Laser Pointers and a Touch Screen: Intuitive Interfaces for Autonomous Mobile Manipulation for the Motor Impaired

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ABSTRACT

El-E ("Ellie") is a prototype assistive robot designed to help people with severe motor impairments manipulate everyday objects. When given a 3D location, El-E can autonomously approach the location and pick up a nearby object. Based on interviews of patients with amyotrophic lateral sclerosis (ALS), we have developed and tested three distinct interfaces that enable a user to provide a 3D location to El-E and thereby select an object to be manipulated: an ear-mounted laser pointer, a hand-held laser pointer, and a touch screen interface. Within this paper, we present the results from a user study comparing these three user interfaces with a total of 134 trials involving eight patients with varying levels of impairment recruited from the Emory ALS Clinic. During this study, participants used the three interfaces to select everyday objects to be approached, grasped, and lifted off of the ground.

The three interfaces enabled motor impaired users to command a robot to pick up an object with a 94.8% success rate overall after less than 10 minutes of learning to use each interface. On average, users selected objects 69% more quickly with the laser pointer interfaces than with the touch screen interface. We also found substantial variation in user preference. With respect to the Revised ALS Functional Rating Scale (ALSFRS-R), users with greater upper-limb mobility tended to prefer the hand-held laser pointer, while those with less upper-limb mobility tended to prefer the ear-mounted laser pointer. Despite the extra efficiency of the laser pointer interfaces, three patients preferred the touch screen interface, which has unique potential for manipulating remote objects out of the user's line of sight. In summary, these results indicate that robots can enhance accessibility by supporting multiple interfaces. Furthermore, this work demonstrates that the communication of 3D locations during human-robot interaction can serve as a powerful abstraction barrier that supports distinct interfaces to assistive robots while using identical, underlying robotic functionality.

Categories and Subject Descriptors

K.4.2 [**Social Issues**]: Assistive technologies for persons with disabilities

General Terms

Performance, Design, Experimentation, Human Factors

1. INTRODUCTION

El-E is a mobile robot with a manipulator on a vertical lift that has been designed to assist people with motor impairments in basic object manipulation tasks such as fetching and carrying everyday objects [16]. In Figure 1, El-E is shown picking up a plastic medicine bottle from the floor during our study. The initial target population for El-E consists of individuals with amyotrophic lateral sclerosis (ALS, also known as Lou Gehrig's disease). ALS is a progressive neurological disease causing whole body weakness and loss of use of the arms and hands. Many ALS patients regard their loss of independence as a significant problem that negatively impacts their relationships with others and their emotional wellbeing. Object manipulation capabilities provided by robotic technologies has the potential to significantly enhance the quality of life for ALS patients and others with severe motor impairments.

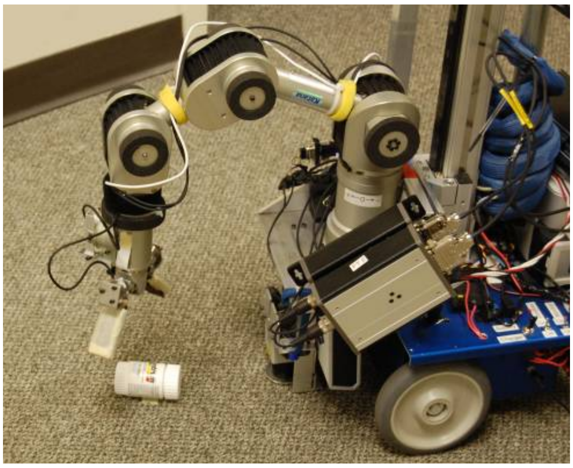

Figure 1. El-E picking up a selected object from the floor

For many forms of assistive object manipulation, such as object fetching, users will want to unambiguously select an object. In our previous work, we have shown that providing a 3D location to El-E, specified with respect to the robot's body, is sufficient to command El-E to perform a variety of tasks, such as moving to a location, picking up an object, delivering an object to a person, and placing an object on a table [16]. We have also shown that an off-the-shelf hand-held laser pointer can be used by ablebodied lab members (robotics experts) to select a 3D location and reliably command the robot.

