

# A Robot Goes to Rehab: A Novel Gamified System for Stroke Rehabilitation using a Socially Assistive Robot: Methodology & Feasibility Testing

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## Methodology

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# Abstract

**Background:** Socially assistive robots (SARs) have been proposed as a tool to help individuals who have had a stroke to perform their exercise during their rehabilitation process.

**Methods:** Here, we describe a robot-based gamified exercise platform, which we developed for long-term post-stroke rehabilitation. The platform uses the humanoid robot Pepper, and also has a computer-based configuration (with no robot). It includes seven gamified sets of exercises, which are based on functional tasks from the everyday life of the patients, such as reaching to a cup, or turning a key in a lock. The platform gives the patients instructions, as well as feedback on their performance, and can track their performance over time. We performed a long-term patient-usability study, where 14 stroke patients exercised with this platform (in either the robot or the computer configuration) over a 5-week period, 3 times per week, for a total of 210 sessions.

**Results:** The stroke patients reported that this rehabilitation platform addressed their arm rehabilitation needs, and they expressed their desire to continue training with the platform even after the study ended.

**Conclusions:** These results are especially encouraging during the COVID-19 pandemic, when the requirement to reduce physical contact and keep a social distance accentuates the need for alternative rehabilitative tools, such as SARs, to enable patients to have an uninterrupted (even if modified) rehabilitation regime.

**Trial Registration:** This trial is registered in the NIH ClinicalTrials.gov database. Registration number NCT03651063, registration date 21.08.2018. <https://clinicaltrials.gov/ct2/show/NCT03651063>

## 1. Background

Retraining coordination of reach-to-grasp movements is one of the major functional goals of rehabilitation after stroke (1), as it is the basis of a substantial number of daily activities, such as reaching to pick up a cup for drinking (2). Intensive, repetitive task-specific training (3–5), over multiple sessions, can improve arm function post stroke (1, 6). However, intensive practice, which requires a large number of repetitions, is challenging both for the patient and for the therapist (4, 6), for a variety of reasons, including the limited time in the individual therapy sessions dedicated to both acquiring and practicing new abilities, the fatigue of the patient (7, 8) and the lack of motivation of the individual with stroke to keep on training alone (9). Therefore, it is imperative to devise feasible, alternative methods for long-term rehabilitation (4), which do not depend solely on the availability of the therapist, to be used both in the rehabilitation center and in patients' homes (10). These methods need to promote and motivate patients to practice their exercise, in order to improve the function of the impaired arm (4). In order for the patient to repeat a certain task many times, they have to be highly motivated and engaged (5). One of the ways to enhance motivation and engagement is to gamify the task; In the context of rehabilitation, this would translate to gamifying the repetitive exercise. Gamification has been demonstrated to increase patient motivation, learning, confidence, and positivity through achievement

and social interaction (11). Competitive and cooperative gamified tasks have been shown to increase motivation and exercise intensity of stroke patients when playing with another patient (12) or when playing with a healthy individual as a partner (9). These suggest that the presence of a partner and of competition increases motivation and engagement. This can be achieved, for example, using competitive elements (such as a score) on a computer screen, or by using interactive robots, which may take on the role of a competition partner, or a coach. Socially Assistive Robots (SARs) have been designed for this purpose (13–21).

Previous works (13–16), on short-term interactions with an SAR, suggest that incorporating SARs into a practice regime that calls for repetitive tasks can increase stroke patients' motivation. In previous works, patients were asked to do tasks such as magazine stacking (16), button pressing (15) or to imitate movements made by the robot (16) while receiving feedback from an SAR in a one-session interaction. These foundational studies demonstrated the feasibility of such an interaction with stroke patients. However, it is not yet known whether stroke patients' motivation will be maintained during a *long-term* interaction with the SAR, and whether it can lead to an improvement in their *functional* ability – that is, their ability to perform everyday tasks with their impaired arm, such as reaching to pick up a cup and drink from it.

Our goals in the current work were therefore: (1) to build a platform for functional post-stroke rehabilitation, which can track the performance of patients over time; More specifically, we aimed to build two implementations of this platform, in which the instructions and the feedback to the patient are given either by a socially assistive robot or by a computer screen; (2) to conduct a usability study with stroke patients, who will undergo a long-term intervention in the clinic with these two implementations of the platform and (3) to measure the patients' willingness to exercise with the platform *following* a long-term intervention with it (15 exercise sessions conducted over 5 weeks).

## 2. Methods

### 2.1 Preliminary work

We developed the first pilot version of the platform, which we describe in detail below, and tested it in a series of studies with young and older healthy adults (18). Our aims in that work were: (1) to test the effects of age on preferences when interacting with an SAR; (2) to test the differences in motivation of users to interact with a computer interface, compared to with an SAR; and (3) to adopt the platform according to the input we received from healthy adults. Following these studies, and prior to introducing the platform to stroke patients, we conducted a focus-groups study with expert clinicians who work with stroke patients in their everyday practice (19, 20). Based on their recommendations, which are detailed in (19, 20), we made several changes to the platform, prior to deploying it in a long-term intervention study with stroke patients. For example: We added functional exercises which required the use of both arms (as opposed to a single arm), as one would be asked to perform in a standard rehabilitation session in the clinic; we added specific instructions on whether to use the impaired arm or both arms for each exercise;

we added a demonstration video for each task, which can be shown if needed; We developed two modes of each exercise set, the first with unlimited time to complete the task, and the second with a time limitation, thus providing both a motor and a cognitive challenge. Below, we describe the platform in detail, and present the results and the conclusions from a long-term intervention study with 14 stroke patients.

## **2.2 The Platform**

### **2.2.1 Overview**

We developed a gamified platform for stroke rehabilitation. The platform can be used in one of two configurations: in one configuration, the patient receives the game instructions and the feedback from a humanoid robot (the ROBOT configuration; we used the Pepper robot, Softbank Robotics Aldebaran), and in the other, from a standard computer screen (the COMPUTER configuration; see Fig. 1). For the sake of clarity, we will refer to the robot configuration when describing the platform, but the same was true for the version with a computer screen. That is, when information is described as presented on the robot's tablet screen, it was presented on the computer screen in the COMPUTER configuration; when the robot gave audio instructions, the screen's speakers emitted the exact same instructions in the COMPUTER configuration; Note that an audio instructions were always accompanied by on-screen text with those same instructions: these were presented on the robot's tablet screen in the ROBOT condition, and on the computer screen in the COMPUTER condition.

