participants' perceptual differences and preferences of, specifically, SORT's task completion modes, group shapes, speed, group size, usage of storage compartment and perceived usefulness.

Previously, there have been numerous studies exploring the impact of cultural differences on HRI. Almost all of these studies are based on interactions with one or two humanoid robots. One such study explored different cultures' acceptance of and attitudes towards various humanoid robots [8]. Other researchers evaluated domestic assistive robots across cultures for various age groups, such as older adults [9], and for different spaces, such as in a smart home environment [10], to understand agency, attitude, trust, usability, and likeability. Another study has also focused on robot anthropomorphism and likeability among Japanese and American users, where a strong interaction effect was observed between cultural backgrounds and robot types [11]. In a recent review paper [12] in which 50 cross-culture HRI studies were surveyed, only one [13] investigated participants' reactions when interacting with a small group of robots in a public cafeteria, including variables such as robot number and group effects. However, researchers in [13] only used up to three robots; it was also not evident that if participants were given the option to determine robot group size, how many robots they would choose, and how the choice may be affected by cultural differences. In addition, none of the surveyed papers, except [6], considered variables' mediating effects.

As shown in [14], using online surveys with robot images and videos can be an effective way to measure users' initial reactions. In addition to allowing the recruitment of large numbers of participants, online surveys are particularly beneficial to human – multi-robot interaction studies where researchers may not have a fully functional MRS and where the Wizard of Oz method is difficult to implement at a group scale. For these reasons, this chapter reports on the development and results of a novel interactive, online survey instrument (especially apt during the pandemic period) and fills a gap in cultural difference investigations with non-humanoid and multi-robot systems.

Methods

Dependent Measures

The following variables were examined, some of which had not been studied extensively before and are novel to human – multi-robot interactions. Variables (a) through (g) measure user preferences, and variable (h) measures perceived usefulness.

(a) Delivery task mode – sequential: robots deliver items one by one.

(b) Delivery task mode – concurrent: robots deliver all items at the same time.

(c) Group shape – Circle over Group shape – Random: previously, much attention had been given to the design of individual robots. However, robots in group can also form various shapes to convey meaning and users may have preferences on different group formations.

(d) Robot speed.

(e) Robot number – Stationary: users may have different preferences for the number of robots in a group.

(f) Robot number – Moving: in addition, users may have different preferences and tolerances for the number of robots that are moving. Participants who select large robot groups may in fact prefer only one or two robots moving at a time.

(g) Storage compartment: as implied from our previous study [7], for items that cannot fit in a SORT container, an additional system of larger storage compartments on a track was provided.

(h) Perceived usefulness: for dependent variables measuring perceived usefulness, we used a validated subscale from [15] with a Cronbach's Alpha of 0.865.

Survey Construction

An interactive online survey was constructed in English on Qualtrics (question items are summarized in Fig. 3.1) which takes 10-15 minutes to complete. Participants were first asked about their background information including age, self-identified gender, nationality, and if they had lived in their home countries for most of their lives (>90%). The authors then introduced the multi-robot system, "Stuff-Organizing Robot Team" (SORT), designed for organizing household belongings, fetching and delivering items to users as scheduled or needed (the robots' design, envisioned use cases and early evaluations are reported in previous chapters [7]). Three images and one animation video of SORT were shown to the participants. After the introduction, the researchers asked participants to self-rate their understanding of the robot on a 5-point scale (1 for

"I do not understand SORT at all"; 5 for "I understand SORT completely").

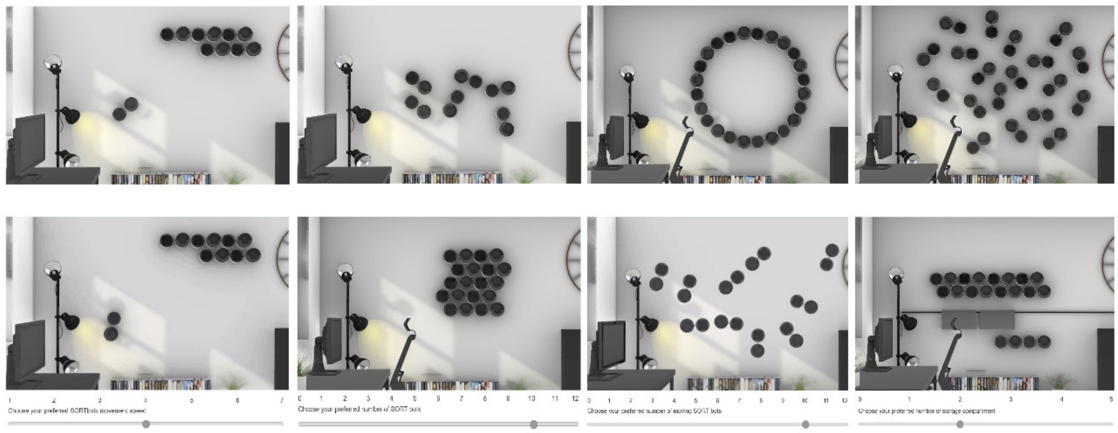

Figure 3.1. Interactive survey items. (a) Delivery task mode – Sequential: animation showing robots deliver items one by one. (b) Delivery task mode – Concurrent: robots deliver items all at once. (c-1) Group shape – circle. (c-2) Group shape – random. (e) Speed: animation with slider showing 7 different speed options. (e) Robot number – Stationary: image with slider showing group size options (0 to 12). (f) Robot number – Moving: animation with slider showing group size options (0 to 12). (g) Storage compartment: image with slider showing 0-5 compartments on a track for larger items.

To measure variables (a) and (b), participants were asked to view two animations. The first animation showed SORT delivering items one by one in a sequential manner; the second showed SORT delivering all items at once. The participants were then asked to rate how much they liked each option on a 7-point scale (1 for "Dislike a great deal"; 7 for "Like a great deal.") To measure variable (c), participants were asked to view two images, one showing robots forming a geometric circle and the other showing random placements, and then select which one they preferred. For variable (d), seven animated GIFs were created showing various robot speeds, participants were asked to use a slider (1 for slowest; 7 for fastest) to select their favorite speed. For variables (e) and (f), participants were asked to use sliders (ranging from 0 to 12) to select their preferred number of stationary robots from thirteen static images and number of moving robots from thirteen animated GIFs. 12 was selected as the maximum based on the previous interview results [7], however, participants were given the option to enter a response if their preferred robot number exceeded 12. Lastly, for variable (g), participants were asked to use a slider (ranging from 0 to 5) to select their preferred number of compartments on a track. To measure perceived usefulness, three questions adapted from [15] were included on a 7-point Likert scale (1 for "Strongly disagree"; 7 for Strongly agree) including: (1) "I think SORT will be useful to me."; (2) "It would be convenient for me to have SORT."; and (3) "It's good to make use of the SORTbots."

The interactive portion of the survey was developed as a JavaScript addon in Qualtrics. For slider questions, each slider position points to a unique JPEG or GIF file rendered to show various robot properties. This novel presentation feature granted increased freedom and better questionnaire delivery, in lieu of the traditional way of asking participants to imagine various robot effects. A demonstration is included here: https://youtu.be/0ppWPkTUXqQ.

Participants

Participants were recruited via the university's human subjects pool management system (SONA), Amazon Mechanical Turk (with filter criteria >98% and >5000 survey completion) and by campus email. Students responded through the university SONA system received 1 research credit for degree course fulfilment; MTurk workers were paid 2 US dollars per survey (approximately $0.15 per minute); while individuals contacted by emails were not compensated, they represent a small percentage (3%) in the participant pool. IRB approval was obtained from the university review board. In total, 242 participants from various cultures who are proficient in English answered the survey, 51 were dropped due to incomplete or illogical responses (e.g., age = 1); countries with fewer than 20 responses [16] and participants who self-rated that they did not understand SORT for the most part or they did not understand SORT at all were also excluded. This resulted in 191 responses (137 from university SONA system, 48 from MTurk, 6 from email contacts) being used for analysis. Among them, 117 were females, 74 were males, and the average age was 23.6 (SD=5.4); 164 (85.9%) had lived in their home countries for over 90% of their lives. No participants had seen the robots prior to the study.

Results

The data were analyzed using the R language and JASP, an R-based graphic interface. The authors used library BayesFactor for Bayesian analysis and library Lavaan for Structural Equation Modeling (SEM). Classical ANCOVA and Bayesian ANCOVA were conducted to examine the effects of culture on dependent measures while controlling for age and gender. The authors used a logistic regression for binary variable (c) on group shape, and a path analysis to investigate mediating effects for variable (h) on perceived usefulness. The results are shown as boxplots in Fig. 3.2 and summarized in Table. 3.1 with post-hoc results in Table. 3.3, variable (c) is shown in Table. 3.2.

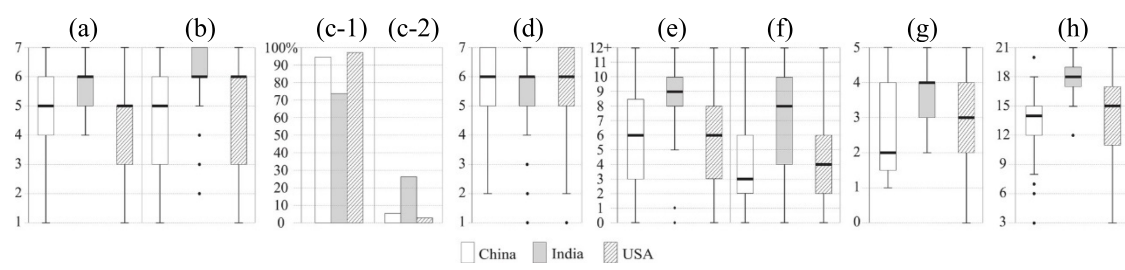

Figure 3.2. Compiled graph results of: (a) Delivery task mode – sequential. (b) Delivery task mode – Concurrent. (c-1) Group shape – Circle. (c-2) Group shape – Random. (d) Robot speed. (e) Robot number – Stationary. (f) Robot number – Moving. (g) Storage compartments. (h) Perceived usefulness.

Table 3.1. Compiled results for user preference and perceived usefulness.

Dependent measures	df	F	p	η²	ω²
(a)	2	9.14	<0.001	0.09	0.08
(b)	2	4.82	0.009	0.05	0.04
(d)	2	2.15	0.120	0.02	0.01
(e)	2	3.94	0.021	0.04	0.03
(f)	2	4.34	0.014	0.04	0.03
(g)	2	2.96	0.054	0.03	0.02
(h)	2	14.17	<0.001	0.13	0.12

Table 3.2. Result for user preference on variable (c) group shape.

Preference by culture (compared to India)	Odds Ratio		z	Wald test - df	Wald test -p
China	0.85		-0.29	1	0.77
USA	0.32		-2.29	1	0.02

Table 3.3. Compiled post hoc mean difference comparisons.

Comparison	(a)	(b)	(e)	(f)	(g)	(h)
China - USA	0.5	-0.1	-0.4	0.4	-0.3	0.3
China - India	-1.1*	-1.4**	0.3	-1.9	-2.3	-4.8***
USA - India	-1.6***	-1.3*	0.7	-2.3*	-2.0	-5.1***

** p(tukey) < 0.05, **p(tukey) <0.01, ***p(tukey) <0.001*

Note: Results shown are mean differences averaged over the levels of Gender: Female.

Note: (a) Delivery task mode – sequential, (b) Delivery task mode – concurrent, (e) Robot speed, (f) Robot number – stationary, (g) Robot number – moving, (h) Perceived usefulness.

User Preferences

(a) Delivery task mode – Sequential. A main effect of culture was found. The difference was significant with medium effect size. Participants showed different preferences: 4.66 (SD = 1.41) for China, 5.73 (SD = 0.67) for India, and 4.29 (SD = 1.61) for the USA. Post-hoc testing using Tukey method revealed significant difference between India and China ($p = 0.01$) or the USA ($p < .001$), but no significant difference between China and the USA ($p = 0.21$).

(b) Delivery task mode – Concurrent. A main effect of culture was found. The difference was significant with small effect size. Participants showed different preferences: 4.40 (SD = 1.90) for China, 5.95 (SD = 1.30) for India, and 4.78 (SD = 2.00) for the USA. Post-hoc testing using Tukey method revealed significant difference between India and China ($p = 0.010$) or the USA ($p = 0.02$), but no significant difference between China and the USA ($p = 0.94$).

(c) Group shape – Circle over Group shape – Random. A main effect of culture was found. 94.3% Chinese participants, 73.2% Indian participants and 98.3% US participants preferred the circle shape over the random formation. A significant difference between India and USA was observed while coding Random shape as 1. As seen from the odds ratio in Table. II, participants from the USA were only 0.32 ($p < 0.02$) times as likely to choose the circle shape over the random shape compared to participants form India.

(d) Robot speed. No main effect was found. The difference was not significant with small effect size. Participants preferred faster speeds on average.

(e) Robot number – Stationary. A main effect of culture was found, participants showed different preferences: 6.23 (SD = 3.47) for China, 8.37 (SD = 2.91) for India, and 5.84 (SD = 3.16) for the USA. Post-hoc testing using Tukey method revealed significant difference between India and the USA ($p = 0.019$), but no significant difference between China and the USA ($p = 0.83$) or India ($p = 0.06$).

(f) Robot number – Moving. A main effect of culture was found. The difference was significant with small effect size. Participants showed different preferences: 4.20 (SD = 3.37) for China, 7.07 (SD = 3.51) for India, and 4.37 (SD = 2.98) for the USA. Post-hoc testing using Tukey method revealed significant difference between India and China ($p = 0.01$) or the USA ($p = 0.04$), but no significant difference between China and the USA ($p = 0.89$).

(g) Storage compartments. A weak main effect of culture was found, the difference was only marginally significant with small effect size. Participants showed different preferences: 2.66 (SD = 1.39) for China, 3.51 (SD = 0.87) for India, and 2.77 (SD = 1.41) for the USA.

(h) Perceived usefulness. A main effect of culture was found. The difference was significant with large effect size. The three Likert scale results were added together with range from 3 to 21. Participants showed different preferences: 13.40 (SD = 3.85) for China, 17.85 (SD = 1.81) for India, and 13.80 (SD = 4.43) for the USA. Post-hoc testing using Tukey method revealed significant difference between India and China ($p < .001$) or the USA ($p < .001$), but no significant difference between China and the USA ($p = 0.941$).

Bayesian ANCOVA

The authors conducted non-parametric Kruskal-Wallis tests since outcomes for variable (a), (b) and (g) did not pass Levene's test for homoscedasticity ($p < 0.05$), and significant differences were found for all three tests ($p < 0.005$). It was also observed that similar results from Bayesian ANCOVA results where the models with culture variable as predictors were favored over the models without culture variable. This serves as confirmation for the classical ANCOVA results reported above.

Mediation Effects

The authors conducted Structural Equation Modeling to explore how the effect of culture on perceived usefulness was mediated by preferences for different delivery task modes (a), (b) and storage compartments (g). The culture variable was coded as 1 for India, and 0 for China and the USA since no significant differences between China and the USA were found in any of the post-hoc tests. The analysis allowed residual covariance between (a) and (b) due to the similarity between the two questions.

Covariance results are shown in Table 3.4.

Table 3.4. Compiled covariance.

	Culture	**(a)**	**(b)**	**(g)**	**(h)**
Culture	0.17	-	-	-	-
(a)	0.23	2.33	-	-	-
(b)	0.21	0.62	3.68	-	-
(g)	0.13	0.36	0.17	1.81	-
(h)	0.70	2.89	3.88	2.11	18.06

Note: (a): Delivery task mode – sequential. (b): Delivery task mode – Concurrent. (g): Storage compartments. (h): Perceived usefulness.

Here the authors proposed and validated a model (Fig. 3.3) where the effect of culture on perceived usefulness – variable (h) was partially mediated by delivery task modes – variables (a) and (b), and storage compartment – variable (g). As shown in Table. V, the model fits the data well. Robot speed – variable (c), group shape – variable (d), and group size – variables (e) and (f) were non-task related preferences that bear weak mediating effects on usefulness and, hence, were excluded. The model indicates that 64.7% of the effect was mediated: 24.7% by (a) delivery task mode – sequential, 24.4% by (b) delivery task mode – concurrent, and 15.6% by (g) storage compartments. Both direct and indirect effects are significant at 0.01 level. The proposed model was also compared with a competing model where the effect of culture was fully mediated, without the direct path from culture to usefulness. The competing model fits the data only marginally well, $\chi 2$ (3, n=191) = 7.307, p = 0.063, and is significantly worse than the proposed model: $\chi diff2 = 5.487$, $df_{diff} = 1$, p = 0.020.

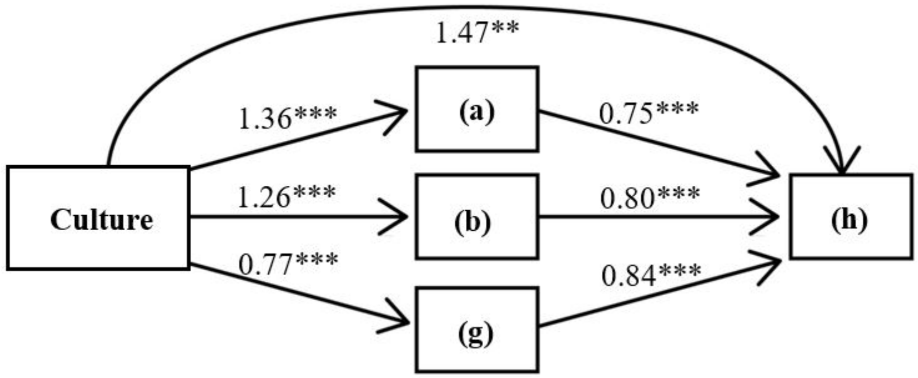

*Figure 3.3. Path diagram of partially mediated model. (a) Delivery task mode – sequential. (b) Delivery task mode – Concurrent. (g) Storage compartments. (h) Perceived usefulness. **: p < 0.01, ***: p < 0.001.*

Table 3.5. Compiled SEM Results.

	χ2	**p**	**GFI**	**AGFI**	**NFI**
Fit measures	1.82	0.402	0.995	0.965	0.989
Ideal threshold *		>0.05	>0.95	>0.95	>0.95
	NNFI	**CFI**	**RMSEA ****	**SRMR**	
Fit measures	1.006	1.000	0.000	0.024	
Ideal threshold *	>0.95	>0.95	Close to 0	<0.05	

** Ideal thresholds indicate range for a good fit model.*

*** 90% Confidence Interval from 0.000 to 0.139 with a p value of 0.556*

Note: Goodness of Fit (GFI) and Adjusted Goodness of Fit (AGFI) indicate the adjusted proportion of variance as accounted for by the estimated population covariance. Normed-Fit Index (NFI) and Non Normed-Fit Index (NNFI) indicate the improvement of fit by the model of interest relative to the null model. Comparative Fit Index (CFI) is a revised form of NFI that is not very sensitive to sample size. Root Mean Square Error of Approximation (RMSEA) is a parsimony-adjusted index. Standardized Root Mean Square Residual (SRMR) is the standardized square-root of the difference between the residuals of the sample covariance matrix and the proposed model.

Discussion

Implication

Participants from India, compared to China and the USA, showed higher favorability toward both delivery task modes, a comparatively higher preference for random group shape over the circle shape, about equally high preference on robot speed, and higher preference on larger group size, storage compartment numbers and higher perceived usefulness of the SORT system. With these findings in mind, it should be acknowledged that it is impossible to create a unique robot for each culture. Instead, the results provided here contribute to the robot design process whereby focusing on adapting soft parameters, such as robot group behaviors, to specific user groups, we may be able to create more culturally appropriate and considerate interactions for all stakeholders.

The differences in delivery task modes and robot numbers may be attributed to the person's polychronic (multi-tasking) or monochronic (one thing at a time) orientation. Monochronic countries such as the USA [17], were expected to prefer lower robot numbers and rate robot single-tasking more favorably. However, as the results contradict this stereotype, it is becoming increasingly difficult, if not impossible, to classify an entire society as polychronic or monochronic. As noted in [17], being aware of cultural differences is an important first step in fostering mutual understanding and productive cross-cultural interaction. Similarly, for robot speed where participants from all three cultures preferred faster options on average, the result contradicts stereotypes about India as a polychronic oriented culture that perceives time as non-linear [18] where a preference for slower robot speed was expected. These results imply that prior theories or assumptions may not be readily applicable in creating hypotheses for human multi-robot interactions across cultures. As previous studies, such as [19], had demonstrated, in the transfer of culture-based knowledge from Human-Human Interaction to HRI, sensitivity to cultural differences is necessary for future studies to avoid biases and stereotypes in designing interactive multi-robot systems.