In this paper, we present two new interfaces that we have developed based on our interviews with ALS patients, which make use of an ear-mounted laser pointer and a touch screen. We also evaluate and compare the efficacy of all three interfaces through a study involving eight patients recruited from the Emory ALS Clinic. In this first study with prospective users, seven ALS patients and a patient with primary lateral sclerosis (PLS) participated in a lab-based experiment with these three user interfaces: an ear-mounted laser pointer (EL), a touch screen graphical user interface (TS), and a hand-held laser pointer (HL). The participants were asked to direct the robot to pick up an object from the floor by selecting it with the interfaces, which involves illuminating the object with a green laser or touching the image of the object on the touch screen.

2. MOTIVATION

Most people take it for granted that they have the requisite physical capabilities to perform tasks of daily living, such as picking up and holding an object. However, these simple tasks, present significant and life-altering challenges for individuals with limited motor capabilities. A survey by the U.S. Census Bureau [19] reported that more than 24 million Americans (about 9.29% of people older than 5 years old) possess some form of physical disability that hinders basic physical activities such as walking, climbing stairs, and fetching objects. A variety of causes can lead to motor impairmens such as old age, injury, and neurological disease.

Amyotrophic lateral sclerosis (ALS), also known as Lou Gehrig's disease, is a severe and progressive neurological disease affecting the voluntary motor system. In comparison to injury-related motor impairments, ALS patients experience increasing motor impairment as time goes on. The disease severity and progressive nature of ALS prompted the choice of this population as the prospective users of an assistive robot. The assistance provided by the robot could improve these individuals' quality of life by mitigating some of the daily troubles and frustration caused by the loss of ability to perform basic motor tasks. In addition, the progressive and varied nature of ALS provides an opportunity to validate the usefulness and adaptability of the robot over a diverse array of physical impairment of varying severity.

One of the most significant problems that individuals with motor impairments experience is a loss of independence due to difficulty in performing daily tasks such as washing, eating, opening doors, and picking up objects. Individuals with motor impairments have consistently cited object retrieval from the floor and shelves as an important area for robotic help [17]. Assistance provided by human caregivers is limited by availability and expense both in care facilities and in the home. Family members are currently a major source of assistance for those with limited motor skills but family assistance requires that they be present for prolonged periods of time, limiting their freedom and creating potential challenges to familial and spousal relationships.

Due to the expense and difficulty of finding human assistance, as well as issues of independence and privacy, helper animals have been trained to aid individuals. For example, helper monkeys have been trained and then placed with motor impaired individuals through organizations such as Helping Hands [8]. Monkeys have high dexterity and are capable of performing various manipulation tasks that are helpful to humans with motor impairments. For example, a monkey can pick up and retrieve an object when directed by a quadriplegic with a mouth-operated laser pointer. This method of interaction has served as an inspiration for our laser pointer interface. Although highly trained animals can provide effective assistance, they come with a host of other complications, including high costs ($17000-$35000), extensive training (2-5 years), reliability issues, and their own need for care.

Robotic manipulation technology has also been developed and explored to meet the needs of people with motor impairments. Wheelchair-mounted robotic arms are one potential solution. For example, the Assistive Robotic Manipulator from Exact Dynamics (Manus), is a commercially-available, wheelchair-mounted robotic arm [12]. Individuals control the Manus using interfaces such as a joystick or keypad. The Manus lacks autonomous capabilities, so users must carefully control it throughout any activity. Moreover, it is designed to be mounted to a wheelchair, which limits the potential user population, and restricts the arm to performing tasks right next to the user. More recently researchers have sought to develop autonomous robots with manipulation capabilities, but these capabilities are still primitive and effective interface standards have yet to emerge [2, 6, 7, 11].

Although technical advancements in robotics have great potential for helping people with motor impairments, we believe that progress towards successful assistive robots will be best achieved by considering the human component of the system – the users with motor impairments – throughout the research process. In this vein, we initially conducted a user needs assessment study prior to the comparison user study in this paper. In the user needs assessment, we recruited 8 ALS participants from the Emory ALS Center, and asked them to take photographs and record life experiences when object manipulation was difficult or impossible for them. After about a week of documentation, we conducted final interviews in their homes. This study strongly influenced the interface designs and testing.