In each of the seven instrumented exercise sets which we developed, patients practice reach-grasp-and-place, or reach-grasp-and-manipulate movements, using real everyday objects such as cups, jars and keys, punch pads, wallets and drawers. These functional exercise sets enable the patients to practice both motor and cognitive abilities. In each exercise set there are between 4 and 7 levels of difficulty, with the level of difficulty being a function of: (1) the number of objects the participant manipulates during each trial (they start with a small number of objects and progress to manipulating more objects), (2) the weight of these objects (they start with picking and placing lightweight objects and progress to heavier ones), and (3) the height of the table or the shelf on which they have to place the objects (they start by manipulating objects at a standard table height (75 cm), or lower, and progress to shoulder height, as a function of their ability). Three of the exercise sets are designed to practice reach-grasp-and-place movements (exercise sets 1,2, 5 detailed below), and the other four are designed to practice reach-grasp-and-manipulate (e.g, pick up a wallet and open its zipper to retrieve a key from it; exercise sets 3,4,6,7 detailed below). All the objects and the surfaces of the platform are equipped with tags and sensors (respectively) that enable tracking of the objects' end location, as detailed below.

We provide the details of the seven exercise sets below. Since they are all gamified, we refer to them as games.

### **2.2.2 The Exercise Sets (1–7)**

## The Cup game (1) and the Target game (2)

In the *Cup Game* (18), in each of sixteen trials, a row of colored cups is displayed on the robot's tablet screen. The participant, seated next to an instrumented table, has to organize a corresponding set of colored cups on the table according to a picture shown on the robot's tablet screen (see Fig. 1 and Fig. 2). There are four levels of game difficulty, depending on: (1) the number of cups, starting from three cups in the first (easiest) level, up to six cups in the fourth (hardest) one; and (2) the weight of the cups: The cups can be either empty (34 gr) or full (180 gr) (for most patients, the empty cup is easier to lift, but for some the full cup provides stability); We used dry beans to fill the cups in the "heavy" configuration. The table on which this exercise set is performed is height adjustable, and was fit with a custom-built top plate, with 8-cm holes, so that the patients can comfortably place the cups in the designated locations, without the risk of knocking them over. This exercise set is considered the simplest one, since the spatial organization of the objects requires mostly sideways movement of the arm, with little movement away from the body, or in the vertical dimension.

The *Target Game* is similar to the *Cup Game*, but rather than organizing the cups in a row, they are to be arranged in a circle, similar to a bullseye board, with six target locations arranged in a circle around a target location in the middle of the circle (see Fig. 2). In the *Target Game*, there are 21 trials with five levels of difficulty, starting from three cups in the first (easiest) level, and progressing to seven cups in the last (hardest) level. As in the *Cup Game*, the cups can be either empty or full. This game is more difficult than the *Cup Game* since it requires spatial perception and a multidimensional movement of the hand in different directions across the plane of the table (i.e., both sideways, and towards-and-away from the body).

## The Keys Game (3) and the Purse Game (4)

In the *Keys Game* the participant takes colored keys out of a box and places them on a key hanger according to an image displayed on the robot's tablet screen. The image on the robot's tablet screen is of a row of circles in different colors (see Fig. 3). In the box there are 12 keys, of different colors: the color of six of them matches the colors that participate in the game, and six other keys are used as distractors.

In the *Purse Game*, the participant takes the keys out of six different zipped purses, whose color matched that of the keys, and attaches each key to the key hanger according to the colors displayed on the robot's tablet screen (see Fig. 3). Both these exercise sets require performing a reaching movement, as well as manipulation of small objects.

## The Kitchen Game (5)

In the *Kitchen Game* (19), in each of fifteen trials, the participant has to organize a set of labeled plastic jars on shelves at three different heights, according to an image shown on the robot's tablet screen (see Fig. 4). The jars are either half full or completely full with actual food items and condiments, such as salt,

sugar, oil, coffee, corn kernels, etc., and a label indicates the contents of the see-through jar. There are six levels of game difficulty. The difficulty is determined by a combination of: (1) the number of jars to be placed on the shelf; (2) their weight (half or completely full), and (3) the height of the shelf (there are 3 shelf heights). The first level has three lightweight jars placed on the lowest shelf (height of a standard table). In the seventh level there are nine jars, of different weights (110–400 gr), placed on shelves at three different heights (see Fig. 4). The kitchen shelves were custom-built with 8-cm holes, so that the patient can comfortably place the jars in the designated locations, without the risk of knocking them over. This game requires users to reach to different heights and lift different weights, as well as practice their spatial perception.

## **The Black Jack Game (6)**

In this implementation of the Black Jack card game, the participant is the dealer and the robot is the player (see Fig. 5). The rules of the game are presented by the robot at the beginning of the game. Then, the participant, in the role of the dealer, hands out the cards to the robot and to themselves, according to the rules of the game. A round is won when both the robot and the participant do not want to add more cards. The winner is the one for whom the sum of their card values is highest, but not higher than 21. We custom-printed a full deck of cards on RFID cards (see details below), for this game.

## **The Escape-Room Game (7)**

In this game, there is a background storyline, where the robot tells the participant it has to leave and go out on a drive (which usually provides some comic relief) and charges the participant with the mission of helping it find its ID card, keys, and its credit card. In a series of guided tasks (listed below) the participant is required to practice everyday actions such as to open a drawer by a gentle pull (to a specified distance), to open a lock using a key, to press switches etc., until the mission is completed. In the end, the participant is asked to organize all the objects they collected during this series of tasks into a wallet, thus practicing yet another everyday activity. In this exercise set, the participant practices manipulation of objects, bilateral movement of both hands, a controlled movement of the hand. The guided tasks are listed below.

1. "The ID card is in the top drawer. It is locked. The key to the top drawer is in the second drawer. Please open the second drawer until you see a red light". A distance sensor installed in the back of the drawer chest is used to measure how far the drawer was opened. The red light on the side of the drawer is lit only when the drawer is opened to exactly 30 cm. The goal of this task is to practice force regulation of the open motion of the drawer (see Fig. 6a).
2. "Look for the key of the top drawer in the second drawer" (among 20 similar keys) (see Fig. 6a).
3. "Use the key to unlock the top drawer, and find the ID card in the top drawer" (among 10 other cards) (see Fig. 6b)

4. "Place the ID card on top of the card reader (see Fig. 6c) and use the 4 last digits of the ID card number as the code for the safe" (press key pads and turn the lock) (see Fig. 6d)
5. "In the safe, there are keys for the lock of the third drawer. Find the right key and open the lock (out of 10 similar keys)."
6. "In the drawer you will find my credit card" (among 10 other cards) (see Fig. 6e)
7. "Place the credit card on top of the card reader; Then open the fourth drawer until the last two digits of the card appear on the digital screen next to the drawer".
8. Take the wallet out of the drawer and put the items you found in it.