This study also uncovered results that are unexpected and require further examination. For example, 26.8% of participants from India preferred the random group shape over the geometric circle, whereas the percentage for China (5.7%) and the USA (1.7%) were significantly smaller. Also, on average, participants from India want more robots and have higher tolerance for robots moving simultaneously. While the survey question used was depicting a specific scenario and room environment, the participants may be thinking about their own environment and ways of completing the same tasks, which could be very different based on cultural customs.

Previous literature had classified societies as Low context (Western) and High context (Asian) [20], where such concept was used in many cross-culture HRI studies such as [6]. However, this study found no difference between participants from China and the USA, and a significant difference for participants from India compared with the other two countries, which suggests that previous comparisons of “East vs. West” maybe an over-simplified model. “Asia” or the “East” carries broad social, political, demographic, historical and religious differences such that it is difficult to provide an all-encompassing definition for what constitutes an Asian culture.

In addition, previous cross-culture HRI studies primarily included participants from developed regions where people may have become more familiar and comfortable with the concept of being assisted by robots. As shown in the review paper that surveyed 50 cross-culture HRI studies [12], very few included participants from developing regions: one study included Kazakhstani and another considered Pakistani, while two included participants from India, which is a populous and quickly developing region with great potential for the growth of domestic assistive technologies. Understanding cultural differences and user needs for these countries, where the deployment of domestic robots must follow local customs, would be an important step forward for human multi-robot interaction designs.

Lastly, variables (a), (b), and (g) were found to be mediating the effects of culture on perceived usefulness. This model demonstrates that including mediators in statistical analysis for cross-culture HRI studies can be beneficial in uncovering relationships and exploring underlying mechanism by which one variable influences another variable.

Limitations

There are a few limitations. First, participants recruited may not fully represent their respective cultures. Even though 85.9% of the participants self-rated that they had lived in their home countries for most of their lives (>90%), it was unknown how much influence they have received from foreign cultures, especially as young adults who can easily access information via the internet. It was also unknown how well the remaining 14.1% participants have integrated into a foreign society (e.g., Chinese international students who have studied in the US for years). In addition, all three countries included in this study have rich and diverse internal cultures across large population sizes, and participants may come from distinct families and religious backgrounds. The participants recruited were not very balanced: among the 115 US participants (85 females, 30 males), most responded through the university participant management system (SONA), representing college students with a mean age of 20.7 (SD=3.1). Among the 35 Chinese participants (26 females, 9 males), some were contacted through emails (6) while others responded through SONA, with a mean age of 26.1 (SD=4.9). Among the 41 Indian participants (6 females, 35 males), the majority responded through MTurk with a mean age of 29.7 (SD=4.9). This difference in recruitment platform may have partially contributed to the significant results observed in the Indian participant sample, which needs to be explored further. In addition, the scenario constructed for the online survey was based on a living and working space within the home, the results may not generalize to other domestic spaces, and participants may be thinking about their own personal space and use cases while answering the surveys. Similarly, only young adults were included for this study, so the results may not generalize to other age groups. For older adults who might have different exposure and acceptability toward technology and who might better represent the more traditional aspects of their cultures (versus more global tendencies), it is expected the results and lessons might be very different.

Future Works

The variables included in this study only represent a small portion of all possible parameters relevant in a human multi-robot interaction study. Future study will propose and incorporate additional dependent measures in experiments such as robot feedback and animistic group behaviors. The study could be expanded to include other age groups, cultures, and spatial contexts. For our own team and others in the research community, additional psychology theories may also need to be studied systematically and introduced to human multi-robot interaction to formulate new hypotheses. The author also intends to fabricate a larger group of SORT robots to be used in an in-person lab study. To account for selection bias and influences from foreign cultures on some participants, additional filters will be applied to further control the recruitment process, such as including participants who have never travelled outside of their home countries.

Conclusion

This chapter presented a study exploring the impact of cultural differences on participants' preferences and perceived usefulness of a multi-robot assistive organizer system. With so few studies investigating the role of culture in human multi-robot interaction at home, the results reported here can provide insights for other researchers working in the domain of non-humanoid domestic robots. The author also investigated mediation effects by using SEM, which has been an under-utilized tool for HRI studies.

Introducing an assistive MRS into the home environment would require understanding of users' cultural backgrounds and preferences, which could have direct impacts on perceived usefulness of the system. More broadly for HRI design, culture is a necessary factor to consider in developing assistive robots as they become ubiquitous in the everyday lives of people around the world, especially in populous but under-studied regions.

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CHAPTER 4

IMPROVING LIFE QUALITY AND UNDERSTANDING DOMESTIC ORGANIZATIONAL BEHAVIORS WITH A MULTI-ROBOT, MAGNETIC WALL-CLIMBING ORGANIZER SYSTEM

Abstract

This chapter proposes a new SORT prototype based on a simple car with wheels embedded with magnets to allow it to be driven on ferrous wall surfaces for conducting a final in-person user study. First, a few design iterations were carried out to create the new prototype. As informed from a preliminary pilot study, the SORT concept was revised to include a new sub-category of stationary dispensers, working as long-term storage compartments. A final set of SORT system was fabricated with 6 stationary dispensers and 4 mobile robots for the study with 30 participants. The results confirmed positive reaction toward SORT's usability (68/100) and satisfaction (80%). Qualitative results summarized here can provide insights for future designers and researchers working on multi-robot groups of domestic assistive technologies to understand user's organizational behaviors, decision making and logic hierarchies, preferences on robot number and speed, and perception of wall-climbing robot gestures. Preliminary quantitative analysis confirmed previous hypothesis that perceived organizer robot usability is unrelated to self-reported domestic conditions, suggesting SORT is useful despite differences in users' own home conditions. As new robotic assistants are being developed for domestic environments across different cultures and markets, designers and researchers must take a multi-disciplinary approach to understand users' needs and preferences to ensure the successful deployment of such technology. The works presented in this chapter can serve as a step forward in the conversation around topics in wall-climbing, domestic assistive technologies, and human-multi robot interaction studies to help improving people's life qualities.

Introduction

In previous chapters, the author had explored a vacuum based suction cup prototype for SORT, composed of two cylindrical units connected with a fulcrum arm. The robot achieved manually assisted locomotion by having each cylinder swing the other one around [1]. Two online user studies were conducted with the suction cup prototype by using a mixture of renderings, photos, videos, Zoom interviews and demonstrations. The first study explored participants' general reactions and perceptions toward the robot concept [1] while the second study focused on understanding how cultural differences may impact users' preferences of SORT [2]. As noted in the limitations of these previous studies, the vacuum suction prototypes were not robust enough, suffering from falling and bending out of plane, which render them insufficient for in-person lab studies. Therefore, a new magnet-based, remote-controlled prototype was fabricated for this chapter, where the design cycle also followed an iterative process with decisions informed from user feedback.

Wall-climbing robots

As summarized in the literature review in previous chapters, SORT fills a gap in domestic assistive technologies that are easy to use and do not compete with users for floor space. In addition, the user studies here also provide insights on how people may perceive the usability and assistance of a multi-robot group. To ensure uninterrupted in-person studies, fabricating robust prototypes becomes a priority in this chapter. To help better understand current practices in wall-climbing robots, five categories of adhesion technologies are summarized here: vacuum negative pressure, bio-inspired, propeller thrust, adhesive, and magnetic.

Vacuum based wall-climbing robots are typically circular with one large impeller and low pressure skirt to seal the edges [3], or multiple smaller suction cups

[4] relying on continuous supply of negative pressure, where locomotion can be achieved with additional track wheels. Suction can also be achieved through vibrating discs. These robots show promises in applications such as building or ship repair, inspection, search and rescue. They work on a variety of surfaces and materials that can carry a reasonable amount of payload (4x body weight). However, there are also many issues with vacuum suction. The major concern is the noise generated from the pump which needs to be continuously operational, any failure would result in surface detachment and robot falling to the ground. To supply the negative pressure, these robots also tend to be tethered, limiting their range of operations. These limitations make this technology not ideal for home use, unless the noise concerns are successfully addressed as documented through user studies in this dissertation.

There have been many new bio-inspired technologies being proposed in wall-climbing robots, such as one based on micro-spine hooks on wheels that can work on very rough out-door surfaces [5], or another inspired by gecko skins [6]. These robots are small, lightweight, quiet, and has low power consumption. However, it is unknown how much weight these robots can carry since their primary applications tend to be in reconnaissance and security. In addition, gecko skin fabrication requires sophisticated equipment and needs initial surface contact alignments, which render them unsuitable for commercialized home-use.

For propeller-based robots, such as [7, 8], they rely on continuously operational thrusters to transition between horizontal and vertical surfaces. Since the intended out-door applications never require the robots to be in a stationary state, hence surface textures and types of wall materials do not play a role in the design and the robots are not concerned with being truly adhered to the surfaces. As a result, these robots are light weight, fast, agile and can travel over very rough surfaces with uncertain conditions such as large gaps and curves. However, noise is again a major concern due to the propeller thruster. Carrying capacity is also unknown. Another major limitation is on air movements, which could be undesirable for in-door home uses.

For robots utilizing adhesives, such as electro adhesive (electrostatic charges) [9], or elastomer adhesive [10], they are very reliable initially in carrying payload, providing high clamping pressure, requiring very low power, and work on most surfaces quietly. While previous efforts focused on developing and analyzing the hardware components and robot behaviors, the applications of these robots are not explicitly clear. Based on their light weights, they may be suitable for indoor use. However, there are some limitations, such as low current but high voltage requirement, unknown carrying capacity, and unknown clamping relation to adhesive size. Probably the most concerning is actually the aesthetics of these types of robots as they appear to be more industrial-looking, or resembling crawling creatures which may not be desirable for home usage.

Lastly, there are also prior efforts in magnetic wall-climbing robots, such as heavy-duty magnetic wheel-based robots for industrial welding applications [11], and magnetic anchor climber robots in a swarm for large ship inspection and repair [12]. These robots are sturdy, work on curved surfaces, can provide a safe resting state, stick firmly and can support extremely high payload. However, since magnetic robots only work on ferrous surfaces, it is inconvenient for end users to install large sheets of metal at home. The author had tested various commercial grade magnetic paints on dry-walls, however, they could not support significant adhesion for robotic purposes. Nevertheless, magnets are selected for the new prototype in this chapter due to their unique properties and benefits. First, small magnets are cheap to acquire and easy to implement, requiring no sophisticated equipment or fabrication process. Second, they are reliable, once the robots stick to the ferrous surface, they are unlikely to detach in resting state, and the physical properties would eliminate any additional electronic components necessary to maintain such state for the robot on the wall. For user study purposes, a custom metal wall can be constructed for Wizard of Oz operations. Since the goal is to understand naïve users' reactions toward SORT and the associated organizational behaviors, it is not a major concern for this chapter if the participants find out that current prototypes only work on metal surfaces.

Robot Design and Fabrication

Hardware and Design

The form factor of the new magnet prototype followed the previous vacuum prototype's initial base dimension, as determined by prior item inventory studies [1]. Each robot unit was composed of a single circular mobile base with a container in front. The hardware components included an Arduino UNO board, two high torque continuous servo motors, a Bluetooth module, LED lights, a LCD screen, custom 3-D printed wheels with 5mm diameter sockets embedded with magnets, and batteries. The unit was finished with hand-cut corrugated plastic sheets as outer shells (Fig 4.1). This first prototype was tested on a single sheet of 24"x24" 22 gauge metal with external power source (Fig 4.2, https://www.youtube.com/watch?v=H16-B2QHCY0).

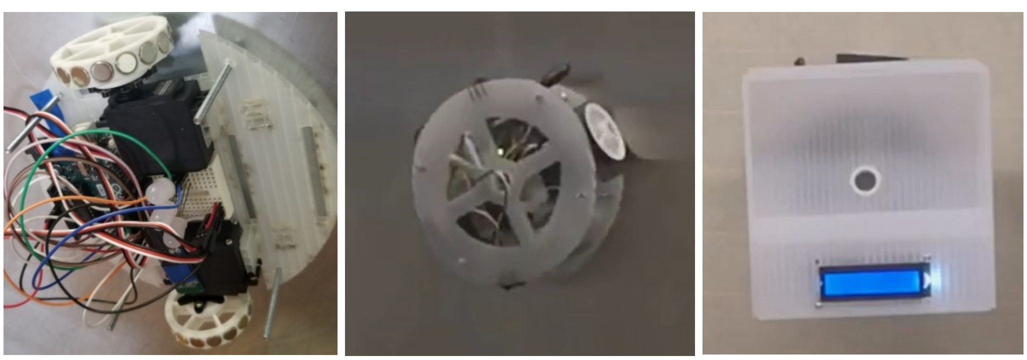

Figure 4.1, ***left****: custom 3D printed wheels with sockets embedded with 5mm diameter magnets,* ***middle****: a robot base,* ***right****: a completed robot prototype with a container and LCD screen attached to the robot base.*

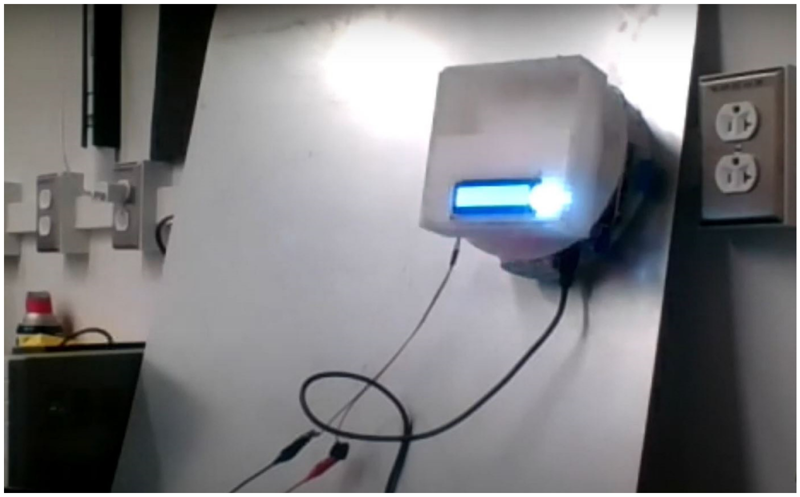

Figure 4.2, A SORT magnet prototype being tested on a sheet metal.

However, there were a few limitations with the first prototype which prompted follow up modifications. Most noticeably, the prototype was only able to move left, right or down on the sheet metal, significant slippage on the magnetic wheels prevented the robot to move up. To improve, the wheels were wrapped in a thin layer of leather felt material, the sheet metal was also covered with masking tapes to help increase friction. As a result, the robot was able to move up the metal surface but still with frequent slippage, partially due to the weight of the container and LCD screen. To test and understand the movement of only the robot base itself, the container was removed, the robot was then brought around various buildings and driven on different ferrous surfaces (Fig 4.3).

*Figure 4.3, A SORT robot base being tested on: **left**: outside of an elevator, **middle**: underneath a steel stairway, **right**: along a steel beam in the basement.*

Upon a closer examination of the base, a possible cause for the slippage was identified. Since the magnets were embedded in the outer rim of the wheel in a circular fashion, there was a 1-2mm gap between each magnet. This meant when the wheel turns, the robot may become temporarily detached from the metal surface for a fraction of a second. To correct this, a new wheel was designed with two layers of magnet, where each layer was offset to allow the magnets to line up with the gaps of the other layer, so the robot will always have a magnet attached to the ferrous surface (Fig 4.4). The new unit with the added container was then tested on a larger vertical surface built with 4 pieces of 24”x24” sheet metal covered with masking tapes. The prototype moved smoothly without much interruption (Fig 4.5).

Remote Control

To streamline and expedite the robot testing process, and also later for conducting user studies with a Wizard of Oz method, a cellphone app was built to remote control the robots via Bluetooth. The app was created with the free online tool MIT App Inventor [13]. The functions included connecting to the Bluetooth module, direction arrows to steer the robot forward (up), backward (down), left (turn), and right (turn), four light buttons to control LED colors R, G, B and off, and a slider to change robot speed (Fig 4.6). A text input box was also included for a previous version that the researcher can send text messages to the LCD screen onboard the robot container.

Figure 4.4, ***left****: updated 3D printed wheel embedded with magnets,* ***right****: wheel wrapped with leather felt materials.*

Figure 4.5, lab setup for five SORT magnet prototypes lined up on the new testing surface, composed of 4 sheets of 22-gauge metal covered with masking tapes.

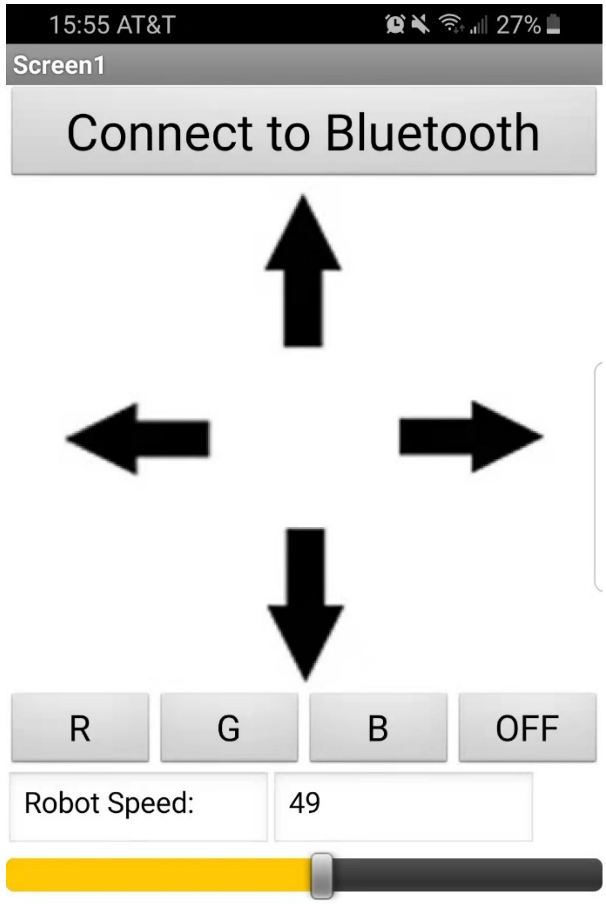

Figure 4.6, Screen capture of the app used to remote control the robots.

Interaction Gestures and Scenarios

To better imagine how SORT may provide assistance indoors, a series of use case scenarios were constructed, including: SORT delivering a facial mask at the exit door to a wheel chair user on the way out, SORT moving down the wall to ask users organize and de-clutter the desk, and SORT delivering a medication bottle to the user. (https://www.youtube.com/watch?v=NNZlB02Gbm0)

In addition to the functional tasks of sorting, retrieving and delivering items, one of the most important aspects of the SORT system is the robots' ability to communicate with users via various gestures and movements. As shown in previous studies, researchers were able to successfully establish human-robot communication through non-verbal means [14]. Since the LCD screen included in the initial prototype was too small and the texts were difficult to read from a reasonable distance, the screen was hence excluded from future prototypes. The interactions then relied purely on the various gestures the robots could make through movements, including a quick jitter, moving up and down, and waving left to right in a semi-circular motion. These gestures were later demonstrated in the final in-person study to understand different people's interpretations.

Pilot Study

A preliminary pilot study was conducted in lab (Fig 4.5) with 9 participants (3 males, 5 females, 1 non-binary) recruited from the college campus via email, IRB approval was obtained through the University. There were three main goals for this study, 1) to understand users' first reactions toward the concept and robots, 2) to gather initial qualitative data and feedback for prototype improvements, and 3) to establish a baseline for the usability score. Each participant was invited into the lab and was briefed on the environment setup, followed by interaction with the robot systems to complete a cleaning task of placing items from the desk into the robot containers upon prompts, and also retrieving a pill bottle brought by the robot. The above-mentioned robot gestures were also demonstrated for feedback.

For the jittery movement, four participants said it looked like something was wrong, the robot was stuck or item was too heavy, three said it was showing an idle state like the robot was waiting for an item or it was trying to give an order, while two mentioned prompts such as "look at me!". For the up-down movement, three participants thought there was again something wrong, such as being stuck or in need of assistance, while five mentioned the robot was trying to prompt the user to place item in the container or asking for direction, one participant was not sure. For the waving gesture, three said the robot was calibrating like power on / off or greeting, two mentioned prompts or questions such as “what direction should I go?”, and two were not sure.