Compared to traditional human-computer interaction (HCI), human-robot interaction (HRI) is still a relatively young field of study. Yanco, Drury, and colleagues [20] have evaluated different implementations of HRI in a search and rescue mission contest. The robots usually performed in an autonomous way while the controllers remotely monitored their activities and gave high-level commands. This study focused on evaluating the graphical user interface (GUI) of the remote control devices, so HRI evaluation in this study was similar to evaluations in traditional HCI studies, in which GUI issues are investigated.

Hutternrauch and Eklundh reported a study involving the development of a service robot designed to help elderly people [9]. Unlike El-E, this robot only transports objects that are placed on it. It does not have manipulation capabilities. In contrast to our work which focuses on controlled lab-based experiments, this study involved long-term field testing of the developed prototype with human users. After a training period, the robot was put into the user's home environment without direct observation, although log files were collected. Our controlled study has enabled us to quantitatively compare the performance of three distinct user interfaces.

A recent study designed and evaluated different robot user interfaces to meet the needs of people with various impairments, including cognitive impairments, comparing a joystick and a touch screen interface to control a semi-autonomous wheelchair-mounted robotic arm [18]. In contrast to this work, our study focuses on motor impairments, uses an autonomous mobile robot manipulator, evaluates whether the robot successfully performs a relevant manipulation task (i.e., picking up an object) when commanded by a user, and tests two novel laser-pointer interfaces in addition to a touch screen user interface.

3. IMPLEMENTATION

3.1 The robot, El-E

Figure 2 shows the robot, El-E. The vertical lift, called the Zenither, moves the laser range finder, a camera, a Katana 5 DOF (degree of freedom) manipulator developed by Neuronics AG, and a 1 DOF gripper up and down. A mobile base, with two driven wheels and a passive caster, holds the above components. The head of the robot includes a visual system for the robot, containing two different types of camera systems. The hyperbolic mirror near the top of Figure 2 and a monochrome camera constitute an omnidirectional camera system. Due to the shape of the mirror, the camera has a comprehensive view of the local surroundings. This view includes an area that is horizontally 240 degrees (a small area is blocked by the Zenither) and vertically from the floor to the ceiling. This enables El-E to monitor most of a room from a vantage point similar to a human who is standing upright. Although this omnidirectional camera is useful to get an overview of the room, the resolution is limited and it only provides a monocular view. The robot uses a stereo camera system, mounted on a pan and tilt unit, to obtain detailed color images of the room and 3D estimates. When the robot detects a point of light from a laser pointer, it moves the stereo camera to look at the point. With its smaller viewing area, color images, and increased resolution, the stereo camera can obtain a high-fidelity image of the area of interest, which facilitates the computation of the point's 3D location.

To increase the reach of the manipulator in the vertical direction, we mounted the manipulator on a vertical lift. Currently, the gripper of the robot consists of a two finger apparatus equipped with force-torque sensors. A URG laser range finder with a 4 meter range is also mounted on the carriage that is moved up and down by the Zenither, which allows the laser range finder to scan across the surfaces of planes of various heights, such as the floor and tables.

During this study, when given a 3D location, the robot moves towards the location and uses its laser range finder to look for an object close to the 3D location. If it finds an object that is sufficiently close to the 3D location, it moves to the object, moves its gripper over the object, uses a camera in its gripper to visually segment the object, moves and rotates the gripper to align with the object, and then moves its gripper down to the object while monitoring the force-torque sensors in its gripper. Once it makes physical contact with the object it stops the gripper's descent and begins closing the gripper. In the event that it does not successfully grasp the object the first time, it will try again, up to four times.