## 2.2.3 Timing of the exercise sets

Each of the five exercise sets numbered (1–5) above can be played with no time limit to complete each trial of the task, or with a limited time to complete it. In the first configuration (unlimited time), the target image is displayed on the screen until the participant indicates they finished arranging the objects. The time they took to complete the task is automatically recorded, and the clinician who is running the experiment is informed – via the user interface on the computer used to run the experiment – The averaged time it takes the patient to complete each trial in a level of the task. In the second configuration (limited time), the image with the target order of the objects disappears from the screen after an individually set period of time, according to the participant's timing in the unlimited-time configuration. The time limit that is set is 2–4 secs less than the time it took the user during the unlimited-time phase.

## 2.2.4 Verbal and visual instructions and feedback

After each trial, the robot either gives the participant feedback on the timing (e.g., "try to do it faster next time") or on their performance on the exercise set (e.g., "you succeeded!", "you were not right but try again"). The robot provides feedback by a combination of a verbal response and visual feedback, which is displayed on the robot's tablet screen. The robot's responses are further accompanied by head and arm gestures (e.g., nodding, clapping, or dancing a victory dance; these gestures are not present in the COMPUTER condition). The robot is semi-autonomous in its function, such that the patient can play without the intervention of a clinician or a caregiver in the game. When the participant is wrong, an image with the correct order of the objects is displayed on the robot's tablet screen, so the patient can see where they went wrong. In each trial, the patient collects points for the objects they ordered correctly. Since the Pepper robot does not support the Hebrew language, we could not use its built-in language capabilities. We therefore pre-recorded all the instructions and verbal feedback, using a female human voice. The same recordings were used for the ROBOT and for the COMPUTER configurations.

## 2.2.5 Exercise Set Progression

In the very first ROBOT session, out of a total of 15 sessions, Pepper presents itself to the participant. In each of the following 14 sessions Pepper welcomes the participants with sentences such as "I'm so happy to see you again", "It is so nice that you came back" etc. In the COMPUTER configuration, there are no welcoming sentences, and the session starts by presenting the exercise game's instructions. In each of

the above-listed exercise games numbered (1–5), in order to indicate that they completed a task, the participants press a big push-button located on the right side of the table (see, for example, Fig. 3).

## **2.2.5.1 Pausing or stopping the game**

In all seven exercise games, the participant can stop at any time if needed. Twice during the games numbered (1–5), after each two levels of game, the robot offers the participant to rest and to join it for a stretching session. In addition, twice during each of these exercise games, after completing the third and the fifth levels, the system offers the participant to stop the game if desired. Furthermore, the participant can take a break or stop the game at any time, and when they continue playing, the game will start from the same point at which it was stopped. In each of the exercise games, after several trials at a certain level, the system offers the participant to advance to a higher level. In order to indicate their choice, the participant presses a green button to continue to the next level or a red button to stay at the same level. The red and green push buttons are placed on the side of the game table. These buttons are also used to indicate whether the patient wants to continue playing, or to stop playing when asked. In each game, the instructions to the participant indicate whether they should use only their impaired hand or both hands in order to complete the task, according to the natural requirements of the task. In case of a fault of the system, it can be restarted from the same place where it stopped and the robot says "So, where were we? Let's continue from the same place".

## **2.2.6 Physical Setup**

### **2.2.6.1 Table Height**

For six of the seven exercise games we designed (games 1–6 listed above), we used a height-adjustable table. It is used to adjust the height of the table, depending on the height of the participant, and on the extent of their arm impairment. When the arm is weak (FMA score < 25, see below) we lower the table to the height of the patient's thighs, when seated; this helps them reach the objects on the table, a task which is harder for them when the table is higher (22, 23).

### **2.2.6.2 The Exercise Platform**

On top of the height-adjustable table, we fixed a second top board, into which we drilled 8-cm holes, such that patients can comfortably place the objects in the designated locations, without the risk of knocking them over. These were used for the "Cup Game" and for the "Target Game". In the "Kitchen Game", on top of each shelf we fixed a second top board, into which we drilled three 8-cm holes as well, where the participant placed the jars and bottles.

### **2.2.6.3 Sensing Apparatus**

In order for the system to detect where the objects are placed on the platform, and to detect completion of the task, we used an Arduino Mega board together with Radio Frequency Identification (RFID) readers. The RFID readers automatically identify and track tags that were attached to the different objects of the

games (e.g., the keychains in Fig. 3). We placed RFID readers in all locations where users were asked to place objects (the table, the kitchen shelves, the key hanger, and the Black Jack board). For the Black Jack game we used RFID cards, upon which we custom-printed the images of actual playing cards. In the "Cup", "Keys" and "Wallet" games, the Arduino board is required to read 6 RFIDs at a time. In the "Target Game" it is required to read 7 RFIDs in parallel, in the "Kitchen" Game 9 RFIDs are read in parallel, and in the Black Jack game 14 RFIDs are read all at once. In the "Escape room" game, we used distance RFID readers, which indicated when the safe and the drawers were open and to what extent. The data are transported from the Arduino board, via a USB cable, to the computer that controls the game. In exercise games (1–5), when the big push-button was pressed the data were processed by the Arduino and then transported from the Arduino to the computer via a USB cable. In the "Black Jack" and "Escape Room" games, the Arduino board continuously read the RFIDs and transmitted the data to the computer.

## 2.2.7 System Autonomy

The gamified system was designed to be semi-autonomous (24), meaning that there is involvement of a third party in setting up the personalized exercise games for each participant, after which the patient can play without the intervention or the presence of a clinician or a caregiver. Before the game starts, the clinician inputs the following data into the computer, which controls the interaction: the patient's anonymized code, gender (so that the robot (or screen audio) will address the patient using correctly gendered pronouns and verbs when speaking to the patient in Hebrew), whether it is their first interaction with the system, whether this is the first time they play this specific exercise game (Cup, Target, etc.), and whether the patient needs to watch a video of the instructions (either this is the first time they play the game or they ask to watch it again). Then, the game instructions and feedback are all provided by the robot or the computer screen, and the patient interacts only with the robot or the computer screen throughout the session. The system is a non-contact system, meaning there is no physical interaction between the robot and the participant.

## 2.3 Feasibility study with stroke patients

We conducted a long-term patient study in the ambulatory unit of the "Aleh Negev" rehabilitation center in Israel. The research was approved by the institutional Helsinki ethical committee for clinical trials (SMC-5273-2018). All patients gave their written informed consent after they received a detailed explanation on the study from a medical doctor specializing in physical medicine and rehabilitation.