Overall, the initial pilot study showed general positive attitude toward the entire SORT system. The compiled System Usability Scale score was 72 out of 100 (62nd percentile), while interpreting this number is quite limited and insignificant due to the extremely small sample size, it nevertheless sets up a reference of comparison for the follow up in-person study. Among the responses, participant 1 was very enthusiastic about the concept, mentioning that the system was “pretty intuitive to use” and “I would definitely use it”, participant 4 commented “I found it interesting how robots can be incorporated in daily life activities”, and participant 5 said “it could potentially save time in organizing clutter at school and office”. Three common issues were raised, feedback, speed and noise. Participant 1 and 5 commented that some color lights would help showing the robots’ status because “It was a bit hard for me to determine what signal the robot was trying to give me”. Participant 3 and 4 felt the robots may not be as useful because “I just don't think the robots are faster than me organizing on my own”. To better understand how people may prefer different robot speeds when carrying out certain tasks, speed preferences will be included for demonstration in the final user study. Furthermore, participant 7 was particularly concerned with the noise from the motors, which were correlated with how fast the robots were moving. As the participants were naïve users who had never seen the SORT robots before, only one (participant 1) asked how the robots would adhere to wall surfaces. Upon knowing that the current study utilized a custom-built wall with sheet metals, participant commented that “I don't have a magnetic wall but if it is not difficult to set up, I would absolutely get this for my room”.

In addition, there were also some interesting observations. The majority of the participants (7 out of 9) intuitively interacted with the robots with voice commands, such as “robot #1, please bring my pill bottle”, and often times these were accompanied by hand gestures. It also appeared that participants tend to put items not frequently needed into the robots, as some participants mentioned their preferences for keeping items closer to hand, which could also be due to a lack of trust with an unfamiliar device. When organizing items, there were a few grouping logics that participants used such as sorting by frequencies of use, item function, and similar categories. These concepts will be included in the final study to understand if there is a pattern of logic or a hierarchy of organizational preferences. Lastly, probably the most important lesson from the study was the concern that the main purpose of SORT is to help clean and de-clutter horizontal surfaces, but having too many SORT robots moving around on the wall would introduce another layer of clutter on vertical surfaces.

Stationary Dispensers

To respond to the pilot study concern, another tier of stationary dispenser units was introduced, complementing the mobile SORT robots. These “vending machine” like compartments would be located near the top of the wall, or potentially hidden away in the ceiling in the future. Each compartment had a clear acrylic front panel, an inner platform which would also serve as a door that can open to release the object, and a dropped panel to ensure objects released would follow a straight path down. During a sorting task, the mobile robots with frequently used items can move out of sight but still within a quick delivery distance, and those with infrequently used items can move up the wall and rotate until the item slides from the robot container into the dispenser. During retrieval, the mobile robot can “dock” with the dispenser by having its semi-circular container opening line up with the dispenser’s dropped panel, which will then activate the platform door to allow the item to drop back into the mobile robot. (for demonstration and user study purposes, all of these robot movements were remote controlled via a cellphone). By introducing these dispenser compartments, the mobile robots' numbers could be reduced to prevent wall-based cluttering (Fig 4.7).

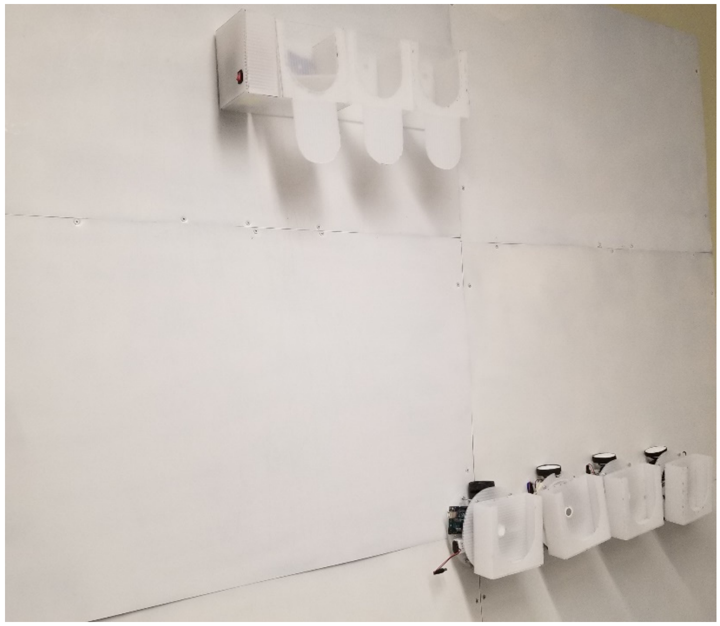

Figure 4.7, Updated SORT system, with 3 stationary dispenser units at the top, and 4 mobile robots below.

Final Prototype

To prepare for the user study, a final SORT system was fabricated to create more polished prototypes that would allow participants to better envision using them as real products at home. To help with better grip and speed, the robot wheels were widened and enlarged to accommodate 8mm diameter magnets. Basic hardware components remained the same, covered by a 3D printed and grey acrylic shell. The container was also redesigned with a corrugated plastic back sheet for light diffusion, and similar grey acrylic shell on the side (Fig 4.8). The stationary dispensers were also redesigned with the same aesthetic elements. A series of circular holes were cut aligning with the mobile robot when docked at the dispenser, this would allow visual feedback when items were being released and falling into the container (Fig 4.9).

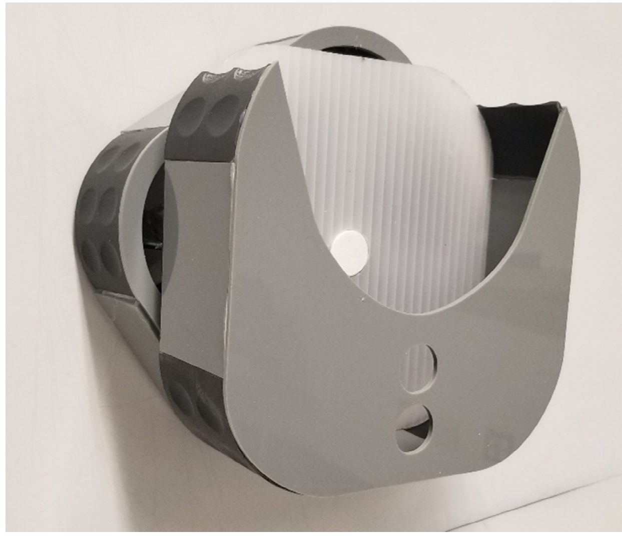

Figure 4.8, Photo of an updated SORT mobile robot.

Figure 4.9, Photo of the final SORT system, with a mobile robot docked at one dispenser unit.

User Studies

Participants

The study recruited participants via the university's human subjects pool management system (SONA). Students responded through the SONA system received 1.5 extra credits for degree course fulfilment. IRB approval was obtained from the university review board. In total, 30 participants were recruited with 20 females, 10 males. No participants had seen the robots prior to the study.

Room Setup

A lab room on campus was selected for conducting the user study. The room was a converted single office with floor carpet, a desk, and a few chairs. The setup included a custom-built wall with 6 sheets of 22 gauge metal measuring 8'x6' in total, supported by a 2x4 lumber frame behind. This metal surface leaned against the side wall at a roughly 5-degree angle. In total, 6 stationary dispensers (with a control unit) and 4 mobile robots were used on this wall. 3 yellow bins on a back shelf and one desktop organizer were provided (Fig 4.10). On the desk, items from the previous inventory study were selected, including keys, a wallet, glasses, paper clips, tape, a pencil sharpener, sticker note pads, a mouse, pens, cellphones, a pill bottle, a hand lotion, a remote control, lip balm, a stapler and a charger, plus a laptop for answering the survey. In addition, all the objects' locations were marked where after each task, every item can be returned to the same place to maintain consistency (Fig 4.11).

Figure 4.10, Photo of the lab setup for conducting in-person studies.

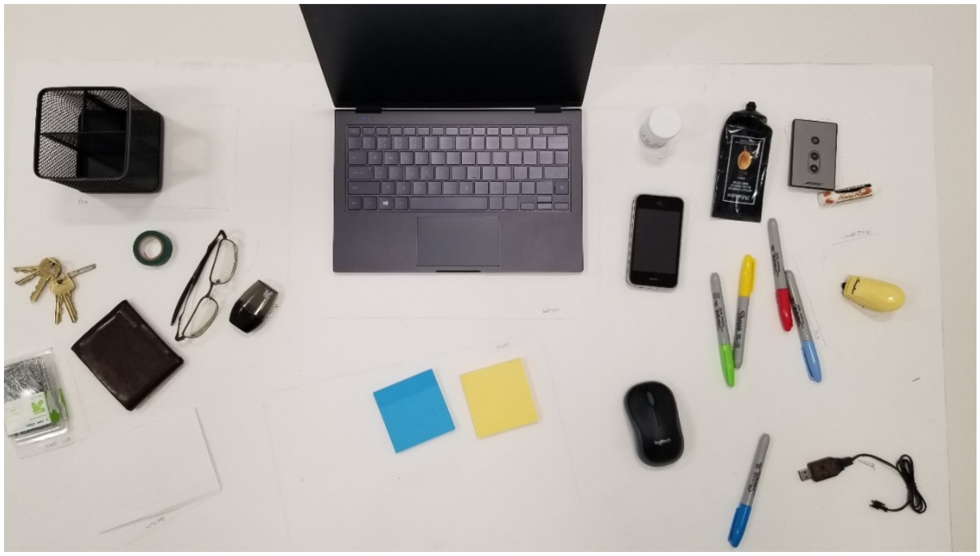

Figure 4.11, Photo of the desk with items selected from previous inventory study, to be organized by participants as part of the study tasks.

Procedure

During the study, the participant was greeted and introduced to the environment followed by a brief introduction to the project and terminologies used. The researcher then proceeded to ask the participant to sit in a chair in front of the messy desk and fill out a consent form. There were mainly 5 sections for the study, which lasted for 40 minutes in total. First, participants answered 5 questions regarding their backgrounds, including gender, types of current residence, usage of existing robotic technologies such as Alexa, self-rating of personal room's cleanliness and self-rating of cleaning frequencies of personal rooms. (Please refer to Appendix B for the study script, and Appendix C for the survey items).

Secondly, the study involved one task repeated twice, which was to clean up and organize the items on the desk based on participants' own habits and preferences, once with the conventional bins, and again by using the SORT robots. The order of which organizer tools were assigned was randomized.

For conventional bins, participants were simply asked to take the items from the desk and place them into the organizers either on the desk or on the shelf. Objects were also allowed to remain on the desk. After the sorting task was done, participant was instructed to look for and retrieve a pill bottle that was just put away and bring it back to the desk. Then a survey on perception of control was distributed, including items asking how much influence the participants felt they had over, for example, the variety of organizational tasks they performed, or the availability of tools and the amount of organizing. The survey was adapted from the perception of control subscale of the NIOSH Generic Job Stress Questionnaire, where 8 questions were included [15]. After one organizational task was completed, the researcher placed all items back to their original locations based on markings on the desk.

Next, for organizing with the robots, a brief introduction and explanation of SORT was made. The participants were asked to put the items into the robot containers. Again, objects were allowed to remain on the desk. Once items were placed in the robot, participants were asked to use their preferred methods of communicating to let the system know that they have finished. When the participant was not sure what to do, the researchers explained using, for example, voice command such as telling the robot to go, or using hand gestures to wave at the system. Then the researcher remote-controlled one of the mobile robots, following the participant's command, to move up the wall above the dispenser unit to be rotated until the container was tilted enough for the item to slide out and into the dispenser below. The participant was asked to imagine having the SORT system at home such that after becoming familiar with using the robots, all the mobile units will move in the same way as demonstrated. Then the researcher proceeded to introduce the retrieval scenario and asked the participant to give a command for the robot to bring the item in the dispenser back down. Following the participant's instruction, the mobile robot first showed a green light to indicate receipt of the message, as remote-controlled again by the researcher. Then the robot moved to dock with the dispenser unit, aligning its container cut out with the semi-circular dropped panel below the dispenser. The platform door rotated open downward to allow the object to fall into the mobile robot's container, which then moved down the wall to the desk level for retrieval. Afterwards, the participant was asked to fill out the perception of control survey again, except this time in respect to the experience interacting with the robots.

The fourth section of the study involved a final survey on the SORT system's usability, as adapted from the Usability System Scale (SUS) [16], including items asking how frequent participants would like to use the SORT robots, if the system appeared complicated or if a technical person was needed for them to feel confident in using the robots. The items were based on a scale of 1-Storngly disagree to 5-Strongly agree. The participants were asked to answer the questionnaire based on their complete understanding of and experience with the SORT system, while comparing against conventional shelves and bins.

The final section of the study focused on open ended questions. To continue exploring users' preferences inspired from previous studies, three robot gestures were demonstrated via remote control. As mentioned above, the first gesture was a quick jitter, the second was moving up and down, and the third was waving left to right. After each gesture, the participant was asked to express what they felt the robot was trying to say. Next, the researcher drove the robot across the wall at 5 different speeds, from 50-fastest (roughly 13cm/s) to 10-slowest. The range was built as a slider on the app shown earlier, where the numbers correspond to the input values mapped onto the continuous servos. Three different use scenarios were explained, and the participant was asked to select a favorite speed mode for each case after the demonstration. The first scenario was an urgent delivery, where the participant was instructed to imagine a case where they would need an item in the robot dispenser immediately. The second scenario was a non-urgent task, where the participant was asked to think about a situation where the robots would carry out sorting tasks in the background. The third scenario was a leisure interaction, where the robots might be performing non-functional tasks, such as serving as a reminder to the user, or simply changing the mood of the atmosphere as a “pet on the wall”. Next the participant was asked if the logic used for organizing and grouping items changed between using the bins versus the robots. A follow up question was then asked about the participant’s hierarchy of organizational logic. When not sure what to say about the order of importance, the researcher gave suggestions such as ranking among choices such as logics in frequencies of use, object category, item functions, or shape and color. Similarly, another question was asked about the hierarchy of drives behind how participant would make a decision to organize. When not sure what to say, the researcher gave suggestions such as addressing mental needs to reduce stress, or physical needs to be able to find things quickly. Next, participant was asked to give feedback on their preferences on the SORT group size, if they felt the current setup of 6 stationary dispensers and 4 mobile robots would satisfy their organizational demands. Participant was then asked to provide additional items that they or their families would like to use the SORT system to manage, followed by final comments.

Results

Background

Among the 30 participants, 3 (10%) reported to live in on campus single dorm rooms, 7 (23.3%) lived in on campus shared dorm rooms, 9 (30%) lived in off campus single rooms, 10 (33.3%) were in off campus shared room, houses or apartments while 1 (3.3%) picked “other”. Only 7 (23.3%) participants reported to use robotic assistants at home now, such as Roomba. When asked to self-rate personal room’s cleanliness on a normal day from 1-Very messy to 5-Very organized, 0 selected very messy, 7 (23.3%)

selected messy, 7 (23.3%) were neutral, 15 (50%) picked organized and 1 (3.3%) chose very organized, the average was 3.3 with SD of 0.88. When asked to self-rate frequencies of room cleaning from 1-Once a few month or less to 5-Everyday or multiple times a day, 0 picked once a few month, 1 (3.3%) chose once a month, 11 (36.7%) selected once a week, 11 (36.7%) answered a few times a week and 7 (23.3%) picked everyday or multiple times a day, the average was 3.8 with SD of 0.85.

Usability

For SUS question 1 (positive) “I think that I would like to use the SORT system frequently”, the average score was 3.73 with SD of 1.01. For question 2 (negative) “I found SORT's intended purpose to be unnecessarily complicated”, the average was 2.67 with SD of 1.06. For question 3 (positive) “I thought SORT was easy to use”, the average was 3.8 with SD of 0.92. For question 4 (negative) “I think I would need the support of a technical person to be able to use the SORT system”, the average was 2 with SD of 1.08. For question 5 (positive) “I found SORT's organizing and retrieving functions were well integrated into the system”, the average was 3.9 with SD of 0.66. For question 6 (negative) “I did not think the SORT system could function in a consistent way”, the average was 2.53 with SD of 0.86. For question 7 (positive) “I would imagine that most people would learn to use the SORT system very quickly”, the average was 4.17 with SD of 0.75. For question 8 (negative) “I found using the SORT system to be overly complicated”, the average was 2.37 with SD of 1.03. For question 9 (positive) “I felt confident using the SORT system”, the average was 3.77 with SD of 0.82. For question 10 (negative) “I needed to learn a lot of things before I could get going with the SORT system”, the average was 2.27 with SD of 1.14.

A standard procedure was followed to calculate the final SUS score: subtracting 1 from the odd number results, subtracting the even number results from 5, sum all the new resulting score averages and multiply it by 2.5. This yielded a SUS final score of 68.83 (Appendix D).

Gesture Perceptions

For the first robot gesture (jitter), the responses could be categorized into 6 types: “stuck” (3 participants, 10%), “heavy” (4 participants, 13.3%), “wait” (3 participants, 10%), “order” (5 participants, 16.7%), “attention” (8 participants, 26.7%), and “status” (6 participants, 20%). One participant was unsure. For the “stuck” type, participants generally felt the robot was in trouble, that it could not move, or something was wrong. For “heavy”, participants thought the robot could not carry the weight of the item and was having trouble moving. For “wait”, participants believed the robot was preparing itself to be ready to receive items. For “order”, the participants said the robot was trying to give some instructions, such as “The robot was asking you to put something in there” (P12). For “attention”, participants mentioned robot was saying “Hi!”, or “Hello” (P8, P11, P14, P16). For “status”, participants thought the robot was trying to show some idling feedback states, such as “The battery is low” (P9), “Remind me to stand up” (P15), “The robot is saying ‘No’ like a rejection of command” (P25).

For the second gesture (moving up and down), the responses could also be categorized into 6 types: “stuck” (3 participants, 10%), “heavy” (3 participants, 10%), “inquire” (4 participants, 13.3%), “order” (5 participants, 16.7%), “attention” (5 participants, 16.7%), and “status” (8 participants, 26.7%). Two participants were unsure. The responses were quite similar to the first gesture except for “attention”, some participants’ reactions were quite opposite, P17 felt the intensity and urgency associated was greater than the quick jitter while P19 felt the opposite. One new interesting feedback type was “inquire” where participants thought the robots were trying to ask for something. For example, P16 said the robot was asking “How can I help you, where do you want me to go?".

For the third gesture (waving left to right), the responses could be categorized into 5 types: "status" (12 participants, 40%), "order" (1 participants, 3.3%), "attention" (4 participants, 13.3%), "inquire" (3 participants, 10%), "stuck" (1 participants, 3.3%). 9 participants (30%) were unsure. There were a variety of responses for "status", but most with increased urgency. P1, P5 thought there was something "seriously wrong", P2 felt the robot positioning was "messed up", P6, P7 believe the robot status was indicating that it was to perform some tasks. For "attention", P17 described the robot in a more anthropomorphic tone, even though SORT was designed to be non-humanoid, that the robot was trying to be "playful", and "welcoming you, saying hi after just arriving at home", similarly, P26 also felt the gesture was energetic and joyful.

Speed Preferences

For the first scenario of urgent item delivery, the average speed (between 10-slowest to 50-fastest) was 45 (11.7cm/s) with SD of 5.8. 6 participants wanted the robot to move even faster than the current prototype allowed. There were also some interesting observations and feedbacks. P30 did not wait for the demonstration to finish and provided the answer of "the fastest option available". P27 mentioned that the preference was not about speed, but dependent on the time it took to complete the task, which would vary a lot. For the second scenario of non-urgent task, the average speed was 29.6 (7.8cm/s) with SD of 8.8. One participant preferred the slowest speed because it felt very "calming". For the third scenario of leisure interaction, the average speed was 23.9 (6.2cm/s) with SD of 14.3. One participant did not want the robot to move at all for casual interactions and selected zero for the speed. P30 preferred a slightly faster speed for altering ambient atmosphere because the slowest movement felt like an "old animal". The speed preferences are summarized in Fig 4.12 below.