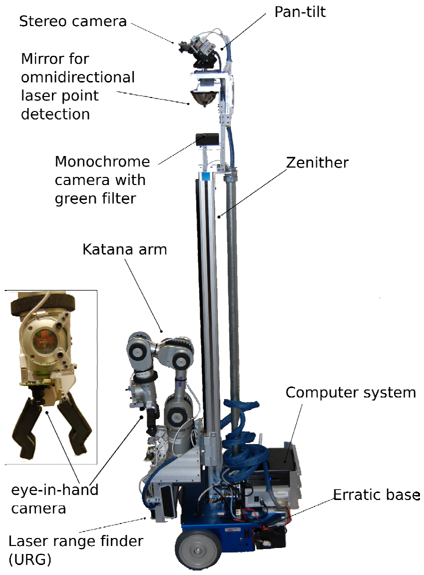

Figure 2. El-E and its components

We built the mobile base using the commercially-available Erratic mobile robot from Videre Design. It transports the other hardware components of the robot and is controlled by an on-board computer with a wireless link. It can move with a maximum speed of 2.0 m/sec. El-E's on board computer is a Mac-Mini with the Ubuntu Linux operating system. We wrote the control and vision processing software for the robot mainly in Python with some C/C++. The Mac-Mini performs all computation for the robot's autonomous operation.

3.2 3D Location as an Abstraction Barrier

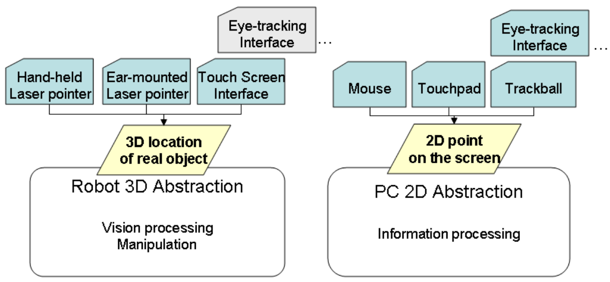

Figure 3. 3D and 2D abstraction layers

A key aspect of this study is that although each of the three interfaces provides a 3D location to the robot using a distinct method, the robot operates in exactly the same way once the 3D location has been provided. The 3D location serves as an abstraction barrier or communication protocol between various human interfaces and the robot's autonomous capabilities, see Figure 3. As such, when designing a new interface, one only needs to ensure that the interface will provide the robot with a 3D location with respect to the robot's body with sufficiently low spatial error. This separation of concerns can simplify the development of new interfaces by enabling the interface designer to focus on the interface as opposed to the robot. As our study shows, this can be especially important for meeting the varied needs of the motor impaired, since a single interface is unlikely to be preferred by all. Our study also validates that this abstraction barrier works, since the robot runs the exact same code once a 3D location has been provided by one of the three interfaces. It's worth noting that this architecture is similar to the point-and-click model of interaction used with personal computers (PCs). Most 2D windowing systems found on modern PCs are agnostic about the specific interface used to provide a 2D location. This has facilitated the development of a diverse array of interfaces for PCs, including track balls, optical mice, and eye tracking devices, and has undoubtedly helped to make PCs accessible. We expect a similar architecture to have a comparable beneficial impact on robotics.

3.3 Hand-Held Laser Pointer

The hand-held laser pointer is a standard off-the-shelf laser pointer with a green laser that is commonly used for slide presentations. Although a hand-held laser pointer provides an easy and intuitive method to unambiguously point to a real world object within the three dimensional world, handling it requires strength and dexterity of the upper-limbs. As shown in Figure 4, a participant with limited hand dexterity uses both hands to point the pointer and press its button.

Figure 4. A hand-held laser pointer being held by a participant

The hand-held and ear-mounted laser pointer interfaces use a point-and-click style of interaction analogous to the interaction style used in common graphical user interfaces (GUIs). This interface enables the user to point to an object in the three dimensional world with a conventional laser pointer, similar to the use of a mouse pointer on the two dimensional screen of a PC interface.