### 2.3.1 Participants

Fourteen stroke patients (six females, eight males; age range 30–77 years, mean  $63 \pm 12.7$  yrs; 60–245 days from stroke onset, mean  $116 \pm 48$  days; FMA score 17–53/60, mean  $41 \pm 11$ ) participated in this study. Patients who met the following inclusion criteria were recruited to the study: (1) First unilateral stroke, confirmed by imaging; (2) Mini-mental state examination (MMSE) score  $\geq 24/30$  (for participants  $\geq 65$  yrs) (25) or the equivalent Montreal Cognitive Assessment (MoCA) score  $\geq 20/30$  (for participants  $< 65$  yrs); (3) Fugl-Meyer Upper Extremity Assessment (FMA) (26, 27) score  $\geq 16/60$  (higher score indicates

less impairment; a score below 16/60 indicates the patient does not have the capacity to reach and grasp objects; (4) No other neurological and/or orthopedic condition that could affect arm movement. Exclusion criteria were as follows: (1) vision/hearing loss that limits the participant's understanding of instructions, or ; (2) Aphasia that limits their understanding of instructions. All participants were right-handed. For 64% of the participants, the affected arm was their dominant (right) arm.

Participants were randomly allocated to perform a long-term functional exercise intervention in one of two groups: either with the Pepper robot or with a computer screen. The clinical outcome measures and the results of a third experimental control group, which did not undergo the intervention, are not reported here.

Participation in the study was *in addition* to the conventional therapy the participants received as part of their rehabilitation program, as this system is designed to support the rehabilitation process and to provide additional training, on top of existing treatment. Following an initial assessment session, patients came to the facility two to three times per week over a period of 5–7 weeks, for a total of 15 therapy sessions with either the Pepper robot or the computer screen. The number of sessions was determined based on previous works (28, 29) that described significant clinical change in the arm and hand function of stroke patients following 12–15 sessions, at a frequency of three times per week. Each session lasted between 30–50 minutes. In each session, the participant played one of the seven exercise games described above. The patients had the option of playing more than one repetition of a game in a single session, if they so desired. After setting up the game parameters (e.g., whether this is the first session, whether a demonstration video is needed, etc.), a clinician was present in the room for safety reasons only. The participant was seated facing either Pepper or the computer screen (see Fig. 1), with their back to the therapist, who stood in the corner of the room, and did not intervene in the interaction with Pepper, with the computer, or in the sequence of the game. The level of game difficulty was determined at first according to the impairment level that was identified by the clinical tests, upon admission to the study. Then, after 4–6 trials in each game-difficulty level (e.g., with 3 cups in the Cup game), the system asked the participant whether they wanted to progress to the next level of difficulty (e.g., with 4 cups in the Cup game), or continue to exercise at the current level of difficulty.

Following 15 sessions, each participant completed a custom-made user-acceptance questionnaire, in order to evaluate their acceptance of the novel system. The custom-made survey was based on the User Satisfaction Evaluation Questionnaire (USEQ), and the questions used are listed in Table 1. The USEQ is a six-questions questionnaire developed by Kizony et al. (2006) in order to assess virtual reality systems for rehabilitation (30, 31). Participants are asked to rate their experience on a 1–5 Likert scale, where 1 indicates 'not at all'; and 5 indicates 'very much'. We added to the USEQ one question: "Would you like to keep using the system during your rehabilitation?". In addition, we asked the participants open-ended questions to allow them to describe their opinion on the system in detail. The open-ended questions are summarized in Table 2.

Table 1  
User Satisfaction Evaluation Questionnaire (USEQ)

Question	Response Not at all-very much
Q1. Did you enjoy using the system?	1 2 3 4 5
Q2. Were you successful using the system?	1 2 3 4 5
Q3. Were you able to control the system?	1 2 3 4 5
Q4. Was the information provided by the system clear to you?	1 2 3 4 5
Q5. Did you feel discomfort during your experience with the system?	1 2 3 4 5
Q6. Do you think that this system will be helpful for your upper-limb rehabilitation?	1 2 3 4 5
Q7. Would you like to keep using the system during your rehabilitation?	1 2 3 4 5

Table 1: The questions from the User Satisfaction Evaluation Questionnaire, where participants evaluate their experience with the system on a Likert scale of 1- "not at all" to 5 – "very much".

Table 2  
Costume-made open-ended questionnaire

<b>What did you think of the system?</b>
What did you like?
What did you not like?
What was your favorite exercise game? Why?
Was there an exercise game you did not like? What game? Why?
What would you add or change?

Table 2: The costume-made open-ended questionnaire, where participants could freely evaluate and describe their experience with the system.

### 3. Results

Eight participants were randomly allocated to the Robot group and six participants to the computer group. They participated in a total of 210 sessions altogether (14 participants x 15 sessions per participant). Due to the small sample size, we did not statistically compare the two groups, but rather analyzed their impressions from the gamified system as a single group.

### 3.1 Results from the modified User Satisfaction Evaluation Questionnaire (USEQ)

All results from the USEQ are summarized in Fig. 7. The mean scores for the questions "Do you think that this system will be helpful for your upper-limb rehabilitation?" and for the question "Did you enjoy using the system?" were  $4.3 \pm 1$  and  $4.4 \pm 0.7$  out of 5, respectively. The mean score for the questions "Were you successful using the system?" and "Were you able to control the system?" was  $4.6 \pm 0.6$  out of 5 for both. The mean score for the question "Was the information provided by the system clear to you?" was  $4.7 \pm 0.7$  out of 5. For the question "Would you like to keep using the system during your rehabilitation?" participants responded with  $4.2 \pm 1.1$  out of 5. Participants responded to the question "Did you feel any discomfort while using the system?" with  $1.4 \pm 1.0$  with 5 indicating 'always' and 1 indicating 'never'.

## 3.2 Results from the open-ended questionnaire

There was no clear agreement between participants on what aspects of the exercise program they preferred. 13 out of 14 (93%) of them mentioned they enjoyed the motor aspect of the task and 9 out of 14 (64%) mentioned they enjoyed the addition of cognitive challenge (memory and spatial perception). 8 out of 14 patients (57%) noted that their favorite exercise game was the "escape room", as it required diversity of both motor tasks and a thinking challenge, participants mentioned it was like solving a riddle. However, some participants mentioned it was too short and they would add more tasks to it.