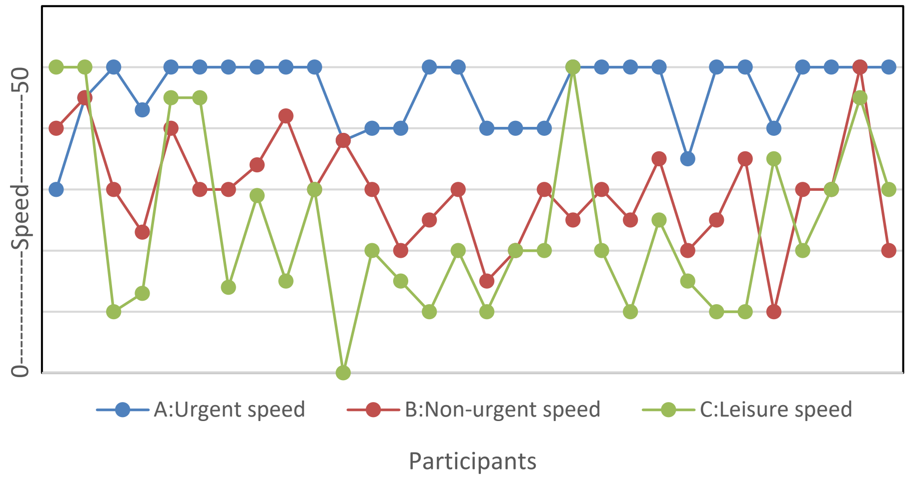

Figure 4.12, compiled graph showing results for robot speed preferences across 3 different use scenarios.

Organizational Habits

Logic change

When asked if organizational logics changed between using the robots versus conventional bins, 21 participants (70%) responded yes. There were mainly 5 different reasons for changes: by category (7 participants, 23.3%), by frequency of use (4 participants, 13.3%), by weight (1 participant, 3.3%), by shape (5 participants, 16.7%), and by reach convenience (4 participants, 13.3%). 9 participants did not report significant changes in organizing logics. For those who changed how they sort by categories, most commented that the differences in container volumes helped them group items differently. P22 said "Yes, for lotion it's big and can't fit in small bin. But for robot, I just put all personal care items in the same robot. That's helpful". For changes by frequency, some perceived the robots as a secondary system and would use them for items not used frequently. P16 commented "Small things are more convenient to be on the table … robot is for things don't need everyday". One participant (P5) decided to organize items by weight differences when using robots due to unfamiliarity with the system's robustness. For those who changed item groupings by shapes, the main cause was due to the design affordance in container geometries and depths. For example, pens and pencils were able to fit in long and slender desktop container openings better than the box receptacle on SORT. P29 said "Yes, I think with the bin, it has thin compartment for pens, or upright, long shaped item. It also has divisions among compartments, so you can organize similar but not completely related things, like pencil and sharpener. Robot is open, you can put anything anywhere, it gives more freedom. But it has no physical divider, so it doesn't give mental correlation of where to put things". Finally, for those who changed by reach convenience, there were two opposing response categories. Some participants thought the robots can substitute the reaching actions one has to take for item retrieval, which helped in reducing mental load associated with object placements, as explained by P17 "…When grouping [with robots], I don't think too much about overlapping objects and issues of retrieving overlapped objects. So, it's easier. But for the shelf, if I need to reach for items, then I will have to think more about putting things apart". However, this perceived convenience was also dependent on how long it would take the robot to bring the item from the dispenser to be within reach. On the other hand, some participants felt more confident in using conventional bins that they are already familiar with, and hence would perceive the robots only as secondary containers for items that do not need to be within reaching distance.

Logic hierarchy

Participants were also asked to rank the most important logics they followed when organizing items (Figure 4.13). The responses can be summarized into 5 types: by category (5 participants, 16.7%), by frequency of use (9 participants, 30%), by need

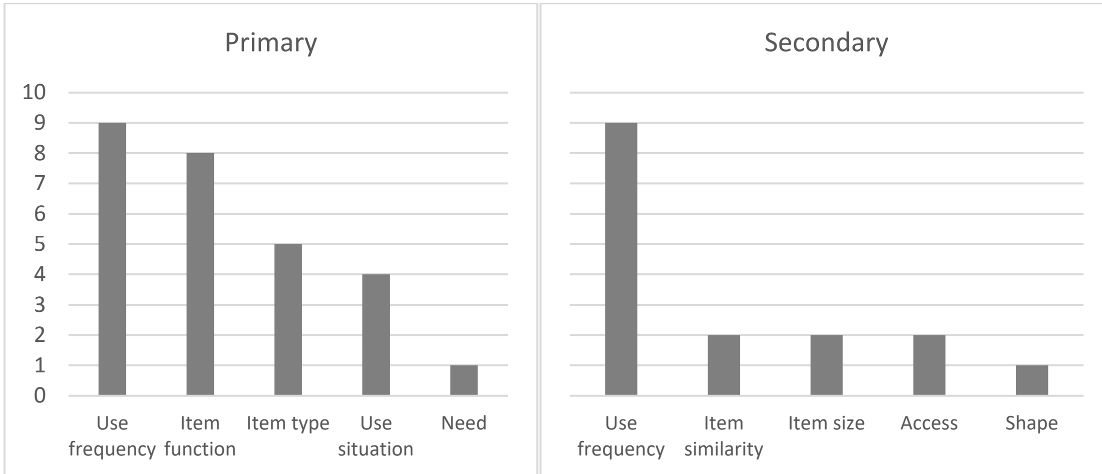

Figure 4.13, graphs showing hierarchy of responses for primary and secondary logics used when organizing items.

(1 participant, 3.3%), by function (8 participants, 26.7%), by situation of use (4 participants, 13.4%), 3 participants did not follow any particular hierarchies of organizational logics. For object category, participants grouped items simply by what they are, such as markers alone, or note pad alone. For frequencies of use, participants preferred to keep items that they use often close by, within quick reach distance. Only one participant organized items by how much they are needed throughout the sorting task. For function, participants grouped items by how similar they are in use. For example, P25 mentioned "…to organize stationary stuff first, then technology related things, then keys". For use situations, participants sorted items by task demands or specific use cases. For example, P22 said "…put technical stuff together, charger, controller. Then by personal hygiene stuff. Keys, wallet in the corner of table so I can grab them when going out". When asked if a secondary logic was followed, 21 participants (70%) said yes. The responses can be summarized into 9 types: by frequency of use (9 participants, 30%), by item similarity (2 participants, 6.7%), by item size (2 participants, 6.7%), by accessibility (2 participants, 6.7%), by shape (1 participant, 3.3%), by function (2 participants, 6.7%), by situation of use (1 participant, 3.3%), by aesthetics (1 participant, 3.3%), by category (1 participant, 3.3%). Besides

the logics already reported at the first hierarchy level, for organizing by similarity, P23 said "… to organize by how things are related to each other, such as similar function, similar use, like flash cards and post it notes". For organizing by size, a few participants wanted to sort items by their dimensions and how well they could fir into certain containers. For organizing by accessibility, participants wanted to make sure that after the items were stored, they would be easily retrievable, proximity was another factor mentioned. One participant said the shape of the container should match the shape of items. Finally, another participant who cared more about the holistic appearance and aesthetics preferred the items to "fit into the container nicely".

Decision hierarchy

There were two tiers of drives behind participants' decisions to organize, which could be divided into 6 categories (Figure 4.14). For primary motivations, 5 participants

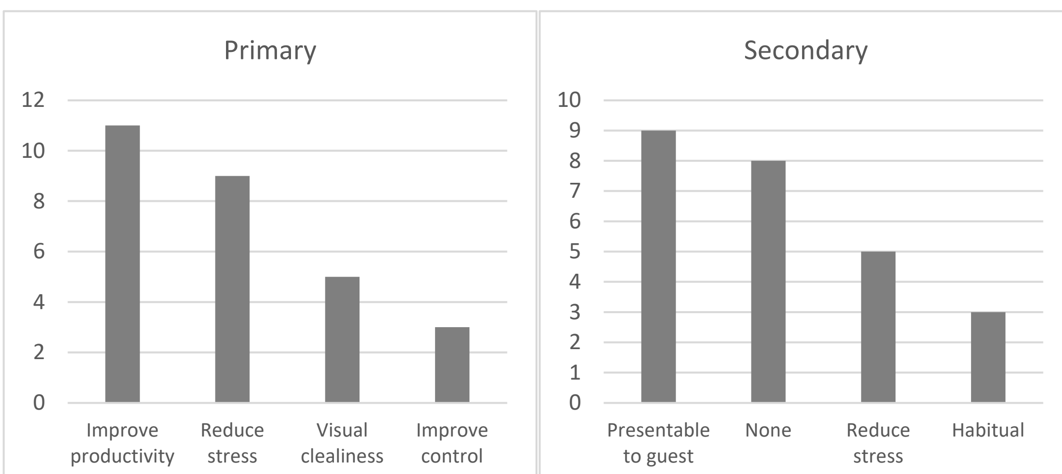

Figure 4.14, graphs showing hierarchy of responses for primary and secondary reasons that drive participants to make a decision to organize items.

(16.7%) said they organize to maintain visual cleanliness, where one would "only do it when I really have to, when it's too chaotic" (P27). 9 participants (30%) organize to reduce stress, for example, P22 mentioned "I get stressful when I see my table is a mess, then I force myself to clean up”. 3 participants (10%) said they wanted to improve control, where for P16, “I do it when feel like my room is getting too messy, feel unorganized, cleaning helps clear my mind, and feel more in control”. 1 participant (3.3%) said it was to appear more presentable for guests, and 1 participant (3.3%) said it was habitual. For 11 participants (36.7%), improving productivity was the primary drive behind cleaning decisions, where a cluttered environment would lead to reduction in object identification and retrieval, adding unnecessary cognitive load and hence decrease work efficiencies, as mentioned by P18 “… to maximize productivity. So I would leave things where it’s easy to perform tasks”. When asked to rank a secondary drive for organizational decisions, 8 participants (26.7%) did not respond. 5 participants (16.7%) said to reduce stress. 3 participants (10%) said improving control (over the items and not the environment). 9 participants (30%) picked making the room more presentable to visitors as the secondary reason for cleaning, or to make themselves appear organized to others. 3 participant (10%) organize out of habits as mentioned by P30 “I clean based on routine. Every Friday, if I don’t clean, then I don’t have things to wear next week”. 3 participants (10%) organize to improve productivity. In addition to the above reasons behind participants’ organizational decisions, a follow up question was asked if such drive was due to a mental or physical need. 17 participants (56.7%) said it was to fulfil a mental need, while 12 (40%) said it was for physical need. One participant distributed these two equally.

Robot Number

Participants’ preferences on the number of mobile robots ranged from 1 to 4, with an average of 3, and the number of stationary dispensers ranged from 3 to 12 with an average of 6. However, the responses were more nuanced. Some participants (P5) were worried that having too many mobile robots on the wall they might interfere or collide with each other. Some participants (P12, P14) also preferred smaller container sizes, or suggested to further compartmentalize the dispensers to have smaller inner cubicles, which might affect their preferences on robot numbers. P16 also wished the robots would provide different choices for container sizes to better fit a variety of objects. It also appeared robot numbers were associated with room functions. P15 preferred more mobile robots in kitchen or dining areas, but fewer in bedrooms. P18 suggested that the dispensers could potentially be hidden above the ceiling, which then the numbers could be as many as possible since they are also "out of sight". It also seemed the preferences on robot numbers were influenced by robot speeds. For P20, if the robots can sort items quickly, then fewer number would be preferred. Both P20 and P23 also used a ratio system, where the former preferred the mobile robot and stationary dispenser numbers to stay 1:2, and the latter said 2:3.

Additional Items

Participants were also asked to imagine any additional items they might use the SORT system to manage. Responses include snacks, more office and craft supplies, scissors, sewing materials, socks, small electronics and tea collections. Makeup was a major category mentioned, including lipsticks, eye brushes, lotions, creams. Kitchen utensils were another important group, such as ladle, spatula, spices and ingredients. Two participants mentioned potential uses in hospitals for medication management. One suggested fishing supplies for parents, such as baits, wires, and various hooks. Participants also mentioned items they would not want to use SORT for, such as school supplies that P25 prefer to be on the desk and nearby, who also did not want to wait for the robot for delivery. P26 suggested using the robots for sorting different colored oil paints and various sized brushes. A few participants expressed interests in future prototypes that can hold larger and heavier items such as books and journals.

Quantitative Results

Perception of Control

For this test, the experiment was a within-subject design, the independent variable was organizational tools (robot vs. bins), and the dependent variable was perception of control as measured by the adapted NIOSH subscale mentioned earlier. *The Null hypothesis is: there is no significant differences between using the robot or conventional bins for improving perceptions of control when organizing personal items. The alternative hypothesis is: there is a significant difference between using the robot or conventional bins for improving perceptions of control when organizing personal items, and that using the robots would increase perceived control compared to conventional bins.*

The data was analyzed by using the R-based graphic interface JASP [17]. A simple paired t-test was performed on the results comparing participants' responses for perceived control after using the robots and conventional bins for organizing items. The descriptive statistics results are shown in Table 4.1 and Fig 4.15. As shown in Table 4.2, the resulting t score was 1.357, with a p value of 0.907 (much greater than the 0.05 threshold) and a Cohen's d of 0.248 which indicated a small effect size. Based these results, we fail to reject the Null hypothesis and therefore declare that there is no statistical significance between using the robots and conventional bins for improving perceptions of control when organizing items.

Table 4.1 Descriptive Statistics

	Mean	**SD**	**Min**	**Max**
Bin	3.883	0.606	3	5
Robot	3.692	0.637	2.375	4.5

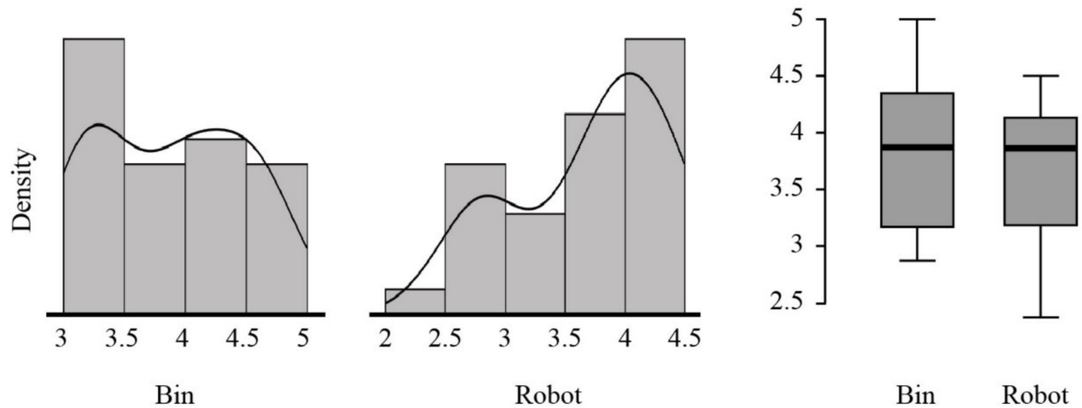

Figure 4.15 Density distribution and boxplots for descriptive statistics results.

Table 4.2 Paired T-test Results for Perception of Control

Comparison	t	df	p	Cohen's d
Bin - Robot	1.357	29	0.907	0.248

Additional t-tests were also performed for each survey question to understand more detailed differences between bin and robot usage, the results are summarized below in Table 4.3. Since the result for Control over task variety is showing some significance (t=2.191, p=0.018 with medium effect size), the result for Control over pacing shows marginal significance (t=1.417, p=0.084 with small effect size) and the result for Control over item arrangements shows a reversed sign, descriptive graphs were also created for these three items (Fig 4.16). For perception of control over task variety, participants felt more in control when using the bins compared to the robots. However, it should be noted that the lower bound of the 95% confidence interval for bin usage overlaps the higher bound of the confidence interval for robot usage, even though the test result shows $p<0.05$. Similarly, participants felt more in control with the bins than robots for controlling over task pacing (insignificant).

Table 4.3 Individual question's paired t-test Results for Perception of Control

Comparison (bin-robot)	t	df	p	Cohen's d
Control over task variety	2.191	29	0.018	0.400
Control over the tools	0.623	29	0.269	0.114
Control over task order	0.000	29	0.5	0.0
Control over amount of work	0.701	29	0.244	0.128
Control over pacing	1.417	29	0.084	0.259
Control over item arrangement	-0.441	29	0.669	-0.081
Control over cleaning duration	0.694	29	0.247	0.127
Overall sense of control	1.140	29	0.132	0.208

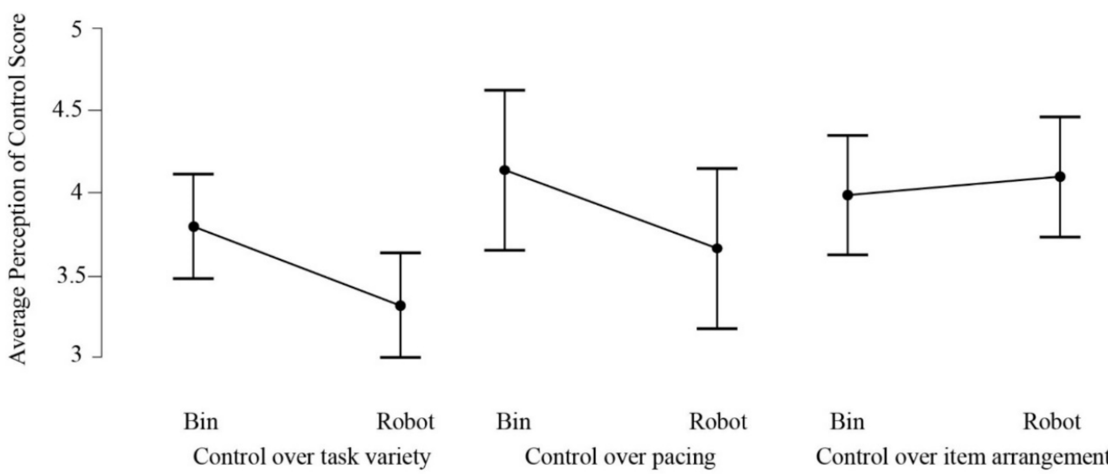

Figure 4.16 graphs for results on questions comparing the perception of control differences between using bins versus robots for Control over task variety, Control over pacing and Control over item arrangement.

Organizational habit correlations

As mentioned earlier, an interesting observation made from a prior study was that participants who self-reported on the lower end of personal room cleanliness did not show more or less willingness to use SORT compared to those who self-rated on the higher end. Therefore, it appeared the perceived degree of personal room's cleanliness is not correlated with one's tendency to use assistive technologies or the perceived usability of the assistive system. This contradicts conventional wisdom that people would be more inclined to use cleaning tools if they perceive their environments as messy, since those who are already actively maintaining an organized room by de-cluttering daily and are satisfied with their cleaning results may not be incentivized to use additional robotic tools. To confirm this, an additional study was performed.

For this test, the dependent measure was the average System Usability Scale score for each participant. The independent variable was the self-reported degrees of personal room cleanliness. Covariates controlled included gender, residence type, current use of other robots, and self-reported frequencies of cleaning. For the two sets of self-reported data, the results were dichotomized where those who reported frequent cleaning (4-a few times a week and 5-Everyday or multiple times a day) were coded as 1, and those who reported personal rooms as clean (4-organized and 5- very organized) were also coded as 1. The rest were coded as 0. *The Null hypothesis is: there is no significant reported robot usability score differences between those who self-rated personal rooms as organized and those who self-rated as disorganized. The Alternative hypothesis is: there is a significant reported robot usability score differences between those who self-rated personal rooms as organized and those who self-rated as disorganized, and that those who self-rated as disorganized reported higher usability on the robots.*

The data was analyzed again by using the R-based graphic interface JASP [17]. An ANCOVA was conducted while controlling for gender, residence type, current use of other robots, and self-reported frequencies of cleaning. The descriptive results are shown in Fig 4.17 and the ANCOVA results are shown in Table 4.2. As shown, the p value for the self-rated cleanliness variable was 0.718, with a small effect size and an F value of 0.134. Therefore, we fail to reject the Null hypothesis and declare that there is no significant reported robot usability score differences between those who self-rated personal rooms as organized and those who self-rated as disorganized. This confirms the prior observation that participants' tendency to user robotic organizer assistant and the resulting perceived usability is not correlated to one's subjective evaluation of personal room conditions. Please refer to Appendix D for the survey data.