When a user turns on the laser pointer and orients it toward a specific object, the laser light emitted from the laser pointer is reflected off the surface of the object. When the user points to an object and illuminates it with the laser pointer for a few seconds, it is recognized as a "click" command. The cameras on the robot produce images of the scene, and the robot analyzes them with vision processing algorithms. Because the laser light has a well-defined frequeny band (color), a characteristic shape, and predictable motion, the robot can readily detect the illuminated location. To enhance the detection of the laser spot with the omnidirectional camera and to effectively increase the sensitivity, the robot uses a narrow-band green filter matched to the specific frequency range of the laser pointer. After detecting the spot the robot looks at it and estimates its 3D location using the stereo camera.

3.4 Ear-Mounted Laser Pointer

Figure 5. Ear-mounted laser pointer and a wired button

We designed the ear-mounted laser pointer to appeal to users with limited upper-limb mobility. We connected a green laser diode, which emits light, to a control unit consisting of 2 AAA batteries and a push button, as shown in Figure 5. Separating the battery and button from the laser diode helps reduce the weight of the ear-mounted component, which is based on an off-the-shelf ear-hook style Bluetooth headset shown in Figure 6. We expect the ear-hook design to be less obtrusive than alternatives, such as a hat, a hair band, or a headphone. The control unit was designed to be attachable to surfaces such as the arm rest of chairs or wheelchairs.

Figure 6. Ear-mounted laser pointer worn by a participant

3.5 Touch Screen Interface

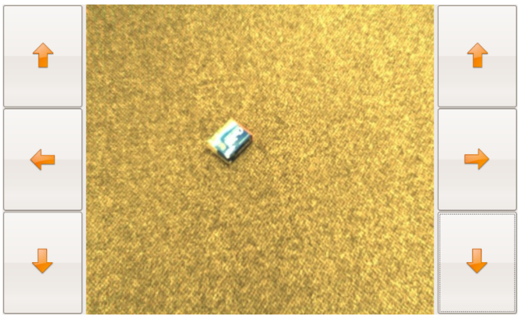

Figure 7. GUI of TS interface

We implemented the touch screen (TS) GUI on a computer separate from the robot and located close to the user. The hardware consisted of an Aopen miniPC with an Intel Core 2 Duo processor running Ubuntu Linux and a 7" Xenarc 700TSV touch screen monitor. We wrote the software for the interface in Python using pygtk and pyro (Python remote objects). The GUI, shown in Figure 7, has a large area in its center that displays images from the robot's right stereo camera. On the left and right side of the image, we included large arrow buttons to enable the user to look around the room by panning and tilting the stereo camera.

When using the interface, the user first orients the view of the camera toward the object of interest by pressing the arrows. Next, the user selects the object by touching the image of the object in the display area of the screen. The robot uses this selection to compute a 3D estimate of the object's location. The 3D estimate is then used by the robot in the same manner as the 3D estimate from the laser pointer interfaces.

In order to estimate the 3D location associated with the user's selection, the robot must have corresponding points in both the left and right camera images. The point in the right camera image is provided by the location of the user's touch on the screen when selecting the object. To determine the corresponding point in the left image, we take a 10x10 patch from the right image centered on the user's selection and search for a match in the left camera image. We limit the search to a region near the epipolar line generated in the left image by the selected point in the right image [5]. By searching in this region, we identify a maximally similar location in the left image to the user's selection in the right image. Within our study, this pair of image coordinates has been sufficient to compute a 3D estimate that successfully commands the robot to pick up an object with comparable spatial errors to the laser pointer interfaces. In experiments, the participants put the touch screen display on their laps and used the interface with both hands, as shown in Figure 8.

Figure 8. The touch screen interface being used by a participant

4. METHODS

4.1 Participants

Eight participants took part in this study and their demographic profiles are listed in Table 1. Seven individuals were diagnosed with ALS, while one was diagnosed with primary lateral sclerosis (PLS) which is different from ALS but also causes severe motor impairments and can be categorized within the same family as ALS. Five subjects had participated in the user needs assessment study and three others were newly recruited. All participants received diagnosis or treatment from the Emory ALS Center and were recruited via the Emory ALS Clinic and telephone calls. Participants had considerable variety in the extent of their impairments from slight difficulty in walking to a serious lack of limb mobility leaving only slight motion in a single hand. The subjects volunteered to come to the Healthcare Robotics Lab at the Georgia Institute of Technology campus and participated in a 2 hour experiment.