11 out of 14 (78%) of the participants mentioned they liked the diversity of the games and the addition of the dual-task cognitive challenge. 2 participants mentioned they preferred the reach-grasp-and-place task games (games 1,2, 5), 2 participants mentioned they preferred the reach-grasp-and-manipulate games which required manipulation of objects (games 3,4,6,7). Importantly, 5 participants mentioned they would like to have greater diversity of exercise games, so that in each session there will be a new kind of game (in the current setup, with seven games used for 15 sessions, there was a repetition of games across sessions). In addition, 4 participants mentioned they would enjoy a more challenging task in terms of both the motor aspect (for example: heavier weight, more levels of game) and the cognitive one (for example: more riddles). Finally, 2 participants mentioned they would rather have a system that can automatically detect their motor and cognitive abilities as well as their performance, and personally fit the level of the training and the feedback according to their motor and cognitive performance.

Below we quote several anecdotal statements made by the participants (all the quotes brought here were made by the participants in the ROBOT group, except the last one, made by a participant in the COMPUTER group):

*"The robot made me regain trust in my arm" (P07);*

*"In none of the other therapy sessions I took part in (not as part of the experiment) was there a focus on the hand like here; Here I dared to do things with the hand that I did not think I would succeed in doing, and it helped me believe I can do it at home as well" (P14);*

*"I really liked the games, I felt you exactly identified the problem and hit the bullseye in treating it" (P13)*

*"I only want to come to the sessions with the robot"* (out of all the rehabilitation activities he was engaged in at the time) (P03);

*"I think that a bigger diversity of games is needed, it is boring to play the same game several times"* (P14).

## 4. Discussion

Here, we describe a robot-based gamified exercise system for long-term post-stroke rehabilitation, which can track the performance of patients over time. The system also has a computer-based configuration (with no robot), and includes a gamified set of functional tasks from the everyday life of the person, such as reaching to a cup, or turning a key in a lock. We also report that results of a patient usability study, where 14 stroke patients exercised with these two platforms over a 5–7 week period, 2–3 times per week, for a total of 210 sessions.

The system we developed is novel in two main aspects: 1) Design and implementation of exercise games using reach-to-grasp movements to real physical objects; 2) Study of a *long-term* interaction of stroke patients with a humanoid robot and a computer screen for rehabilitation. Our study showed that patients found the gamified system engaging and motivating for rehabilitation following a long-term intervention. They found the system to address their needs in upper-limb rehabilitation and expressed their desire to continue training with the system even after the study ended.

As was stressed by (3) in a review of robotic devices for rehabilitation, the goal of the system is to augment the work of the clinician, not replace it. It is designed to complement the one-on-one sessions with the clinician and to help the clinician and the patient to achieve repetitive task-specific training in an engaging and motivating manner, while using every-day tasks and objects.

### 4.1 Long-Term SAR study

To the best of our knowledge, this is the first study to evaluate a long-term intervention using an SAR with post-stroke patients in a rehabilitation center, as part of their conventional rehabilitation program. Though in the domains of health care and therapy there is great potential for social robots to assist users over extended periods of time [for examples see (32, 33)], there is still a limited number of works describing longitudinal studies within this domain (34). Leite et al., in a survey of social robots for long-term interaction, noted several reasons for this. First, longitudinal studies are much more laborious and time consuming than short-term studies, especially in ecological environments and in the wild. Second, only in the last few years technology has become robust enough to allow for some degree of autonomy when users interact with robots for extended periods of time (34).

### 4.2 Physical environment of training in stroke rehabilitation

One of our main goals in the current study was the use of real objects from everyday tasks as part of the exercise gaming program. Hubbard et al. (2009) mentioned that when guiding application of task-specific training in clinical practice a task-specific training should be repetitive and relevant to the patient and to

the context (5). (35–39) have demonstrated that our specific functional goal when reaching to an object (e.g., do I reach for a cup in order to drink, or in order to pour water into it) affects the way we perform the movement. Reach to grasp movements often requires precise application of grip forces. Skilled grip force relies on prediction and sensory feedback (40). (41) showed that during a grip-lift task, healthy individuals were able to rapidly establish an association between an arbitrary sensory cue with a given weight, and scale grip force precisely to the actual weight. Force regulation have an important effect on stroke patients' independence level (42) as difficulties in applying and adapting adequate grip forces (43) limit their ability to perform daily activities (44).

In the last decade there is vast research on the use of virtual reality (VR) technologies for rehabilitation, specifically of the upper limb. While being cheap, accessible and encourage high-intensity training (45), one of the problems that still remain unsolved is that upper limb kinematics have been reported to be altered compared to physical environments (46, 47). The virtual environment still lacks the ability of providing haptic feedback to the user (46) and by that practicing force-regulation as part of reach-to-grasp training. Here we use an engaging and motivating technology (SAR) while using reach to grasp movements in a physical environment using real everyday objects and by that enabling participants to practice both RTG kinematics and force regulation.

## **4.3 Suggested Guidelines for Future Designs of SARs for Rehabilitation**

Matarić et al. (14) suggested that the design of interactions with social robots for post-stroke rehabilitation should follow two guiding principles: (1) high intensity of task-specific training and (2) a system that will be engaging and user-friendly. In the robot-based system that we developed, we followed these guidelines. Based on our earlier work (18, 20, 48) and on the current study we added several guidelines which expand these recommendations: (1) Task Variety: For a system to be applicable to a wide variety of patients and different levels of impairments, and in order for it to engage patients in the long-term, there should be a variety of tasks, with different levels of complexity, which can be executed by both low-functioning and high-functioning patients. Users should be able to progress in the task according to their ability and motor performance. (2) Communication: The instructions given to the user should be simple, gradually increasing in difficulty, and spoken slowly and clearly. However, the response time of the robot should be as fast as in human-human interaction (18). From our experience from the current study and from previous ones (18, 48), the response time of the system is longer than 4–5 sec participants experience it as slow (for more on the effect of timing on users' perception of HRI, see (49)). (3) Fatigue management: Since stroke patients experience frequent fatigue [8, 9] and muscle weakness, patients should have the ability to rest when needed. When the patient is fatigued and cannot complete the task without using undesirable compensatory movements (10), either the patient should rest, or the session should end. (4) Feedback and Reward: Users need to receive feedback on their performance and on their results, as this is an essential component of their motor learning (50). However, as the participants in our study noted, the feedback should be given in a manner and at a frequency that will not negatively affect their compliance to keep on training. Some of the participants in our study, especially

the younger ones (< 45 yo) mentioned they do not wish to receive verbal feedback on their performance after each trial, but would rather receive verbal feedback after several trials and visual feedback (like the sign of raised thumb for "like") following the other trials. In addition, they mentioned they would like to receive feedback on their motor performance. That is, they sought feedback on their body movements as they performed the task, whether they involved any compensatory movements, in addition to their task performance. We are currently in the process of developing this capability (10). (5) Personalization of the system and of the interaction this point is discussed at length in Sect. 4.4.