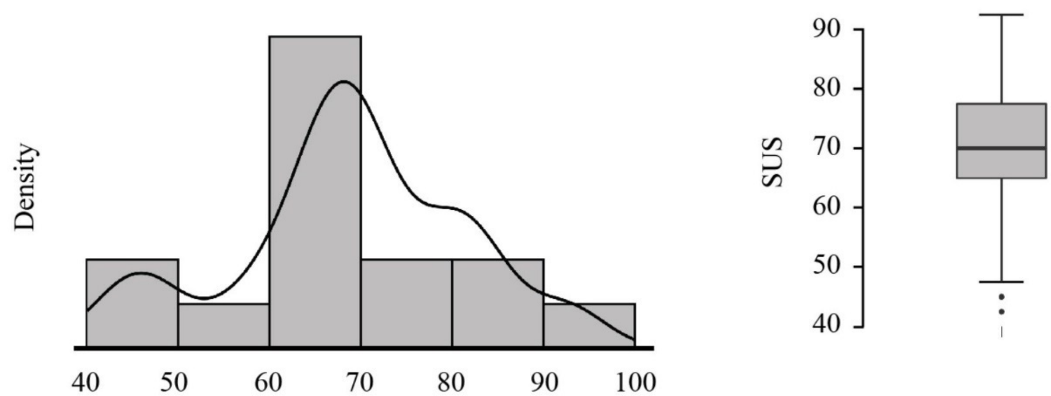

Figure 4.17, Density distribution and boxplots for descriptive statistics results.

Table 4.2 Results for ANCOVA

	df	F	p	η^2	ω^2
Self-rated cleanliness	1	0.134	0.718	0.005	0.000
Gender	1	0.430	0.518	0.016	0.000
Residence type	1	0.502	0.485	0.019	0.000
Use of robots	1	0.821	0.374	0.031	0.000
Self-rated frequency	1	0.956	0.338	0.036	0.000

Since the results are statistically insignificant, to better understand the nuanced relationships between measures, scattered plots with regression lines were created for Self-rated cleanliness and Self-rated frequency of cleaning (Fig 4.18). Gender and current use of robot are binary variables and therefore were not plotted. Residence type data is categorical which is not suitable for regression and hence was excluded as well.

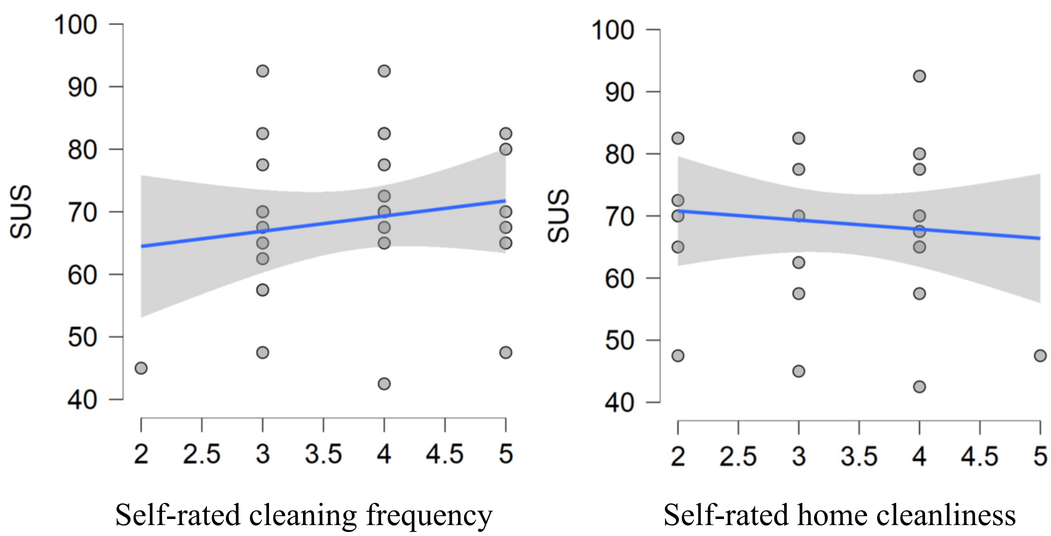

Figure 4.18, Scatter plots with regression lines for Self-rated home cleanliness and Self-rated cleaning frequency on x axis, and System Usability Scores (SUS) on y axis.

Discussion

As mentioned above, the overall SUS score obtained was 68.83, which puts the system at the average acceptable cut off threshold [18]. While the score was the simplest approach to start evaluating the SORT system, the result cannot be used for comparing with other organizer systems, rather it establishes a benchmark for future studies. At the conclusion of the user study, a final question was asked for participants to indicate how satisfied they were with the SORT robots for completing the organizational task. Combined, 24 participants (80%) said they were either satisfied or very satisfied. Only one participant (3.3%) selected very dissatisfied. The average score (1-very dissatisfied, to 5-very satisfied) was 3.87 with a SD of 0.94. Despite the enthusiasm and overall satisfaction of this new assistive technology, participants' responses were far more nuanced, which may provide insights for future studies in the area of wall-climbing domestic assistive robots.

Logically one would expect a person to always select the fastest robot speed to complete urgent delivery tasks. However, it was not always the case. P1, P2, P11 and P29 rated preferred robot speed for non-urgent task and leisure interaction the same or faster than that of urgent task. P5, P6, P10, P17, P19, P26 and P28 rated leisure interaction speed the same or faster than the speed of non-urgent task. As one participant explained, if it was for something urgent, the item must be very important or delicate. Therefore, having the robot successfully deliver the item was more important than how fast it can deliver as no risk was tolerated for fast speed associated interruption or mechanical failure.

Regarding perception of control, this study did not find the use of robots increased people's sense of overall control significantly compared to conventional bins. This may be due to unfamiliarity of the system, as mentioned by one participant who was hesitant to trust the robot at first sight. Another potential explanation was the degrees of robot autonomy. As SORT was designed for personal items to be out of sight, the system focuses on relieving some control from users. However, there could be a problem with having too much robot autonomy as it may inadvertently decrease perceived control. Especially as participants were already used to desktop bins and organizers and that they prefer to grab items nearby. As such, the SORT robots appeared to be a secondary organizer system compared to conventional tools for college students. Future studies can focus on investigating the relationship between SORT's autonomy versus user's perception of environmental control, or how much robot control is just enough for organizational purposes (Fig 4.19).

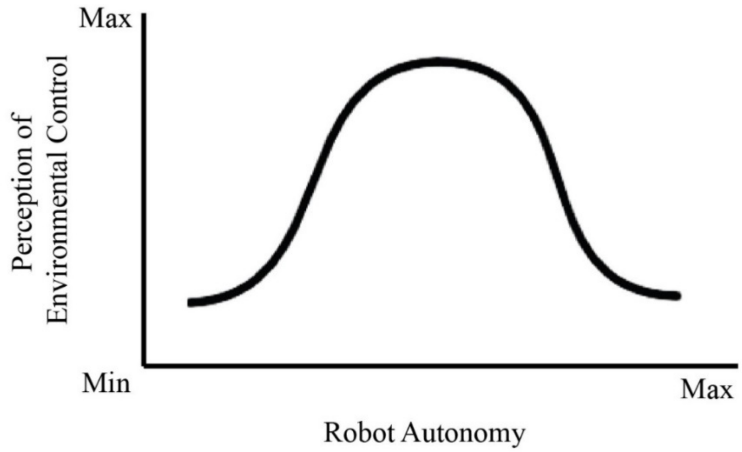

Figure 4.19, hypothetical graph depicting a possible relationship between perception of environmental control versus robot autonomy, where having too little or too much robot autonomy may deprive users of their senses of control over the environments.

However, the t-test results on each individual question did reveal some interesting patterns. It appeared the use of conventional bins increased participants' perceived control over the variety of organizational tasks. As mentioned by a few participants, the different sub-dividers and shapes of conventional bins helped them associate items with container spaces (e.g., long and slender objects such as pens should be placed into smaller but deeper container pockets). SORT, when equipped with improved container receptacles that adopt similar design philosophy for increasing its own affordance, is expected to increase people's perceptions of control in future studies. Although marginally significant, participants who used bins reported slightly higher level of control over task pacing compared to robots. This could be due to the fact that the robot speed was another set design variable controlled by the researcher. While it was not in this study's scope to allow participants to control robot speed, future study may implement a gesture-based speed control to help compensate this difference in task pacing compared to conventional bins. Lastly, SORT helped to increase participants' perception of control over item arrangements compared to conventional bins. The benefits of using SORT in this aspect was based on two factors. First, the robots can move freely on the wall and therefore can arrange items' placements according to user command or preference. Secondly, some participants commented that it was quite convenient not having to get up every time to place an object on the shelf. This improved task efficiency in item placements which in turn helped increase perception of control. However, the result was statistically insignificant and need to be further studied.

When examining the individual scatter plots with regression lines for correlations between organizational habits and perceived robot usability, it appeared Self-rated cleaning frequency is proportional (slightly) to the usability score (SUS) where participants who reported to clean more often rated SORT to be more useful. While conventional wisdom may suggest that people who do not clean frequently might be more willing to use cleaning robots, participants from this study who self-reported to clean often, expressed that since cleaning and organizing items are important daily routines, they will be more receptive to trying new tools that would assist them in completing the various organizational tasks. Additional efforts are needed to understand, design and improve SORT and its usability for those who do not maintain regular cleaning habits. For the variable on Self-rated home cleanliness, participants who do not believe their current home environments are clean rated SORT as higher (slightly) in usability, which was not surprising. However, such relationship was quite weak and statistically insignificant.

One clarification needs to be made on participants' organizational logic changes during the study was that such change did not necessarily imply one system (robot) is better or worse than the other (bins). As suggested by some participants, there were things robots can do that bins cannot, but also convenience inherit in conventional systems that cannot be substituted due to familiarity and comfort. In addition, there may be trade-offs. If a container is designed to be very detailed to fit different shaped and sized objects, it may not satisfy users who group items by activities, as some participants preferred a big generic box for objects related to the same activity. This would also imply differences in robot commands, instead of asking for individual specific item, users can say “I’m working school craft project”, so robot would bring all items related to that activity.

Another important feedback from the study was on design affordance. Many participants mentioned one advantage of conventional bins over the robots were the subdividers, where the different shapes and sizes imply which objects should be placed inside (e.g., almost all participants started the task by placing markers into the long and deep pocket in the conventional organizer, suggesting that after an initial visual assessment of the environment, such pairing was the easiest and most intuitive decision to begin with). As affordance is a fundamental concept in design, tracing back to Gibson [21], future explorations can focus on understanding how different SORT container designs may improve user experience in item placements and further increase the efficiency and efficacy of the whole system.

For logic hierarchy ranking, one concept that needs to be clarified is item category, which was a phrase used often by participants but might have carried different interpretations. For the purpose of this section, there are mainly three levels of meaning, 1) category simply as the representation of what the item is (e.g., a pen, a pill bottle) that is not associated with any types of grouping; 2) category as the representation of the item’s function (e.g., something to write with, something to treat an illness) that is often associated with other objects with similar uses; 3) category as the representation of different use situations (e.g., a school project, personal care), which often involves other types of items. For example, one may need pens, pencils, markers, paper and scissors to complete a school craft project. There were two important feedback from participants that the researcher had not considered before. P12 included the factor of time and environmental familiarity into the organizing logic. When moving into a new place, the participant wanted to sort objects first by functionality then by size. But after becoming familiar with the environment, the participant preferred to sort items by frequencies of use and be reminded of where everything is located even though some may be not used often. P21 categorized objects according to the function of the room as well. For example, in a workshop space, items like paperclips and pens should be placed together and close to the user, while keys and wallet are also important personal belongings but since they are not typically associated with a workshop space, they should be placed further away and apart. these indicate that organizational logics change over time based on environmental adaptions. Any assistive robotics at home should also take these factors into consideration when designing interaction scenarios to improve the perceived usability and usefulness.

One participant (P4) commented on the benefits of not having to get up to retrieve items when being assisted by robots compared to using conventional bins and shelves, and that the system "would be useful for people in wheelchair. As this was an intended design feature, almost no other participants made similar comment on this convenience. This probably was due to the fact that all participants (expect one with crutches) were able-bodied college students and did not regularly experience the difficulties of living with mobility impairments. Another interesting observation made during the study was participants' reactions during robot speed demonstrations. Almost all participants unintentionally smiled when the slowest robot speed was shown. Some commented that it looked like an "old dog" (P30), or that the changes in speed "feels like there is life" (P2).

Limitations

Hardware

One major issue raised during the user study was noise. In some instances, participants preferred slower robot speed due to noise disturbance from the servo. In one interesting case, a participant selected speed by listening to, as opposed to watching, the robots moving on the wall. Despite the nuisance, one participant (P7) preferred the noise since it gave some extra auditory cue of what the robot was doing. Since the magnetic prototypes relied on a ferrous wall surface, the robots used in this study can not be readily distributed to home environments. While most participants were naïve users, a few asked how the robots adhered to the wall surface and commented that they do not have a metal wall at home for the system, which might have implicitly affected their perceived usefulness of SORT. Additionally, in rare occasions when the robot moved over a warped metal seam, it detached from the surface and fell on the desk, which might have negatively impacted users' perceptions of the system's robustness. Lastly, since the robots were remotely controlled by the researcher via a cellphone app, only one robot could be moved at a time. Therefore, the true potentials of multi-robot interactions and robot-robot collaborations could not be demonstrated to the fullest extent.

Threats to Validity

When recruiting participants from the University SONA management system, students had the option to browse and choose from a list of available research studies. Selection bias was a possibility since a few students did express that they signed up for the study because of their inherit interests in either assistive robotics or organizing personal items. However, it was unknown how this initial self-selection might have impacted participants' perceptions toward SORT, which was a novel system they had not seen before.

Since self-reporting was used for gathering data on two independent variables: frequencies of room cleaning and perceived room cleanliness, the subjective measures may lead to threats to construct validity. Also, different people's interpretations of cleanliness might also be different. A room that appears messy to one person might be perceived as organized to another. In the future, an objective reference could be used such as images of rooms with varying degrees of mess and ask participants to compare the state of their rooms to the reference. However, since the dependent variable was obtained through a survey, there should be no methodological overlap and shared method variance yielding mono method bias.

Another potential issue was researcher presence. While the majority of participants did not inquire about robots' autonomy, a few asked who was controlling the robots. Also it was unknown how the experimenter's characteristics (gender, ethnicity) might have affected participants' task performance.

While the statistical analysis was not a major focus for this chapter, there are a few statistical threats. The results may be susceptible to Type II error due to the small sample size (30) and low power. Also the subscale used from the NIOSH questionnaire included items on co-worker relationships, which might have been tailored to office environment as opposed to working in a home environment. The reliability and validity of the adapted measures was unknown.

In general, the purpose of this study was to gather qualitative results to understand potential areas of improvements for the robot prototypes and also how college students may use this SORT system when performing organizational tasks. The results can not be generalized to the entire campus, or even larger population groups. Similarly, the study was conducted in a controlled lab environment, the results may not generalize to other settings or environmental conditions.

Future works

Prototyping

Based on the study, some user comments should be considered for design improvements. For example, one participant was worried items may spill from the container and preferred if a cover can be installed when robot was moving. Some participants were hesitant to use the system for phones and other delicate objects due to concerns of how the mobile robots dropped items into the dispenser. To compensate, a foam pad was installed at the dispenser platform. Alternative item transfer methods will be explored which may lead to different robot designs. For example, instead of sliding out of the container, the mobile unit could be fully docked into the dispenser to place objects directly onto the internal platform. As suggested, different receptacle shapes and sizes may help participants better categorize items, the associated affordance would inform how well objects can fit into the robots. A more rigorous exercise will be conducted to explore different robot container designs to improve usability.

In addition, improvements are being made to the vacuum suction prototypes. As shown in Fig 4.20, a new connection bridge was fabricated (by Mark Worsley) that would correct problems of the robot bending out of plane. Custom-made suction cups are also being investigated to substitute the generic commercial suction cups. The goal for the next phase is to develop the vacuum prototypes to be adequate enough to work on typical drywalls untethered, and without too much noise disturbance for potential in-home user studies.

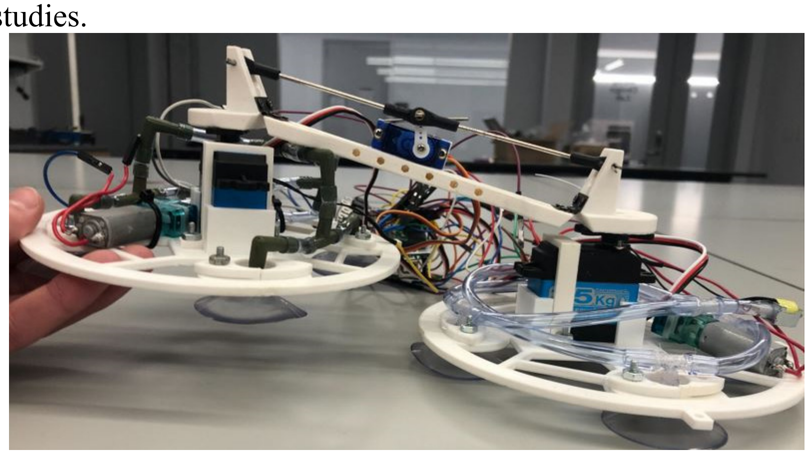

Figure 4.20, an updated SORT suction cup prototype, with new connection bridge.

User Studies

As one participant pointed out, the quantity of items may impact their preferences and perceptions toward the SORT system. Just having more objects to be sorted (e.g., instead of 5 markers, have a box of markers of different sizes and colors which may reflect real task situations) would help in further understanding how people would use the robots in more complicated organizational tasks.

While this chapter focuses more on the qualitative results of SORT, as a novel system it would be difficult to conduct reliable and valid statistical analyses with limited sample sizes when participants are not yet familiar with how to use the robot. A longitudinal study would be appropriate where users can live with the robots at home for an extended period of time to evaluate the true efficacy of the system. Nevertheless, to prepare follow up user studies, a power analysis was performed on the final data with 30 participants by using the software GPower (v3.1) [19, 20]. As shown in Fig 4.21, the

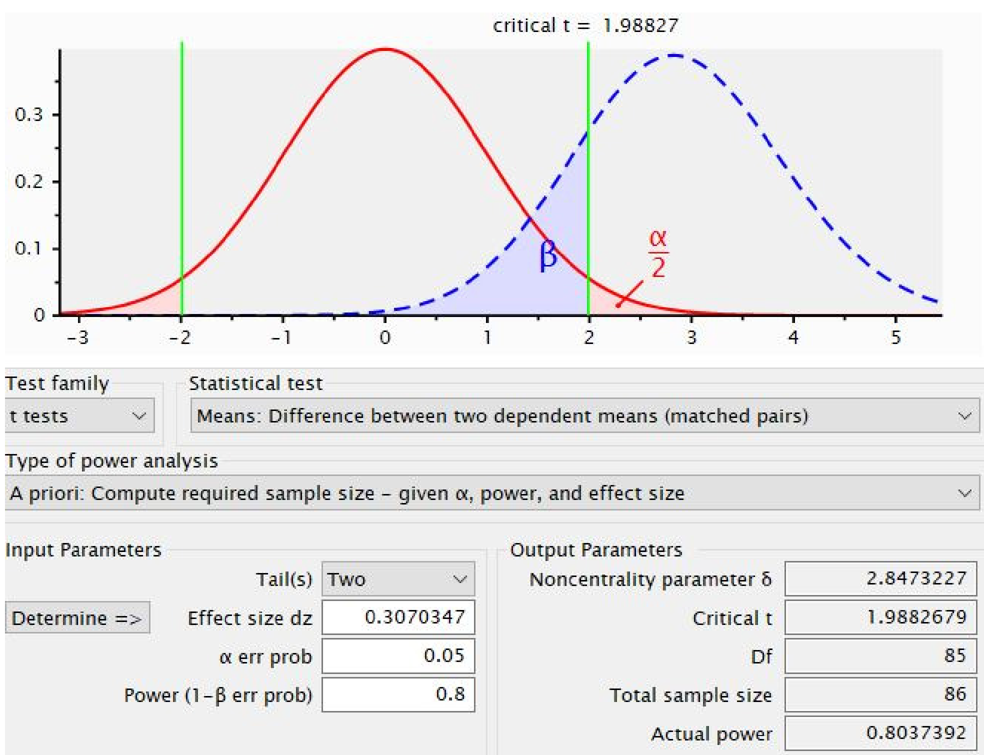

Figure 4.21, screen capture of GPower 3.1 results.

current perception of control t-test yielded a small effect size of 0.3, by using the standard power of 0.8 and a two-tail error threshold of 0.05, the resulting sample size was 86. This number can help further establish a baseline of future user studies. By fabricating more robust prototypes, updating the procedure, improving experimental designs and finding more relevant validated questionnaire, the effect size is expected to increase and sample size to decrease while maintaining same power and error threshold.