Table 1. Demographic information

Gender	Male (6), Female (2)
Ethnicity	White (6), African American (2)
Age	53.13 years on average (35 to 67)
Education	17 years on average
Diagnosis	25.63 months ago on average 15 months ago on average for 7 ALS patients

4.2 Experiments

4.2.1 Experimental Setting

Figure 9 gives an overview of the experimental setting. A patient sat on a wheelchair or a chair beside the robot's initial position similar to the position of the chair shown in the figure. We chose this relative positioning of the robot and the user to emulate the use of a service dog. In this sense, one can think of the robot as a companion robot that stays by the side of the user.

For this study, all objects were placed in one of two positions, as shown in Figure 9. From the user's perspective, and in Figure 9, position A is on the left and position B is on the right. The two positions were selected to represent different directions and distances from the robot. When placed in these two positions the objects were in plain sight of both the robot and the participant. Table 2 shows the 3D locations in meters relative to the robot's body in its initial location. The Z location is 0 meters for each object because the objects were sitting on the floor. We use these known 3D locations when evaluating the performance of the interfaces, as described in detail later in this section.

Table 2. Object locations in meters

Position ID	X	Y	Z	Distance
A	1.965	0.195	0	1.975
B	1.54	-0.57	0	1.642

Figure 9. Overview of the experimental setting

To validate the performance of the robot with objects with different shapes, weight, and colors, we used three everyday health-related objects for the experiment; 1) a cordless phone, 2) a paper medicine box, and 3) a plastic medicine bottle, as shown in Figure 10.

Figure 10. Objects; a cordless phone, a paper medicine box, and a plastic medicine bottle

4.2.2 Experimental Procedures

For this study we used within-subject design. All users conducted tasks with all conditions. The order of two factors, interface type and object type, was randomized to minimize order effect and for counterbalancing. We used the following procedure to conduct the experiment with each participant

1) First-time participants read and signed consent forms and all participants responded to background surveys related to computer experiences and difficulty in upper-limb and neck mobility.
2) For the first interface type randomly chosen from EL (ear-mounted laser pointer), TS (touch screen), and HL (hand-held laser pointer), the participant was instructed on how to use the interface and practiced its use until he/she indicated comfort and confidence (less than 10 minutes in all cases).
3) For each of the three object types (presented in randomized order), the participant conducted two trials, one for each position (A&B). This resulted in a total of 6 trials for each interface type. For each trial, the participant was asked to select an object for the robot to pick up. After this selection, the robot autonomously moved to the object, grasped it, and lifted it off of the floor.
4) We conducted a satisfaction survey to record the user's experience with the interface.
5) We repeated procedures 2 through 4 for the other two interface types.
6) The participants answered final post-task interview questions.

We designed the experiment to last less than 2 hours to prevent fatigue. On average, the experiments lasted approximately 1.5 hours.

Within a week of this experiment, a nurse in the Emory ALS Center conducted an assessment of the extent of ALS disease progress for each patient using the ALSFRS-R (The revised ALS functional rating scale). This survey instrument assesses the physical condition of a patient with 13 assessment items scored from 0 (most severe impairment) to 4 (normal condition, without any impairment) [3]. ALSFRS-R has proven effective in predicting the survival time of patients [10].

4.2.3 Quantitative Performance Measures

Time to completion is a primary measure of assessing the performance of human-machine systems [1]. In the experiment, we divided the total time to completion into:

1) Selection time: The time elapsed between when the user started to use the interface by notifying the experimenter (e.g., saying a word "OK" or nodding, for a participant who had difficulty in speech) to when the robot detected the target's 3D position.
2) Movement time: The time from selection to when the robot approached the target and fixed its position, prior to grasping.
3) Grasping time: The time from when the robot finished navigating to the object to when the robot finished the task of picking up the object.

Out of these three decompositions, we expected the selection time to be the most relevant measure to detect differences among the three different user interfaces. We expected movement time to be highly correlated with the position of the objects and the grasping time to be dependent on the object types.