## **4.4 Personalization in Rehabilitation**

In the last few years, patient-centered care has been widely accepted as an essential component of healthcare and specifically in the rehabilitation care (51). The importance of adapting the rehabilitation program to the personal needs of the patient was also stressed by the participants in our study, who mentioned the importance of personalizing the design of HRI and HCI (Human-Computer Interaction) and tailoring it to the specific task and patient needs. In previous works (14, 18, 20, 48, 52–54) one of the most repeatedly noted requirement of SAR for rehabilitation was the need for personalization of the system and of the interaction. This is especially important in vulnerable populations such as neurologically impaired patients, where interactions with robots are designed to assist them in maintaining a training regime, and where establishing long-term trust between the user and the robot is essential (55, 56). Stroke patients often depend on reliable and effective relationships with their therapists. They are often older and multi-morbid and suffer from psychological distress because of their disability (56). Due to the limitations and frustration a stroke patient may experience because of their impairments, a system that is designed for stroke patients should be as trustworthy as possible. Thus, in order for the robotic device to be effective for therapy, and accepted by both the patient and the clinician, it has to be flexible and adjustable, taking into account the complexity of the specific impairment. For the experience of the user to be positive, and to achieve engagement in the task, it is important to personalize the interaction according to the age, the needs of the user, their abilities and the characteristics of the task.

## **4.5 SAR for rehabilitation during the COVID 19 pandemic**

In March 2020, the World health Organization declared the COVID-19 as a pandemic. The rehabilitation world is now facing new challenges because of the requirement for social distancing, especially for at-risk populations. (57) noted the following two challenges that the realm of rehabilitation faces in light of COVID-19: (1) "Providing safe physical environments within rehabilitation wards that comply with social distancing and hygiene ...; (2) Mitigating risk (as able) for a potential COVID-19 exposure to patients and staff ". The requirement to keep a social distance and reduce physical contact stresses the need for alternative rehabilitative tools, such as SARs, to enable patients to have an uninterrupted (even if modified) rehabilitation regime.

## **Study limitations**

While the number of participants is sufficient for a feasibility study, it would be important to collect data from a larger number of participants to study the clinical benefit of this system.

## **Conclusions**

We demonstrated the feasibility of using the platform we developed for a long-term rehabilitation with stroke patients in a clinical setting, and found a strong trend of acceptance of the SAR by stroke patients following this long-term interaction. We provide a list of guidelines that can be used when designing and implementing other technological tools for rehabilitation.

## **List Of Abbreviations**

UL Upper Limb

RTG Reach-To-Grasp

SAR Socially Assistive Robot

FMA Fugl Meyer Assessment

MMSE Mini Mental State Examination

MoCA Montreal Cognitive Assessment

HRI Human Robotic Interaction

HCI Human Computer Interaction

USEQ User Satisfaction Evaluation Questionnaire

COVID-19 Coronavirus Disease 2019

## **Declarations**

## **Ethics approval and consent to participate**

The research was approved by Sheba Medical Center institutional Helsinki ethical committee for clinical trials (SMC-5273-2018). All patients gave their written informed consent after they received a detailed explanation on the study from a medical doctor specializing in physical medicine and rehabilitation.

## **Consent for publication**

Not applicable

# Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

# Competing interests

The authors declare that they have no competing interests.

# Authors' contributions

RFP developed the system, collected the patient data, analyzed and interpreted the patient data and wrote the manuscript. SLT developed the system and was a major contributor in writing the manuscript. Both authors read and approved the final manuscript.

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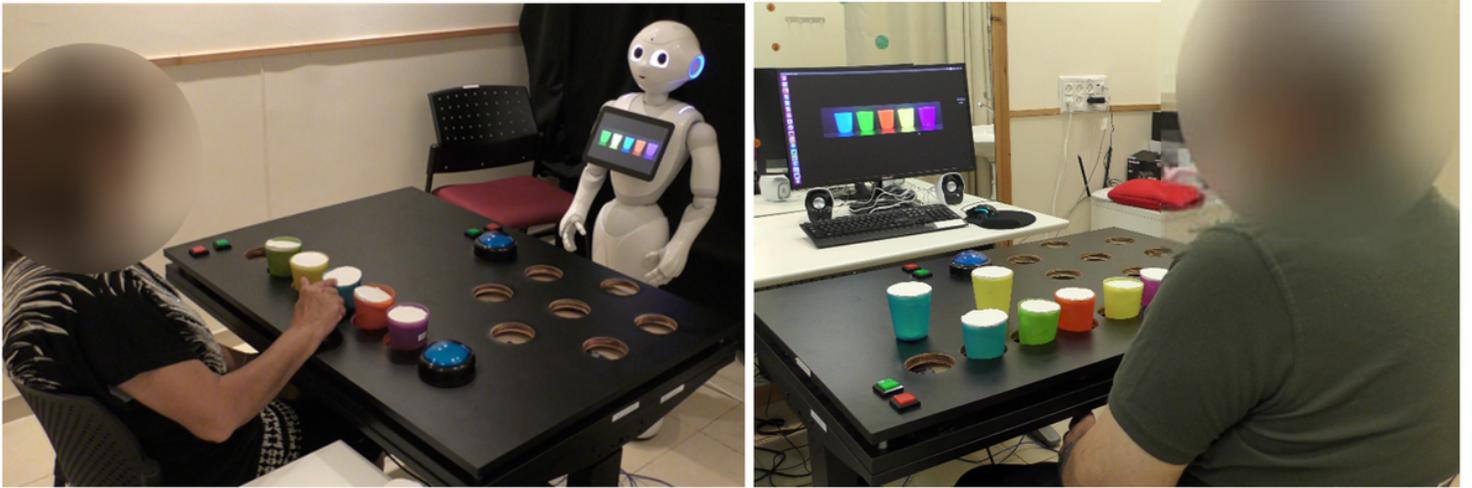
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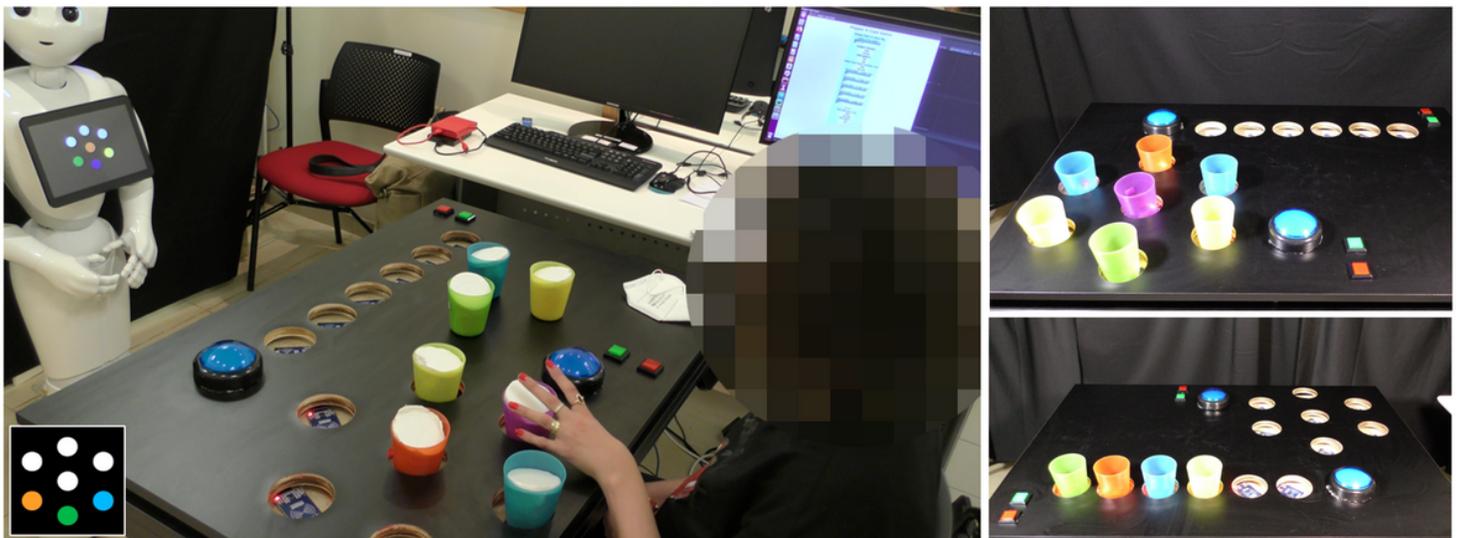
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## Figures