Conclusion

In this chapter, a magnetic wall-climbing, multi-robot system was introduced as an extension of the SORT system proposed in the dissertation, to be embedded within the home environment to aid users in organizing domestic items to improve life quality. The author reported on the ideation process, design iterations of the robots, a lab experiment with a working prototype, and results from an in-person user study. Future improvements on the robot could be made in the area of sensing, localization and autonomy. A more systematic investigation is needed to understand the carrying capacities, failure points and receptacle container designs. Insulation materials will be added to reduce noise. A control algorithm is also needed to allow communication between robots and permit the system to orient itself on the wall, assemble in orderly configurations, and locate users. As demonstrated, wall-based multi-robot systems are a viable means for exploring interaction design experiences. As a "design exemplar" of an interactive system leveraging everyday domestic spaces, SORT promises to support independence and improve people's perception of control in their familiar surroundings. We believe SORT offers inspiration for designing multi-robot systems fulfilling a wellness agenda. For researchers working in the domain of domestic assistive robots, the user study results presented here may provide some initial insights into how people perceive and understand their personal spaces in terms of clutter and organization.

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CHAPTER 5

CONCLUSION

Contribution

Exploring new potentials and pushing the boundaries of domestic assistive technologies is an important venture both in academia and in practice to further improve the life qualities of people, especially for the elderly and those with various impairments. As advanced technologies are continuously being made available in the domains of HCI and HRI for domestic robotics, understanding how potential users may interact with the assistive prototypes should be an integral part of the robot development process. The works presented in this dissertation contribute to this scope of research in the following categories: human organizational behavior, domestic assistive technologies, wall-climbing robots, Human-Multi Robot interaction studies, cultural differences in HRI, and architectural robotics.

The majority of this dissertation took place during the COVID-19 pandemic, the lockdowns had significantly changed our lives both physically and psychologically. There have been a plethora of online articles giving advice on how to remain organized at home, such as [1, 2, 3], just to give a few recent examples. However, upon an extensive search, the author could not find any empirical studies on understanding human behaviors in organizing personal items, especially when assisted by robots. The user studies in this dissertation provided some initial insights on people's organizational habits and logics. From Chapter II, organization does not seem to be correlated with quantitative presence of objects. This implies that, in addition to conventional wisdom that cleanliness is associated with objects being "out of sight", user satisfaction can be achieved by improving item placement logics as opposed to trying to hide everything. This section also provided an inventory study that could be helpful in designing future domestic organizer robots. Chapter IV revealed that when organizing, any tools should be designed to balance both users' mental and physical needs, namely, to reduce stress, lower cognitive loads and improve work productivity. People also unconsciously look for design affordance, an organizer with a variety of sub-dividers can better inform users which objects are meant to be stored inside, which in turn may increase organizing task efficiency. The findings in this study may provide insights on organizational behaviors for future designers to create better organizers, robotic or not.

Similarly, there is a gap to be filled in domestic organizer robots that are easy to use and do not require physical alterations to the home structures. Robotics organizers are already implemented and widely used in commercial and industrial applications. Such as those in large warehouses or storage facilities. These systems, such as PAR Systems [4] and AutoStore [5], often occupy large floor areas and rely on additional structures. Since most of these solutions are track and robotic arm based, much attention has been paid to researching in computer vision, object identification and various gripper designs for retrieval. SORT was proposed as a design exemplar of an alternative solution to item management at home. The results from Chapter IV confirmed that the proposed robot group can successfully assist people in managing personal items (80% participant satisfaction and 68/100 usability score). While the college students participated in the study may have perceived the SORT system as secondary, supplementing conventional organizers for infrequently used objects, SORT could be proven to be more helpful assisting the elderly or people with physical impairments as suggested by some participants. In addition, this dissertation explored other SORT functions that previous organizer robots do not possess, particularly in the realm of HRI. For example, some participants were more interested in interacting with the robots than sorting items. Robot movements could also deliver non-verbal messages, such as the jittery gesture as associated with greeting, the up-down gesture as associated with attention demands, and the waving gesture as associated with robot status indications.

This dissertation also fills a gap in exploring wall-climbing robots for indoor uses. There have been numerous precedents in wall-climbing robots, the majority of which were designed for out-door uses. Such as vacuum-based City Climber robots for building inspection and search / rescue [6], magnet-based Anchor Climber for ship inspection and repair [7], micro-spine hook based robots for reconnaissance and security [8]. As demonstrated by SORT in the video [9], in-door wall-climbing robots have great potentials to be part of the Internet of Things domain to create embedded interactions and provide assistance in a variety of scenarios. While the second prototype was based on magnets and can only work on ferrous surfaces, with improvements in other wall-climbing prototypes, additional use cases can be further illustrated in future studies.

Furthermore, within the domain of HRI, there is a lack of Human-Multi Robot Interaction studies. There have been previous efforts in Human-Swarm Interaction (HIS) [10], however, SORT cannot be categorized as a swarm due to the robots' size, control, power demands and stand-alone functionality. There were efforts similar in intention, but different in scope, such as an investigation in impact of robot-robot interaction on HRI [11]. SORT is positioned at a scale in between swarm robots and larger humanoid robots. As a multi-robot group, the studies on SORT also provided insights in user preferences on robot number and group size. When the robots were singular moving agents, users' preferred robot numbers varied from 1 to 20 (Chapter II). Also, such preference may vary based on participants' cultural differences and if the robots are static or moving (Chapter III). However, if the robots form a group with robot-robot interaction (RRI) or collaboration, users' preferred number range became narrower, with 1 to 4 for mobile robots and 3 to 12 for static robots (Chapter IV).

As mentioned, cultural differences may play a role in explaining people's preferences on assistive robots, which has been an under-studied area in HCI / HRI. This dissertation provided an example of building cultural difference as a variable in human-multi robot interaction studies, revealing the diverse perceptions of people from different countries toward the SORT system. Based on results from Chapter III, it is evident that we cannot assume a universal design of assistive technologies that would work for everyone, especially when such technology is meant to be deployed in developing or under-developed regions, more rigorous studies with participants recruited in those areas are needed. In addition, HRI study hypotheses based on prior psychology theories are becoming obsolete, new efforts are required to update these old theories to reflect current situations and events around the world that would help dispelling stereotypes.

Another goal of this dissertation is use SORT to explore previously underutilized domains where robots can live and provide ambient interactions, in this case, on wall or vertical surfaces. As illustrated in Chapter II, SORT's group formations and light-movement effects can enhance and augment our ambient environments. There have been numerous previous HRI efforts in singular robot communication. The scenarios SORT promised here may open up or reinforce an emerging HRI field in architectural robotics, or human-built environment interaction. Previously, there have been designs aimed at using room scale interventions to fulfil interaction goals such as supportive learning [12]. These studies tend to involve larger non-humanoid artifacts. SORT, as a multi-robot group, demonstrated an alternative in design that can also expand the domain of using architectural robotics for ambient interaction purposes.

To achieve the above-mentioned contributions, this dissertation presented the design and fabrication processes of two robot prototypes accompanied by both online and in-person user studies to demonstrate how such technology may provide assistance in organizing domestic items in various scenarios. The results presented in this document confirmed that such technology has great potentials in improving people's life qualities at home, and that users were receptive to the concept and found the system useful, innovative and can solve real world problems for them.

Limitation

The works presented in this dissertation include results that are preliminary and with some limitations.

First, the majority of the user studies, especially the in-person study, included participants who were college students and therefore the results may not generalize to other population groups. While Chapter III recruited participants online and from other parts of the world, the filters used are provided by third party company (Amazon), it is difficult to assess how accurate those participants can represent their own cultures and nations.

Secondly, while previous study has shown that using online surveys can be an effective way to obtain initial user feedback [13], such practice is not yet widely used and the validity of which is yet to be fully established and accepted into general HRI study practices. The lack of direct physical interaction with the robot prototype and reliance on asking participants to imagine the interactive scenarios may skew the results. The authors tried to compensate this with an additional self-evaluation question to filter out illogical responses. Another limitation is on validated survey measures. Besides the standard SUS scale, which was adapted with minimal changes, the reliability and validity of other measures, and those adapted from subscales of existing questionnaire are unknown.

In addition, the prototypes used throughout the studies (both for the in-person study and during online interview demonstrations) were not fully autonomous. A Wizard of Oz method was used to remotely control the robots to interact with participants, some of whom were able to guess that the researchers were controlling the robots. As such, it was unknown how this might have affected those participants' perceptions toward SORT's usability.

Lastly, as a novel system designed for long term home use, the studies conducted in this dissertation may not accurately capture users' true reactions. As several participants expressed that their unfamiliarity toward SORT made them hesitant in selecting the robot group as primary organizational tools. A longitudinal study, where a group of SORT robots can be sent to participants' homes, may help address this limitation. Also, more studies are needed to support the conclusion and any theoretical frameworks proposed for future designs of assistive domestic organizer robot groups.

Future Directions and Impacts

One interesting observation made from all the user studies was participants' reactions when they first see how the SORT robots move. Some expressed that they found the movements and various gestures as more appealing than the functional assistance, and described the robots as "cute", or animal-like. Evidently, a utilitarian system, like SORT, which has no resemblance of any human-traits, was able to generate some social qualities. While there have been numerous studies in social robots, especially within the home environment [14, 15, 16], however, more empirical studies are needed to verify and validate how multi-robot groups may play socially interactive roles with human users and their associated characteristics in agency and animacy.

As originally intended, and supported by user feedback, SORT could be more helpful for older adults to enhance independent living. To understand SORT potentials, the robots can be introduced to environments such as assisted living facilities for future longitudinal studies. In addition, other in-door applications outside of homes should also be explored, such as in transportations (trains, planes) or workplaces (offices, hospitals).

In addition, it is unknown if current survey measures for singular robot HRI studies will be reliable and valid for multi-robot interaction studies. As shown in this dissertation. There are extra variables to be considered for robot groups, such as robot number, group formation, and speed differences. Therefore, new survey measures need to be validated for conducting multi-robot HRI studies.

The prototypes proposed in this dissertation could serve as the start of a conversation on extending the domains of domestic assistive technologies, which traditionally had been floor-based singular agent. As robots are also becoming more versatile at a room scale, such as efforts in an interactive space robot for learning [17], or soft inflatable robots for breathing exercises [18], multi-robot groups, like SORT, that occupy a substantial portion of an architectural element, can also be classified as architectural robotics serving spatial functions. As discussed in Chapter 1, design artifacts are inseparable from the context where they exist, as such any HRI studies involving architectural robots would need to take an ecological approach considering the environmental factors as design variables to understand human-environment relations. This also implies that such context-conscious approach would also need to be adopted throughout the iterative design process. In order to create a multi-robot system of robotic assistants at home, a new framework need to be proposed in the future that can leverage and augment the ambient environments to create a more well-integrated and embedded Internet of Things system by taking design factors listed below (Fig 5.1).

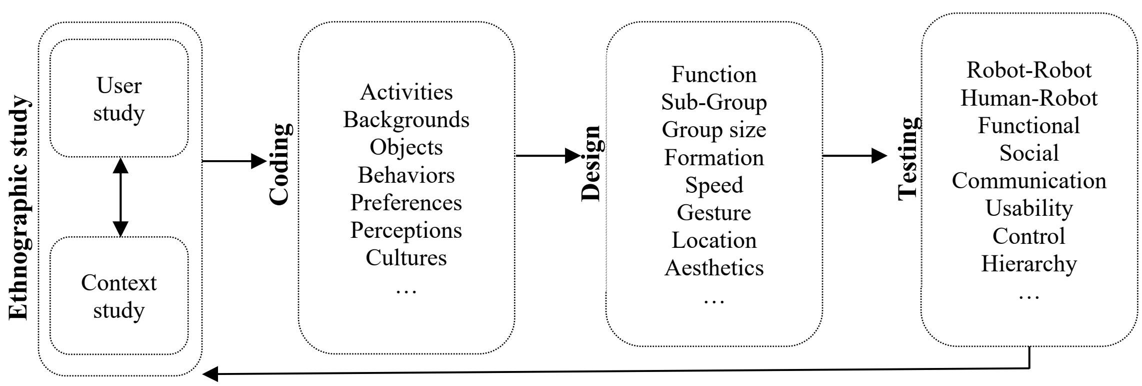

Figure 5.1, factors to consider when designing a multi-robot organizing system.

From “Stuff Organizing” to “Self Organizing”

As demonstrated in the online study, a group of SORT modules can form shapes and move about to communicate with users. In order for the system to create the illustrated effects, SORT might transition from “Stuff-Organizing” to “Self-Organizing,” depending on lessons learned. There are many previous studies on multi-robot system controls and communications, such as [19, 20], where multiple robots can also form different shapes or self-assemble [21]. Novel swarm communications were also possible as demonstrated in using varying degrees of light reflection as sensor input mechanism [22]. To create a true multi-robot system, additional hardware will be explored and added onto SORT, such as infrared for short range robot-robot communications. Localization is another important aspect to be further studied and implemented. To test, AprilTags can be used [23] where each SORT robot carries a unique tag, a camera can be mounted on the opposite wall to help localize SORT so that each robot will know the relative distance and direction of other robots within the group.

Two scenarios can be imagined where the self-organizing aspect of the robot group will be the most beneficial for functions that one robot cannot perform alone. As mentioned by some student participants, who wanted to use SORT for large items such as books, multiple mobile robots can team up to accomplish this task. Containers with different designs and sizes can be fabricated that fit specific item groups. When a user puts a book in a larger container, two SORT robots can move down the wall and station themselves at the right distance for the container to be snapped onto the magnetic connectors (Figure 5.2). Then the robots would need synchronized movements to carry the container up the wall.

Secondly, as shown in the vacuum prototype study, participants were intrigued by the various group formations of SORT and the subsequent message implied by the group shape. To create the envisioned robot group behavior, such as a wave pattern

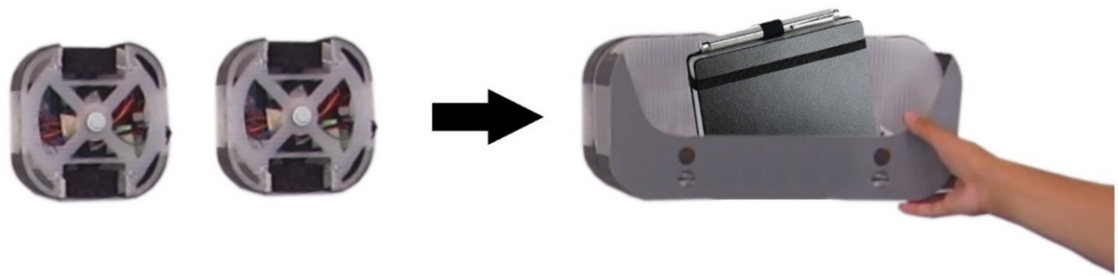

Figure 5.2, photo collage showing two SORT robots paired up to support a larger container with a notebook inside.

(Figure 5.3), users can first input a desired shape (user control), or SORT can initiate a group formation command as scheduled (programmed control) or in response to human activity (autonomous control). The robots will first be localized by the AprilTag system and camera, then a leader agent can be selected to move to an initial starting position followed by calling the next robots one by one to move to the correct position until the assembly is finished. Then the robots can move up and down gracefully to mimic the ocean wave motions, coupled by breathing blue lights. These group behaviors may provide the most valuable interaction experiences to users in providing assistance to address mental needs related functionalities, such as positive distraction and stress reduction.

Figure 5.3, photo collage showing nine SORT robots recreating the "ocean wave" pattern.

User Groups

One important lesson learned from the user studies is that participants' responses were very diverse. Older adults' reactions and concerns over SORT were very different than those from able-bodied college students. These differences span across both the functional and leisure interaction aspects of the robots. This revelation indicates that SORT's behaviors must be designed to fit the preferences of different user groups.

For older adults, based on the initial feedback (Table 5.1) on the vacuum-based prototypes, the participants found SORT to be the most useful in helping them gaining more independence, feeling more self-reliant and less overwhelmed. Three major concerns included a lack of open wall space, uncertainty in interaction modalities with the robots and issues with mobility impairment. The main preferred usage of SORT was related to care planning and medication management. As elderly users may already be experiencing health issues such as arthritis, poor eyesight, and hearing difficulties, which inhibit their abilities to interact with the robots physically, the most appropriate interaction modality is speculated to be voice command where the robots could be connected with other home devices such as Alexa in the future, and accompanied by frequent robot gesture as supportive feedback for command confirmation.

For the older adult user group, SORT could be the most useful when assisting in tasks that the users are slowly losing the abilities to perform. While this implies a high level of robot autonomy, older participants were also prone to feeling "out of control" when technology and the expected task pace are "out of sync". To compensate, a slower robot speed may be selected and multiple check points can be created where the robots can communicate with the user through gesture and non-verbal means to confirm user intention. The lack of wall space indicates limited domain and robot movement range, where the robots may take more pre-defined path and move less freely on the wall. This may be beneficial in allowing participants to better anticipate robot movements when delivering items.

Table 5.1: Summary of older adult participant's feedback and interaction speculation

Perceived Benefits of using SORT
• Gaining more independence. • Feeling more self-reliant. • Feeling less overwhelmed.
Concerns
• Open wall spaces for robots. • Calling the robots to the user. • Need for a "good hand" to use the system.
Preferred Use Scenarios
• As a calendar or care plan. • Serving as a medication manager and reminder.
Speculated Interaction Modalities
• Primary: Voice.

For healthy college students, based on the initial feedback (Table 5.2) on both the vacuum based and magnet-based prototypes, participants found SORT to be the most useful in non-critical item management situations for its convenience, where the system was described as time-saving and space-saving while providing pleasant gestural movements that were "cute". Compared to older adults, college students described SORT with more anthropomorphized terms, such as "penguin like" or "toddler like", implying that the robots may be perceived to play a different role at home that can be associated with companionship, where older adults may use them purely for functional purposes. A logical next study might focus on contrasting what makes non-humanoid robots to display human traits perceived by users of different age groups.

In addition, student participants in general perceived SORT as a secondary tool, performing non-urgent tasks where older adults may use the robots as medication reminder which is a more vital part of daily routine. As some student participants commented that they were more interested in watching the robots move on walls than to have them assist in organizing items, SORT's emergent behaviors as a multi-robot system should be further explored for young adult users.

Aesthetics is another important factor participants mentioned repeatedly. For young adult users, SORT needs to provide design options where users can select the color and appearance of the robots to better fit in their rooms. Through observation during user studies, participants intuitively interacted with the robots by issuing voice commands and a few also used gesture such as waving or nodding at the robots for attention and confirmation. For able-bodied young adults, a combination of interaction and feedback modalities should be implemented, including voice, gesture, light and sound.

While studies presented here did not include wheel-chair users, or those with other physical impairments, two participants who helped in reenacting use case scenario for video demonstrations were asked to perform the organizational tasks with SORT while remain seated in a wheelchair. Through observation and feedback, SORT was the most useful for them in providing functional delivery assistance since the robots could bring items to be within reaching distance. Objects placed at high shelves would be especially difficulty, if not impossible, for people in a wheelchair to reach. In both demonstrations, participants used more hand gestures to communicate with the robots, such as waving and pointing. Due to wheelchair users' limited mobility range, a remote controller or touch pad, coupled with gesture recognition and secondary voice command may be the most appropriate combination of interaction modality for those who still have intact upper body functions.

Table 5.2: Summary of college student participant's feedback and interaction speculation

Perceived Benefits of using SORT
• Convenience. • Pleasant movement and motion. • Time-saving and space-saving. • Relieve cognitive load.
Concerns
• Reaching distance. • Noise level. • Style personalization. • Items spilling and damage. • Limited container sizes. • Lack of trust.
Preferred Use Scenarios
• Interactive art. • Toy for pets. • Cooking assistant. • Large item display such as books.
Speculated Interaction Modalities
• Voice. • Gesture. • Light and sound feedback.

Based on the three targeted user populations above and the feedback from studies, SORT is expected to be the most successful in assisting high functioning adults in daily domestic item managements and providing pleasant non-critical leisure interactions for younger users. For those who suffer from pro-longed debilitating illnesses, such as Alzheimer's, and amputees, additional robotic assistants will be needed to work with SORT to provide the intended functionalities.

Toward An Integrated Suite of Domestic Assistive Robots

The research reported in this thesis, on developing and testing of the proposed SORT system serves only as the beginning of investigating how wall-climbing robots can provide viable domestic assistance. The robots alone have many limitations as mentioned earlier. To create a more robust system that can provide more versatile aid to users of various backgrounds throughout the day, robot-robot collaborations could be explored. The SORT robots first and foremost fulfil a functional need in item sorting, retrieval and delivery. Under the umbrella of domestic assistive technologies, however, there is a much larger question to be asked: ***<u>Can an assistive multi-robot group enhance domestic routines?</u>*** To answer this question, two example robot groups are proposed below, with each categorized based on the group composition and intended role within the home.