We used the Euclidian distance between the hand-measured location of the object and the 3D location estimated by the robot as a measure of accuracy for pointing tasks with the three interfaces. Larger distances indicate greater error in pointing accuracy. Although we used two different positions for the objects, we did not consider the object's position as a factor in the analysis for this study.

4.2.4 Qualitative Measures

HCI researchers often conduct satisfaction questionnaires after experimental trials to measure the user's satisfaction with a computer interface and this method has proven effective in long term user studies [4]. Because the purpose of this study is to evaluate the user interface for directing the robot, we used an existing satisfaction questionnaire developed for evaluating computer systems [13-15] to derive a questionnaire with 8 items. We asked the following questions to qualitatively measure participant satisfaction:

- I could effectively use the system to accomplish the given tasks.
- I am satisfied with the time between when I gave command and when the robot detected the object.
- I am satisfied with the total time between when I gave command and when the robot finally picked up the object.
- It was easy to find an object with the interface
- It was easy to point an object with the interface.
- It was easy to learn to use the system.
- It was not physically burdensome to use the system.
- Overall, I was satisfied to use the system.

The participants were asked to answer on a 7 point Likert scale from strongly disagree (-3) to strongly agree (3).

5. RESULTS

5.1 Quantitative Performance Measures

We conducted a total of 134 trials. 6 participants performed 18 trials and used all three interfaces. One participant could only perform 12 trials with EL and TS due to weak upper-limb mobility. The remaining participant performed 12 trials with TS and EL but only 2 trials for HL. In 127 out of 134 trials (94.8%), the robot successfully picked up the object. The seven failed trials involved all three interfaces; 2 for EL, 3 for TS, and 2 for HL, and 6 out of 7 were from one participant. In Table 3, we list the averages and standard deviations of quantitative performance measures based on the interface type.

Table 3. Averages (standard deviation) of quantitative measures by interface type

	Selection seconds	Move seconds	Grasp seconds	Total seconds	Pointing Error meters
EL	4.80 (3.80)	24.51 (4.11)	148.01 (64.20)	176.76 (65.89)	0.25 (0.27)
TS	17.16 (29.31)	28.94 (31.45)	144.72 (50.12)	187.46 (56.71)	0.30 (0.85)
HL	5.27 (3.59)	24.46 (4.22)	134.79 (32.87)	159.55 (43.52)	0.22 (0.27)

Table 4. ANOVA table of the selection time

	Df	Mean Square	F	Sig.
Between Groups	2.00	2138.32	7.023	0.001
Within Groups	125.00	304.49		
Total	127.00			

As anticipated, the most apparent difference between the performance of the interfaces was the selection time. The TS interface took considerably longer to select objects compared to the EL and HL interfaces. Based on the results from the analysis of variance (ANOVA) test, the only statistically significant difference was found in the selection time (see Table 4). After the one-way ANOVA, we conducted Tukey's post-hoc tests to find the significant differences between selection times of the interface types. The results showed that there was a significant difference between selection times of EL and TS, and between selection times of HL and TS. On average, the laser pointer interfaces (HL and EL) were 69% faster (see the first column of Table 3) than the touch screen interface (TS).

Improving the design of the touch screen interface could potentially reduce this selection time. However, we believe a difference between selection time for the laser pointers and the touch screen would persist. The TS interface requires that the user first make the desired object visible on the touch screen at a high enough resolution to touch it. For our current implementation, this requires the user to move the robot's stereo camera around with arrow buttons until the object is in view. During this operation, most users first located the object using his or her own eyes and then moved the robot's cameras accordingly. Even with changes to this process, such as integrating an omnidirectional camera view with the touch screen, we expect humans to find a nearby object more efficiently by looking for it in the real world.. Moreover, if the person is already involved in a real-world task involving nearby objects, using the touch screen could require the user to momentarily shift perspectives, which could reduce efficiency further. As we have previously mentioned, these advantages disappear if the object is out of the line-of-sight of the user and the robot, in which case the laser pointer interfaces would be ineffective. In this case, a touch screen does have distinct advantages.