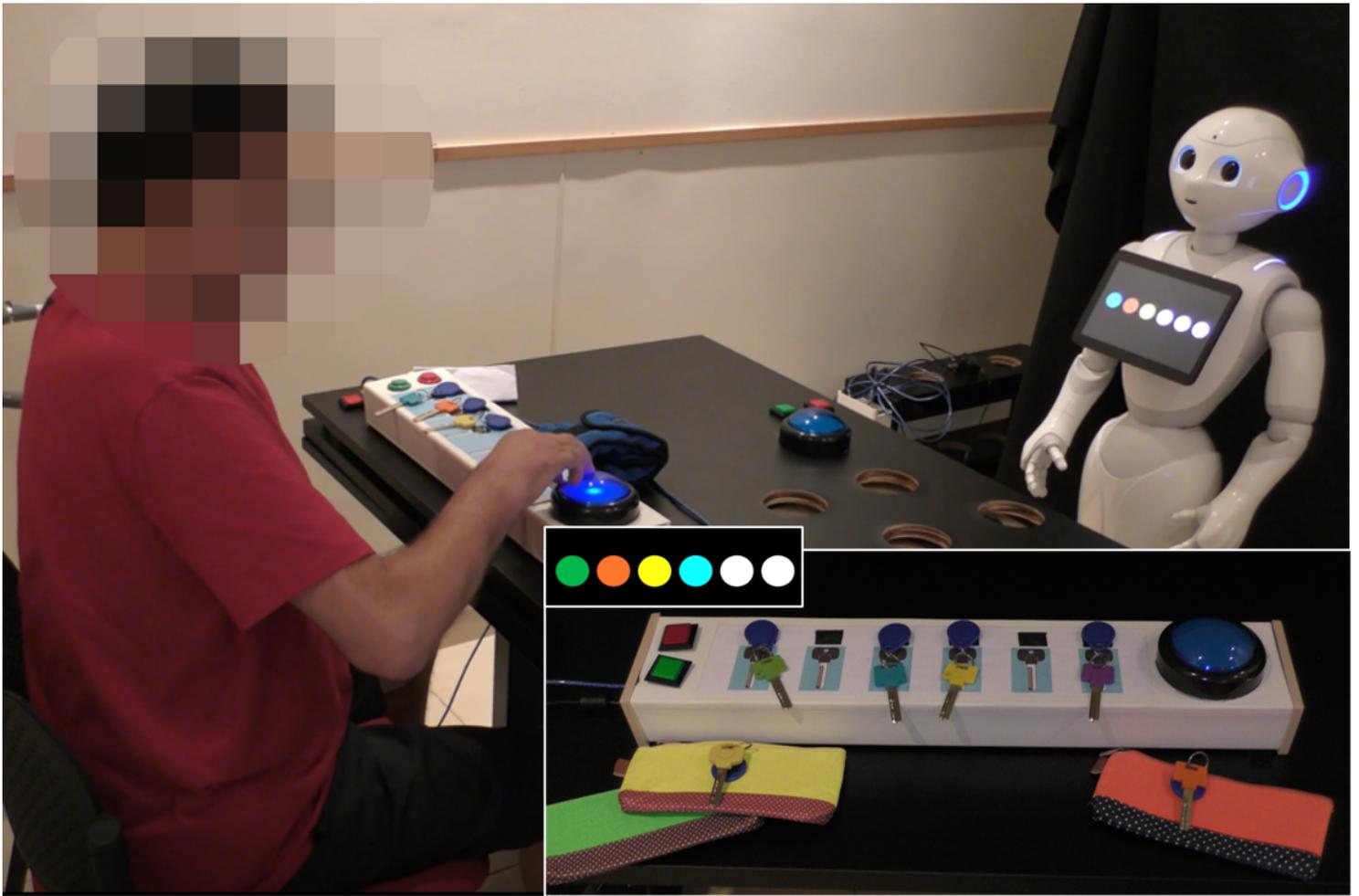
**Figure 1**

The two implementations of the stroke rehabilitation system. Left: the social robot Pepper gives instructions and feedback to the patient (ROBOT). Right: the instructions and feedback are presented on a computer screen (COMPUTER).