Robot Group Type 1: Lifestyle

In this case, SORT is imagined as a part of a larger domestic assistive suite (Fig 5.4), working in tandem with other robots being developed in our lab, in particular *home+* [24], which is a pair of robotic table and floor lamp with a continuum robot arm and grippers capable of picking up items from the floor and various surfaces, and delivering them to users. Together with existing vacuum robots like Roomba and voice command devices like Amazon Alexa, the "Lifestyle" suite can provide assistance related to cleaning and organizing.

The SORT and home+ systems can complement each other, expanding their operation domains while providing a more fluid item management service to users at home and in an independent living environment, especially those with mild cognitive or mobility impairments. In concept, the home+ table and the SORT robots would manage the floor space and the wall space respectively. The home+ Lamp equipped with a continuum arm and gripper, would serve as the intermediary agent between the two other robotic systems. In addition, by mounting a camera on the lamp arm, it could potentially help the SORT robots localize themselves on the wall. This robot-robot collaboration can enhance each system's capabilities and capacities to achieve

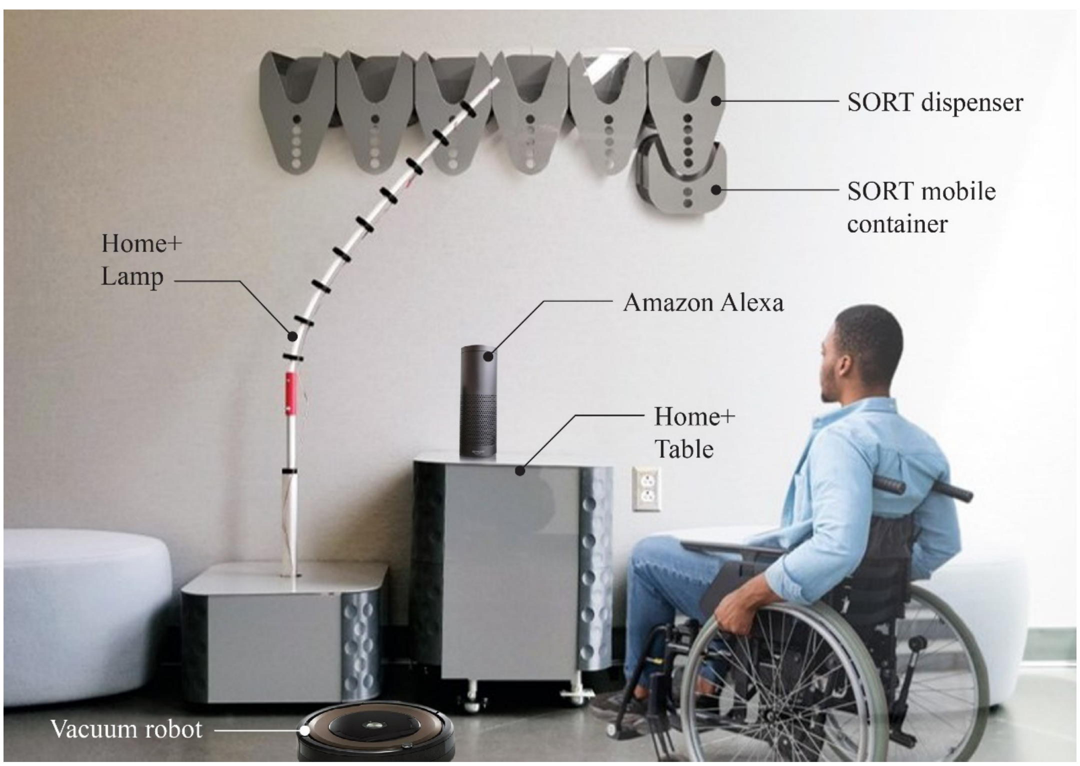

Figure 5.4, Photo collage illustrating the "Lifestyle" suite of robots consisting of SORT, home+, Vacuum (Roomba) and Alexa, ready to clean and organize the domestic environment for a wheelchair user.

functionality that each one would not be able to accomplish on its own. This would enable the exploration of the suite in providing non-functional goals such as artistic or mental wellness supports, and associated Human-Multi Robot interactions, which historically have been an under-studied areas within the larger domains of HCI and HRI.

To illustrate, two scenarios can be imagined with this new suite. 1) After finishing taking a pill, a user drops the medication bottle on the floor. The home+ table moves over to pick up the bottle with its inner jamming gripper and swings the item to the tabletop. The home+ lamp then comes to pick up the bottle and places it into a SORT robot container, which then proceeds to climb up the wall and drops the bottle into the SORT dispenser, ready for the next time use. 2) A user comes home after a long day of work and throws the wallet and keys on the table. With the assistive suite, the user never has to worry about misplacing important items. Later at night, the home+ Lamp picks up the wallet and keys and drops them into a SORT robot, which then moves to the entry door, waiting for the user to pick them up the next morning on the way out. With more robust SORT prototypes fabricated, these two scenarios can be created to understand human-multi robot interactions and the efficacy of the entire suite system.

Robot Group Type 2: Support

In addition to functional services, a suite of robots may also provide social or mental support to users, especially for people with special needs. As part of a larger architectural robotic system, the social support aspect has also been well established in allied design fields such as interior architecture [25]. As shown in this dissertation, participants were able to recognize the majority of the robot gestures and associated them with specific messages, showing promises of SORT in non-functional, leisure interaction scenarios.

Here, SORT is imagined in an assisted learning environment with other spatial artifacts developed in our lab (Fig 5.5), in particular, the LIT Room [26] and CyberPLAYce [27]. Together, they enhance and reinforce the learning process of school children during storytelling. To illustrate, a scenario can be imagined with this suite. In a reading and crafting event, a schoolteacher narrates a story to a group of elementary school students to help them finish a puzzle assignment (CyberPLAYce). During certain important events in the story, the LIT Room starts to move and illuminate according to the hints and cues in the story. As instructed, the students proceed to select puzzle pieces that need to be inserted into the CyberPLAYce robot, however they were not sure which shape to choose. After a while, the SORT group on the wall behind start to form a geometry of the correct puzzle shape, providing further hints corresponding to the story and the LIT Room's lighting effects. The movements and SORT formations caught

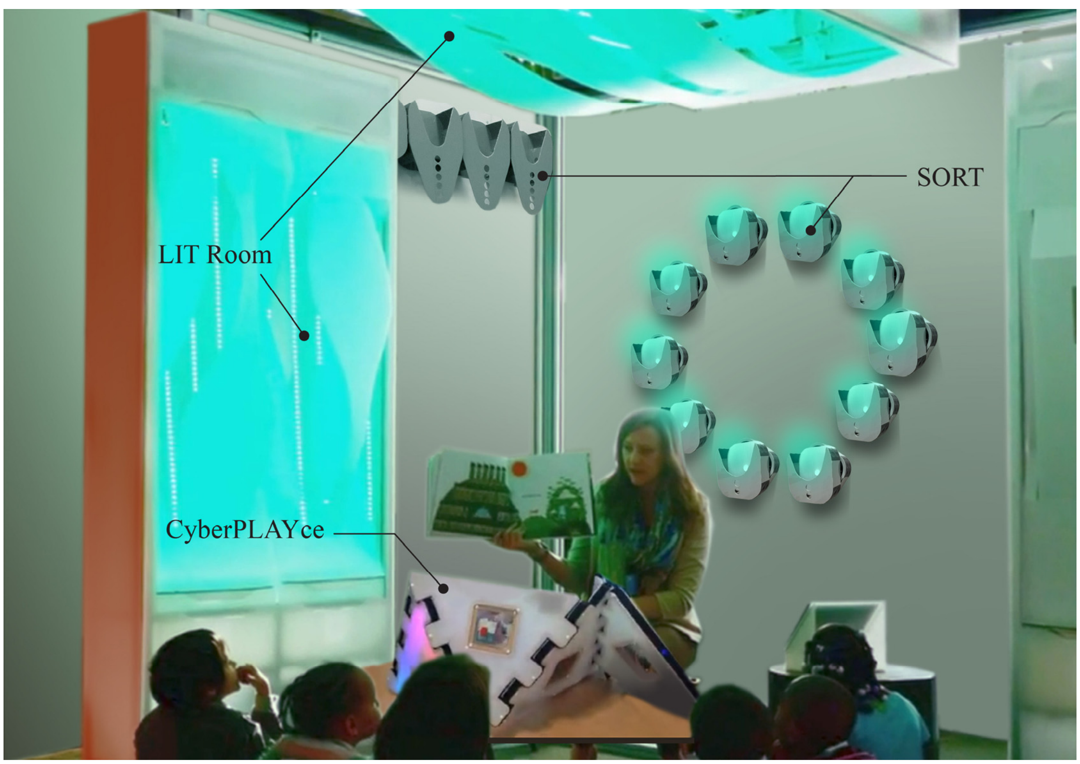

Figure 5.5, Photo collage illustrating the "Support" suite of robots consisting of SORT, LIT Room, and CyberPLAYce, ready to enhance and reinforce in story-telling and learning of school children.

students’ eyes whom then were able to successfully complete the assignment.

In closing, since assistive robots are becoming more ubiquitous and embedded in our everyday lives, forming an increasingly intricate and collaborative Internet of Things ecosystem, it is imperative that designers, engineers and researchers understand from a user’s perspective how the implementation of such assistive system may alter or shape our lives. As explained in this chapter and demonstrated throughout this dissertation, multi-robot groups, like SORT, can be helpful in augmenting and enhancing domestic routines to improve people’s life qualities, especially for populations in need such as older adults, where the population is “projected to reach 80.8 million by 2040 and 94.7 million by 2060” in the US alone [28]. Coupled with increasing shortage of care providers [29] and potentials in cost savings from homecare [30], we will see a rise of developments in assistive robotic suites being deployed to people’s homes. However, both within academia and in the real world, we have yet to witness a fully functional and verified multi-robot system, working seamlessly alongside users. To imagine such use case, we as design researchers must take a multi-disciplinary approach, considering previously under-studied areas such as human-multi robot interaction and cultural differences as design variables to ensure the holistic success of such system in the future.

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APPENDIX

Appendix A: Interactive Online Survey

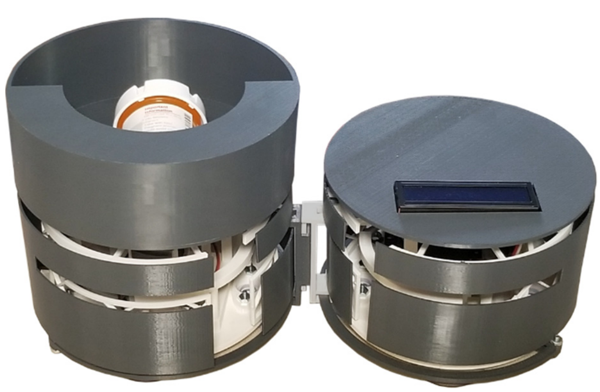
Survey Link:
https://cornell.ca1.qualtrics.com/jfe/form/SV_es44UCxe3ZYlkDc

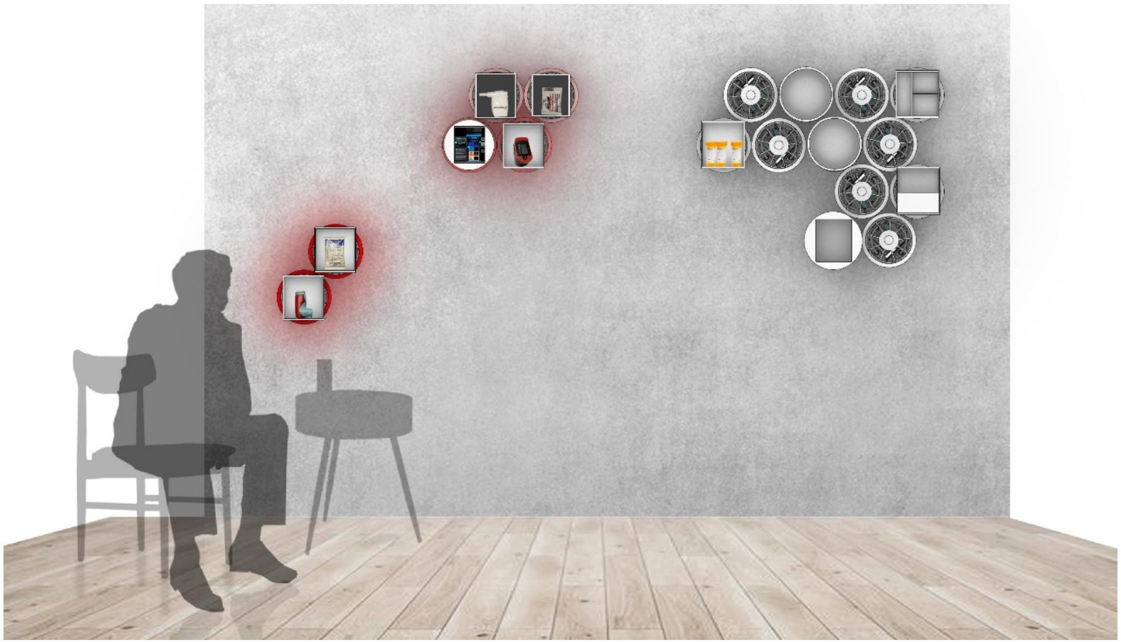
Background Questions:

	Background
1	What is your age?
2	What gender do you identify as?
	• Female • Male • Prefer not to say • Other
3	What is your nationality
4	If your country is not in the drop down menu above, please enter it below:
5	Have you lived in your home country for most of your life (>90%)?

Robot Introduction:

SORT (Stuff Organizing Robot Team) is a group of robots that can move on wall surfaces for home use. SORT may help organize household belonging, de-clutter personal space, serve as an alarm or reminder, and deliver items at scheduled times. An individual robot in the group is a "SORTbot" and the entire group of robots is "SORT". Each SORTbot is made of 2 connected cylindrical units 6" in diameter that use a suction system to adhere to walls.





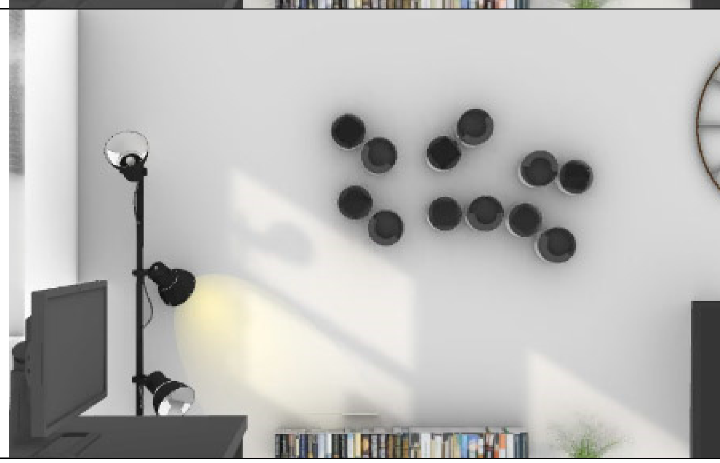
Video link:
https://cornell.ca1.qualtrics.com/CP/File.php?F=F_cCHsZoCeSCjEAbs

Self-Rated Understanding of SORT

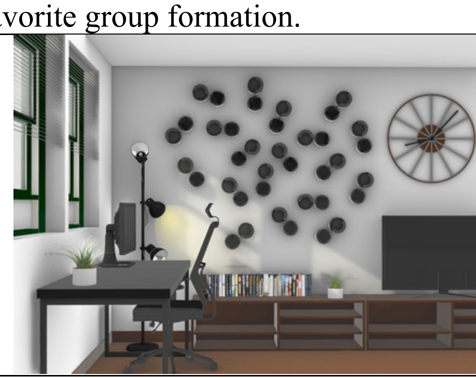
1	Based on the images and video you have seen so far, please rate how much you understand SORT's functionalities and intended uses.
	• I do not understand SORT at all. • I do not understand SORT for the most parts. • I have a moderate understanding of SORT. • I understand SORT for the most parts. • I understand SORT completely.

Group size

1	Imagine you are working at your desk and SORT is scheduled to deliver multiple items to you, please view each of the videos below and rate how much you like each one in terms of delivery method. • Dislike a great deal • Dislike a moderate amount • Dislike a little • Neither like nor dislike • Like a little • Like a moderate amount • Like a great deal

Group shape

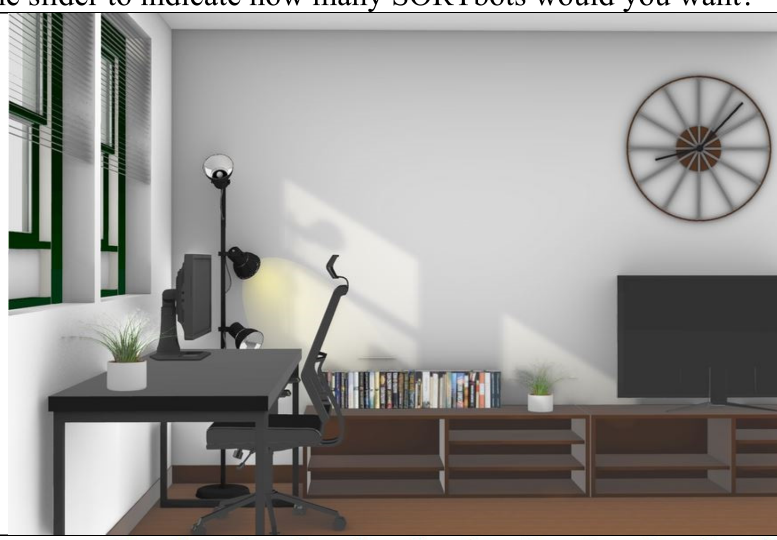
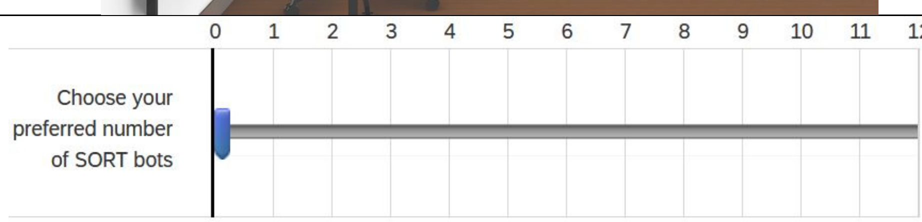
1	Imagine SORT can form various group shapes at resting states as shown below, please pick one that is your favorite group formation.
	 

Speed

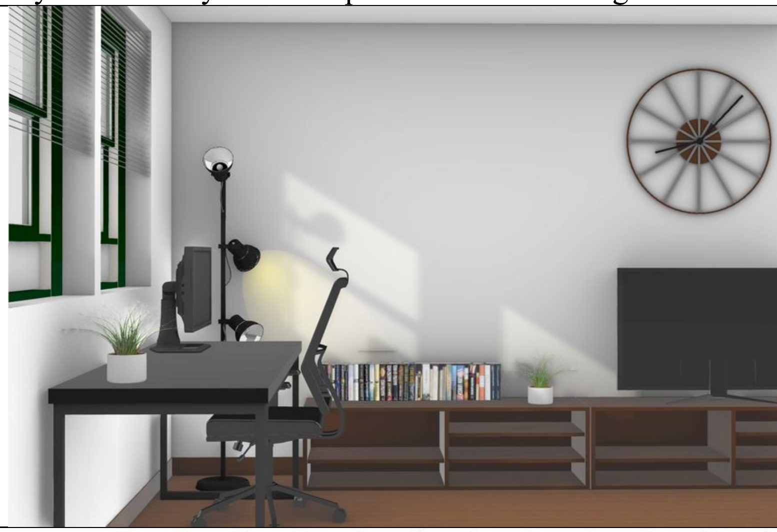
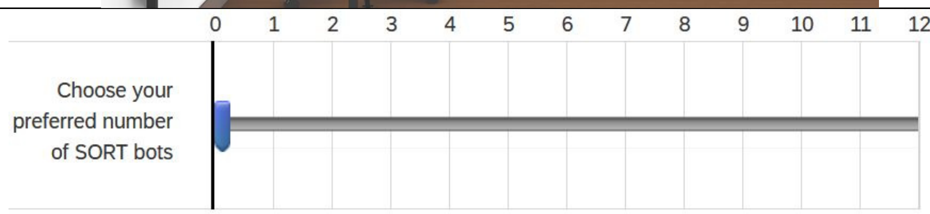
1	Imagine you can choose SORTbots' movement speeds, please drag the slider to indicate your preferred robot speed? (1-Slowest, 7-Fastest)

Robot Number

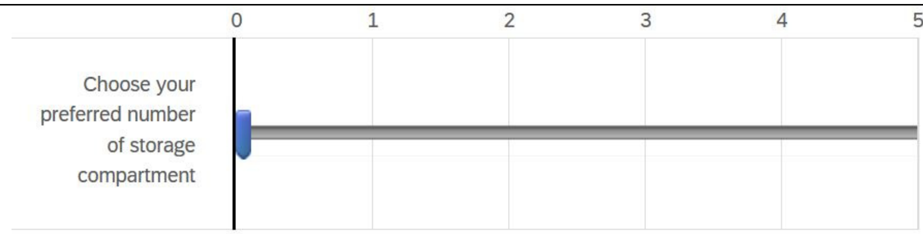
1	Imagine you can select the number of SORTbots to have in a room, please drag the slider to indicate how many SORTbots would you want?
	