As expected, the movement and grasp time did not vary significantly with the interface types. As a measure of the error in pointing, we calculated the distance between the object's location and the selected location. The average pointing error with HL and EL was smaller than with TS, although the difference was not statistically significant. The variance of the pointing error was much greater with TS.

5.2 Qualitative Responses

The total scores for the satisfaction survey for each interface were; 50.86 for EL, 49.71 for TS, 47 for HL with a maximum value of 56. Across the user population, there were no apparent differences between the average satisfactions for the interface types, with all being well accepted by the participants. In the final interviews, participants were asked which laser pointer was more comfortable and which interface, including TS, they preferred to use. The laser pointer interface that users described as more comfortable was highly related to their upper-limb mobility. Among the 13 items of ALSFRS-R scores, Handwriting, Dressing & Hygiene is more related to upper-limb ability than other items. The total ALSFRS-R score includes other general health and respiratory assessment attributes which are important but are not directly related to the strength and dexterity of the hands and arms. As shown in Table 5, all participants with higher Handwriting scores (e.g., greater than or equal to three) answered that HL was more comfortable than EL. Combined with Dressing & Hygiene, it is clear that EL is more comfortable to participants with limited upper-limb mobility. However, three participants preferred to use TS regardless of which laser pointer interface was more comfortable, despite the fact that TS required longer selection times than the laser pointers.

Table 5. Interface preferences and ALSFRS-R scores

	P1	P2	P3	P4	P5	P6	P7	P8
Comfortable (HL vs. EL)	HL	EL	EL	HL	EL	EL	HL	HL
Prefer to use (HL vs. EL vs. TS)	HL	EL	EL	HL	TS	TS	HL	TS
Handwriting	3	0	0	4	2	1	3	3
Dressing & Hygiene	2	0	0	2	1	1	3	1
Total ALSFRS-R	37	18	27	30	25	19	39	16

In the post-task interviews, we learned the reasons why participants preferred one specific interface to the others. HL was preferred because it was easier and quicker. EL was preferred because it made a participant feel more in control and did not require upper-limb strength and/or fine motor skills. One participant said that TS was more functional and more accurate.

Each interface design could be improved. HL was heavy and the button was difficult to press and hold for some participants. One participant noted that the button of EL was difficult to press and a larger button would be preferred. Participants suggested using a trackball or joystick to control TS or rearranging the buttons to make it more easily controllable during one-handed use. These suggestions will be valuable in improving the user interfaces.

Overall, EL had wider applicability because all participants could effectively move their head to use it while many participants experienced difficulty in holding HL. One participant used both hands and both legs to support HL during the experiment. Even though HL had slightly longer selection time, some participants preferred HL to EL.

6. CONCLUSION

This work represents an initial study in an important area of assistive technology. Future research could build on this work in a number of ways, including the use of larger populations, more diverse environments with clutter, and greater numbers of objects with more varied placement.

In our interviews of ALS patients in the needs assessment conducted prior to the present study, participants stated that they frequently dropped objects and had considerable difficulty in retrieving them without help from their caregivers. Our experimental results demonstrate El-E's usefulness for acquiring objects to meet the needs of prospective users. All three interfaces were effective in the object manipulation task with an overall success rate of 94.8%. Even though no participant had previous experiences with robots like El-E, all of participants were able to use the robot with any of the three interfaces in less than 10 minutes, which implies that the robot was easy to use for the prospective users.

Although we found a significant difference in selection time between laser pointers and the touch screen interface, all the three interfaces were well accepted by the prospective users. Through the satisfaction questionnaire and post-task interviews, participants consistently expressed satisfaction in their experiences with the robot using all three interfaces. Specifically, the ear-mounted laser pointer was identified as the more comfortable laser pointer interface for those patients with limited strength and dexterity of upper-limbs. Among the eight participants, EL, HL, and TS were preferred by two, three, and three participants respectively. This suggests that different individuals will benefit from different user interfaces to assistive robots; as one participant mentioned, a "one-size-fits-all solution does not work."

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