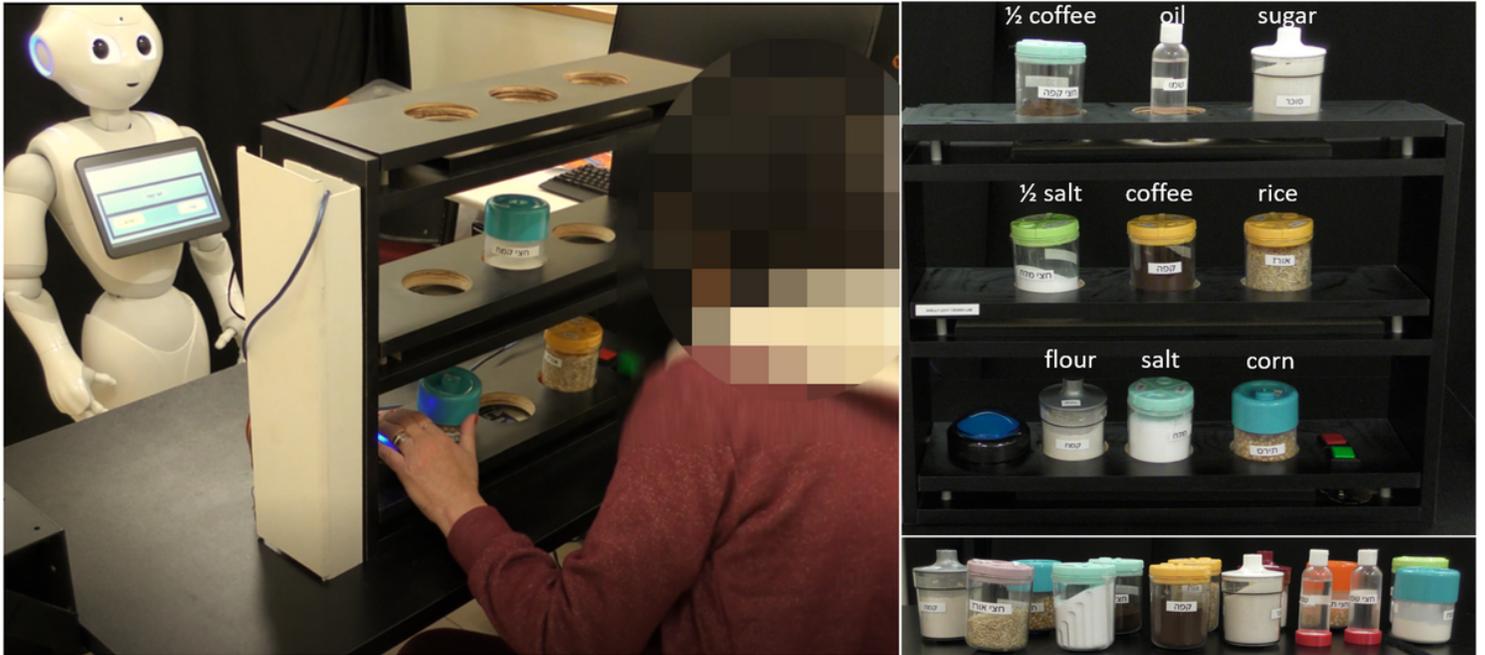
**Figure 2**

The Target and the Cup Games. Left: A patient playing the Target Game with the instructions provided by the robot. Inset: an example of an instruction in this game, where three colored cups should be placed along a circle; white circles denote empty spaces. Top right: an illustration of the Target Game with all seven cup locations occupied. Bottom right: an illustration of the Cup Game with four occupied cup locations, out of the possible six.



**Figure 3**

The Keys and the Purse Games. A patient playing the Keys Game with the instructions provided by the robot. Large inset: an illustration of the Purse Game, showing the keys, taken out of color-matched zipped purses, to be placed on the sensorized key hanger. Small inset: an example of an instruction in either of these two games, where four colored keys should be placed on the key hanger; white circles denote empty spaces.



**Figure 4**

The Kitchen Game. Left: A patient playing the Kitchen Game with the instructions provided by the robot. Top right: an illustration of the Kitchen Game, with all nine shelf locations occupied. The white text above each jar/bottle indicates the content of each item, which is also printed on the item itself; “1/2” indicates that the jar or bottle is half full. Bottom right: The variety of kitchen items which are used in this exercise game.



Figure 5

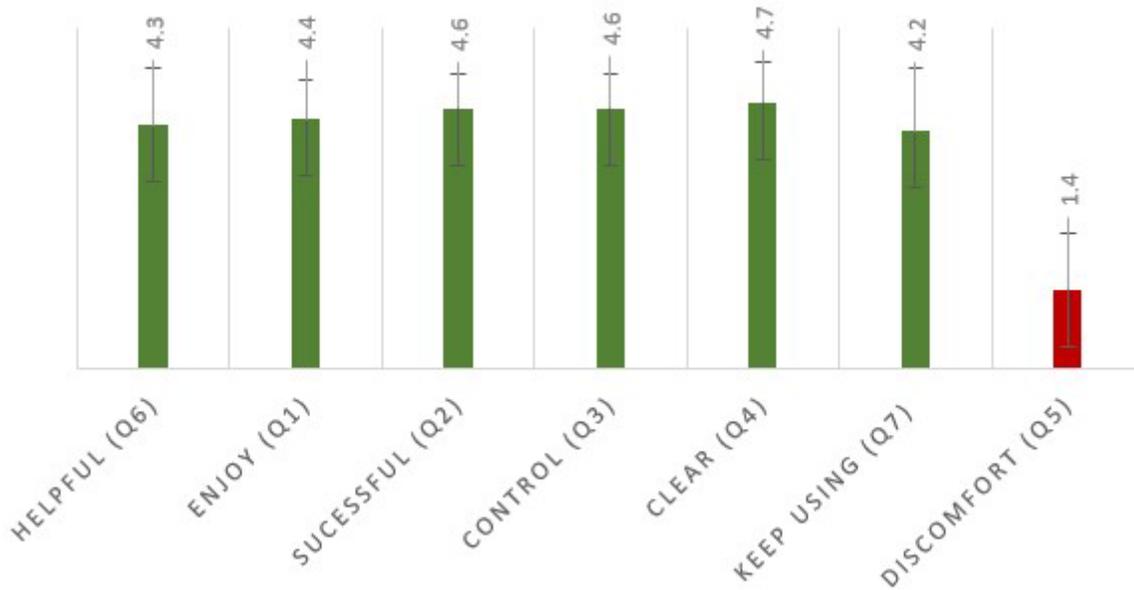
The Black Jack Game. A patient playing the Black Jack Game in the role of the dealer, with the robot in the role of the player. The cards, custom-printed on RFID tags, are placed on the sensorized table by the patient.



Figure 6

The Escape-Room Game. (A-E) some of the tasks of the exercise, including opening drawers to a specific distance, identifying a key or a card among distractors, punching numbers on a key pad, turning a lock, etc. (F-G) a patient performing the tasks in this exercise, corresponding to instructions 5 and 6 in the text.

## USEQ RESULTS



**Figure 7**

Results of the User Satisfaction Evaluation Questionnaire (USEQ), mean±SD. A score of 1 denotes "not at all" and 5 denotes "very much".