	
	If you want more than 12 SORTbots, how many would you want? (Leave blank if not applicable)

Robot Number (Moving)

1	Imagine SORTbots can move all at once, please drag the slider to indicate how many SORTbots you would prefer to have moving at the same time?
	
	
	If you want more than 12 SORTbots to move at the same time, how many would you want? (Leave blank if not applicable)

Bin

1	Imagine you have a SORT system that also includes storage compartments to hold larger, heavier objects or several smaller objects. SORTbots are able to push these compartments along a rail to help organize and deliver the contents. How many of these storage compartments would you want?
	



Usefulness

	Based on your preferences selected in previous questions, please imagine using SORT at home and answer the following questions: • Strongly disagree • Disagree • Somewhat disagree • Neither agree nor disagree • Somewhat agree • Agree • Strongly agree
1	I think SORT will be useful to me.
2	It would be convenient for me to have SORT.
3	It's good to make use of the SORTbots.

Appendix B: Final In-Person Study Script

Participant arriving: "Good morning/ afternoon, welcome to our study on evaluating robotic organizers. For this study, you will be asked to organize some objects on this desk, are you comfortable picking up and touching these items? (wait for response) There is a hand sanitizer for your use, it is not part of the study. Please get yourself comfortable and I will briefly introduce the project.

Participant seated.

"As we spend more time indoors, especially during this pandemic lockdown, maintaining an organized lifestyle is an important daily routine that can help us . Often, we have too many small items lying around that are difficult to find when we need them, such as keys, wallets and pill bottles. We are developing a group of robotic organizers as you can see on the wall here, more about the robots in a few minutes.

"Before we begin the study, please use this laptop to review and sign the consent form, followed by 5 general background questions"

"Thank you for filling out those question. For the next part, you will be asked to carry out 4 tasks. Please imagine you are sitting in front of your desk at home or in your dorm room, where you typically do your homework. For the first task, please use the bins and the shelf on the wall to re-arrange and organize the items you see on the desk. You can do it just the same as if you were cleaning up your space at home"

Participant completes task. (answer question if needed)

"Could you briefly elaborate the logic behind how you organized the items?"

Take note of participant response.

Ask participant to take survey. "Please use the laptop to answer these questions based on your experience just now using the bins and shelf"

Participant finishes questions.

Researchers put all items back to the original positions.

“For the second task, it’s just repeating the first task, but now you can also use the robots on the wall. The robots can they can climb walls to help you organize, retrieve and deliver items throughout the day. We will refer to these robots now as SORT, which stands for self organizing robot team. Currently there are 4 mobile robots next to you, there are also 4 stationary container at the top of the wall. The mobile robots can take items that you do not use frequently, and move them into the containers. Do you have any questions regarding the robot?”. Please re-organize the items, you do not have to put all objects in the robot, if there are things you feel strongly that should be in the bins or left on the desk that is fine.”

Participant completes task. (answer question if needed)

Researcher operates the robots to move on the wall accordingly. For object that are not used frequently, the robot moves to the container at the top and release the item into the “bar”.

“Could you briefly elaborate the logic behind how you organized the items? Did anything change compared to the first task?”

Take note of participant response.

Ask participant to take survey. “Please use the laptop to answer these questions based on your experience just now using the robots”

Participant finishes questions.

Researcher puts the pill bottle to where it was in task 1.

“For the third task, there was a pill bottle that you put away from the first task. Imagine that you are at home recovering from a cold, and it is time to take a medication. Please go to the place where you stored the bottle, pretend that you are taking the medication, and then come back once you finish.”

Participant completes task. (answer question if needed)

Researcher puts the pill bottle to the bar container.

“For the final task, it’s also repeating the previous task, but now you saw the bottle is in one of the containers at the top, the robot can retrieve and deliver it to you. Please call the robot, using gesture, voice or any other ways you prefer, to get the pill bottle and pretend you are taking the pill. You can put it back into the robot once finished”

Participant calls robot. Researcher controls the bar to release bottle into robot, then operates the robot to deliver the medication.

Participant completes task. (answer question if needed)

Ask participant to take survey. “Please use the laptop to answer these questions based on your experiences through all the tasks. Once finished you will be prompted to call the researcher for the final robot demonstration, you may stop there.”

Participant finishes questions and calls researcher.

“For the final demonstration, please look at the robot on the wall, it will perform some gestures and please tell me after each one what you think the robot is trying to say.”

Researcher controls robot to perform three gestures: 1) quick jitter, 2) move up-down, 3) wave left to right, stop after each one and ask participant “what do you think the robot is trying say?”

Participant completes the feedback.

“For the next question, we would like to understand you preferences on robot speeds. I will demonstrate 5 different robot speeds, from 1 – the fastest to 5 – the slowest. I will also explain 3 different use scenarios. After each one please let me know your favorite speed mode, you can also pick in between speed numbers”.

“For the first scenario, imagine there is something you need urgently from the dispenser. You saw the item and would like the robot to bring it to you. Under this circumstance, how fast do you want the robot to move?” Research proceeds to control the robot to show the 5 speed modes, pause for participant to answer. “Now for the second scenario, imagine the robots are performing non-urgent tasks in the background. Maybe you just finished a writing assignment and put pens and pencils into the container and you may step away from the desk while the robots work on their own. Under this circumstance, how fast do you want the robot to move?” Researcher controls the robot to show the 5 speed modes, pause for participant to answer. “For the final scenario, the robots are performing non-functional tasks, perhaps it’s for leisure interactions, imagine you have these robots on the wall potentially as pets, altering the atmosphere of your room. Under this circumstance, how fast do you want the robot to move?” Researcher controls the robot to show the 5 speed modes, pause for participant to answer.

Participant competes the feedback.

“Thank you for the answers. Now I have just a few more open-ended questions. For the first question, between using the robots and the desktop bins, did you have to change your organizational logic?” If participants do not know how to answer, provide some suggestions such as “Did you have to group the items in one way for the robots, and in another way for the bin?” Wait for participants to answer, follow up if there are unclear or interesting points.

“For the next question, could you provide a hierarchy of your organizational logic?” If participants are unsure how to answer, give some suggestions such as “When organizing personal items, which would be more important for you to follow, organize by object types, categories, functions, or frequencies of use, or even shapes and colors?” Wait for participants to answer, follow up if there are unclear or interesting points.

“Now, could you provide a hierarchy of the reasons of why you would decide to organize your room?” If participants are unsure how to answer, give some suggestions such as “What might be some reasons that would drive you to decide ‘I have to get organized now!’ For example, you can not find things when you need them, or the clutter is causing too much stress.” Wait for participants to answer, follow up if there are unclear or interesting points. After participants responded, ask “would you say it’s more important to address mental need or physical need for organizing items?”

“Now, I would like to understand your preferences on SORT group size. The robots we used in today’s study is composed of 6 stationary dispensers at the top, and 4 mobile robots below, how do you like this arrangement? Would you want more or fewer numbers of each types of robot?”

“Besides the items you just organized in this study, could you think of any additional personal belongings at home that you would like to use SORT to manage?”

“Finally, do you have any final comments? Things you liked or disliked about the SORT robot, the concept or the design.”

“Thank you very much for participating, the study is now concluded. Please gather your belongings, I will grant the SONA credits afterward and please message me if there are any issues”

Appendix C: Final In-Person Survey Questions

Survey Links:

Background:

https://cornell.ca1.qualtrics.com/jfe/form/SV_3Ob7pw3x0faeSz4

Usability:

https://cornell.ca1.qualtrics.com/jfe/form/SV_8ekbLme2A2r19Q2

Perception of Control (after task 1):

https://cornell.ca1.qualtrics.com/jfe/form/SV_cSir2bT0nxjc3no

Perception of Control (after task 2):

https://cornell.ca1.qualtrics.com/jfe/form/SV_6sbZEFBF0d5pvCe

Background Questions:

	Background
1	Which gender do you identify as?
	• Male • Female • Non-binary / third gender • Prefer not to say
2	What kind of residence do you live in currently?
	• On campus single room • On campus shared room (>= 2 occupants) • Off campus single room (in a house or apartment) • Off campus shared room (>= 2 occupants, in a house or apartment) • Other
3	Do you use any robot assistant at home now? (like Roomba, Alexa)
	• Yes • No
4	Please rate how organized your personal room or space normally is on a scale of 1 to 5 (1 = very messy, 5 = very organized). - Room organization
	1 Very messy 2 Messy 3 Neutral 4 Organized 5 Very organized
5	How often do you clean up (organize) your personal space? - Clean up frequency

	• Once a few months or less • Once a month • Once a week • A few times a week • Every day or multiple times a day

Adapted System Usability Scale:

	Usability
Prompt	Based on your experience using the desk and shelf, and interacting with the robots for organizational tasks just now, please answer the following questions based on a scale of 1 (Strongly disagree) to 5 (Strongly agree). *Compared to conventional ways of organizing small personal items (by using desk and shelf):*
1	I think that I would like to use the SORT system to organize small personal items frequently.
2	I found the SORT system unnecessarily complex.
3	I thought SORT was easy to use compared to the shelf.
4	I think I would need the support of a technical person to be able to use the SORT system.
5	I found the various functions in the SORT system were well integrated.
6	I thought the SORT system did not consistently perform the organizational tasks I need.
7	I would imagine that most people would learn to use the SORT system very quickly.
8	I found the SORT system very cumbersome to use.
9	I felt very confident using the SORT system.
10	I needed to learn a lot of things before I could get going with the SORT system.

**Usability survey was distributed once after all organizational tasks were completed.*

Adapted NIOSH Perception of Control:

	Perception of Control
Prompt	Please answer the following questions based on how you have organized the items just now by using the bins / robots, on a scale of 1 (Strongly disagree) to 5 (Strongly agree). *(given after task 1): After using the desk and shelf for organizing items:* *(given after task 2): After using the SORT robots for organizing items:*
1	How much influence do you have over the variety of organizational tasks you perform?
2	How much influence do you have over the tool(s) you need to organize the items?
3	How much influence do you have over the order in which you perform the

	organizational tasks?
4	How much influence do you have over the amount of organizing you do?
5	How much influence do you have over the pace of the organizational tasks?
6	How much influence do you have over the arrangements of items?
7	How much influence do you have over the decisions as to when the organizing will be done?
8	How much influence do you have over the organizational tasks you perform in general?

**Perception of control survey was distributed twice throughout the study, once after participants completed task 1, and once after task 2.*

Appendix D: Final Survey Results

Please refer to Appendix C for question items.

Results for questions on background.

	Q1	Q2	Q3	Q4	Q5
P1	1	4	1	3	3
P2	2	4	1	4	3
P3	2	2	1	3	3
P4	1	3	0	5	5
P5	2	2	1	2	3
P6	1	3	1	4	4
P7	2	5	0	4	3
P8	1	2	0	4	3
P9	2	4	1	3	2
P10	2	3	1	4	4
P11	1	4	1	4	3
P12	1	3	1	2	3
P13	2	2	1	4	5
P14	2	3	1	4	4
P15	2	4	1	2	4
P16	2	3	0	3	5
P17	1	4	0	3	3
P18	2	2	1	2	5
P19	2	1	1	3	4
P20	2	3	1	4	4
P21	2	4	1	4	5
P22	2	4	1	2	4
P23	1	3	1	2	3
P24	2	3	1	4	5
P25	2	4	0	4	5
P26	2	1	0	2	3
P27	2	2	1	3	4
P28	1	4	1	4	4
P29	1	2	1	4	4
P30	2	1	1	4	4

Results for questions on perception of control after task 1.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
P1	4	3	4	4	3	4	4	4
P2	4	4	5	4	5	3	4	4

P3	4	5	4	2	2	5	3	4
P4	3	4	5	5	3	5	5	5
P5	5	4	5	5	5	5	4	5
P6	4	3	3	2	3	2	4	3
P7	5	2	5	5	5	5	2	5
P8	5	5	5	5	5	5	5	5
P9	4	4	5	5	5	4	5	5
P10	4	2	5	5	5	5	5	5
P11	4	2	3	5	4	2	4	3
P12	4	5	4	4	5	5	4	4
P13	3	2	5	4	5	4	5	4
P14	4	4	5	5	5	4	5	5
P15	3	2	3	4	3	4	3	3
P16	3	2	2	3	4	3	5	4
P17	4	3	2	3	4	4	3	3
P18	3	4	4	2	5	5	4	4
P19	3	2	3	3	4	3	5	5
P20	3	4	5	5	5	5	5	5
P21	4	2	4	4	2	4	2	4
P22	4	5	3	3	3	4	4	4
P23	1	5	3	2	5	3	4	4
P24	4	4	5	4	4	4	4	4
P25	5	5	4	5	4	5	5	4
P26	4	2	4	3	2	4	2	3
P27	3	2	3	3	4	3	4	3
P28	5	3	2	5	5	5	4	3
P29	3	2	5	3	4	2	3	3
P30	5	4	4	5	5	4	2	4

Results for questions on perception of control after task 2.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
P1	4	4	4	5	5	5	4	5
P2	4	4	5	5	5	3	4	3
P3	4	5	4	4	5	5	5	4
P4	3	3	5	5	5	3	4	5
P5	4	4	5	3	4	3	3	4
P6	4	3	5	5	5	4	4	4
P7	4	2	5	5	5	5	5	5
P8	4	4	5	3	2	4	2	4
P9	2	2	3	2	3	2	4	3
P10	4	4	5	5	3	5	5	5

P11	3	1	3	2	3	3	4	4
P12	3	4	4	3	5	2	5	5
P13	3	2	4	3	4	4	2	3
P14	3	3	4	4	2	5	5	4
P15	3	5	4	4	3	4	4	4
P16	5	4	3	5	5	5	4	4
P17	2	3	3	2	4	4	2	2
P18	4	4	5	3	2	4	4	4
P19	4	4	4	4	3	4	5	5
P20	3	3	5	4	5	4	4	4
P21	1	1	1	4	4	5	4	3
P22	2	1	3	2	3	4	2	2
P23	3	3	5	5	4	4	4	3
P24	4	3	5	4	3	5	4	4
P25	5	3	4	5	2	5	5	4
P26	4	2	4	2	4	4	3	4
P27	3	2	1	3	3	4	3	3
P28	3	5	3	5	4	5	3	5
P29	2	3	3	3	1	4	4	3
P30	3	4	5	2	4	5	2	3

Results for questions on usability.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
P1	4	3	4	4	4	3	5	2	4	4
P2	4	2	3	1	4	3	5	2	4	4
P3	4	3	3	2	3	3	5	3	2	3
P4	2	5	4	2	3	4	4	4	3	2
P5	4	3	4	1	5	2	3	3	4	3
P6	4	3	3	2	2	2	4	2	4	2
P7	4	1	5	1	4	2	5	1	5	1
P8	2	1	3	1	4	3	4	4	4	1
P9	2	4	2	2	3	4	4	3	3	3
P10	4	4	2	4	5	4	3	4	2	3
P11	3	4	3	2	4	4	4	2	3	2
P12	2	4	3	4	4	2	4	2	2	4
P13	5	2	5	2	4	4	4	2	5	1
P14	2	3	4	1	4	2	4	2	4	2
P15	4	2	4	2	3	2	4	2	4	2
P16	4	2	4	2	5	1	5	3	4	1
P17	4	3	4	1	4	2	4	2	4	1
P18	4	2	4	1	4	2	2	2	4	3

P19	5	2	4	1	4	3	4	1	4	1
P20	4	1	5	1	4	2	5	1	5	1
P21	4	2	2	1	4	2	4	4	3	2
P22	5	2	5	4	5	1	4	1	5	3
P23	5	2	4	3	4	2	5	1	4	1
P24	3	4	5	2	4	2	4	4	4	2
P25	4	3	5	2	4	2	5	4	4	4
P26	5	1	3	4	4	3	4	1	3	4
P27	4	3	4	1	4	3	4	3	4	2
P28	4	2	4	3	4	2	5	2	4	1
P29	2	4	5	1	3	3	5	2	4	1
P30	5	3	4	2	4	2	3	2	4	4

Appendix E: Code

```
#include <Wire.h>
#include <SoftwareSerial.h>
#include <Servo.h>
SoftwareSerial BTSerial(10, 11); //
Servo myservo1;
Servo myservo2;
Servo myservo3;
Servo myservo4;
String incomingValue;
char servoTest;
int R = 2;
int G = 7;
int B = 8;
int robotSpeed1;
int robotSpeed2;
int robotSpeed3;
int robotSpeed4;
void setup()
{
 Serial.begin(9600);
 BTSerial.begin(38400);
 Serial.setTimeout(10);
 BTSerial.setTimeout(10);
 Serial.println("Ready");
 myservo1.attach(3);
 myservo2.attach(5);
 myservo3.attach(6);
 myservo4.attach(9);
 pinMode(R, OUTPUT);
 pinMode(G, OUTPUT);
 pinMode(B, OUTPUT);
}

void loop()
{
 if (BTSerial.available() > 0)
 {
  incomingValue = BTSerial.readString();
  //Serial.println(incomingValue);
  servoTest = incomingValue[0];
  /*
   String value = incomingValue.substring(8, 10);
   //Serial.println(value);
   robotSpeed1 = value.toInt();
```

```
  robotSpeed2 = (92 - robotSpeed1) + 92;
  if (robotSpeed1 != 0) {
  robotSpeed3 = robotSpeed1;
  robotSpeed4 = robotSpeed2;
*/

if (servoTest == 'S')
{
  String servoS = incomingValue.substring(incomingValue.lastIndexOf('S') + 1);
  robotSpeed1 = 91 - servoS.toInt();
  robotSpeed2 = (91 - robotSpeed1) + 91;
  if (robotSpeed1 != 0) {
    robotSpeed3 = robotSpeed1;
    robotSpeed4 = robotSpeed2;
  }

}
/*
    if (servoTest == 'P')
    {
      lcd.clear();
      String line1 = incomingValue.substring(8, 24);
      String line2 = incomingValue.substring(24);
      lcd.setCursor(0, 0);
      lcd.print(line1);
      lcd.setCursor(0, 1);
      lcd.print(line2);
    }*/

if (incomingValue == "UpPressed")
{
  myservo1.write(robotSpeed4);
  myservo2.write(robotSpeed3);
  myservo3.write(robotSpeed4);
  myservo4.write(robotSpeed3);
}

else if (incomingValue == "DownPressed")
{
  myservo1.write(robotSpeed3);
  myservo2.write(robotSpeed4);
  myservo3.write(robotSpeed3);
  myservo4.write(robotSpeed4);

}
```

```
 else if (incomingValue == "LeftPressed")
 {
  myservo1.write(robotSpeed3);
  myservo2.write(robotSpeed3);
  myservo3.write(robotSpeed3);
  myservo4.write(robotSpeed3);
 }
 else if (incomingValue == "RightPressed")
 {
  myservo1.write(robotSpeed4);
  myservo2.write(robotSpeed4);
  myservo3.write(robotSpeed4);
  myservo4.write(robotSpeed4);
 }
 else if (incomingValue == "R")
 {
  digitalWrite(R, HIGH);
 }
 else if (incomingValue == "G")
 {
  digitalWrite(G, HIGH);
 }
 else if (incomingValue == "B")
 {
  digitalWrite(B, HIGH);
 }
 else if (incomingValue == "OFF")
 {
  digitalWrite(R, LOW);
  digitalWrite(G, LOW);
  digitalWrite(B, LOW);
 }
 else
 {
  Serial.println(" <Stop> ");
  myservo1.write(92);
  myservo2.write(92);
  myservo3.write(92);
  myservo4.write(92);
 }
}
```