Evaluating automated real time feedback and instructions during computerized mirror therapy for upper limb rehabilitation using augmented reflection technology

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ABSTRACT

The use of Virtual and Augmented Reality (VR/AR) in physical rehabilitation can provide better control, improved user motivation, and flexibility in how therapy is offered. Mirror therapy is a therapeutic intervention that has been shown to be beneficial for upper limb stroke rehabilitation. However it requires, in its clinical application, the constant presence and attention of a skilled therapist who provides instructions. This paper presents an AR mirror therapy system that provides automatic instructions and feedback. A within-subjects design user study with healthy volunteers was conducted to evaluate the usability (System Usability Scale), perceived suitability (Suitability Evaluation Questionnaire for Virtual Rehabilitation Systems), satisfaction (subset of Usability Satisfaction Questionnaire), general experience (Mixed Reality Experience Questionnaire) and participants' performance and preference. We compared two conditions where the system automatically instructed the participants and (i) where the system additionally provided feedback, or (ii) the system did not provide feedback. All participants were able to complete the automated mirror therapy intervention. Participants significantly rated the usability and suitability of the automated intervention as positive. The comparisons between the two conditions on *user experience* and *satisfaction* indicated preferences for the feedback condition; however it was not statistically significant. In the direct comparison between systems, participants showed a strong and significant preference for the feedback condition. A few participants reported a mild level of discomfort attributed to the sitting position, exercises and placement of their hands on the table. With this study, further progress towards an automated system for the provision of mirror therapy was achieved and successfully evaluated with healthy participants. Preparations for clinical evaluations using this automated system with patients suffering from motor impairments after stroke can now commence.

1. INTRODUCTION

Computer mediated visual feedback systems using virtual reality and augmented reality such as Augmented Reflection Technology (ART) show promising potential as part of a rehabilitation program for motor impairments after a stroke, to improve arm function and assist in daily living (Laver, George, Thomas, Deutsch, & Crotty, 2011).

Despite the availability of many protocols for stroke rehabilitation and intervention, today only about 10% of stroke patients recover completely, while 25% will suffer from minor impairments, 40% will experience moderate to severe impairments that require special care, 10% will require care in a nursing home or long term care facility, and 15% will die shortly after (stroke.org, 2015).

An emerging possibility to improve the therapeutic outcomes of stroke rehabilitation is the use of technology such as ART. ART uses computer mediated visual feedback to provide an alternative to traditional therapeutic methods (Hoermann, Hale, Winser, & Regenbrecht, 2012). An ART system consists of two monitors connected to a single computer, with one monitor for the patient and one for the therapist. The patient's hand movements are captured by web camera(s), the captured video is processed and manipulated by software and the results are displayed on the patient screen. This approach allows for a variety of computer mediated therapeutic interventions. ART has been clinically evaluated as part of an upper limb stroke rehabilitation scheme and a specifically tailored protocol for the intervention was established (Hoermann et al., 2015).

This tailored protocol is based on a validated therapeutic intervention called mirror therapy (MT). During MT, a mirror is placed between limbs with the mirror facing the unimpaired side; patients can see a visual overlay of their unimpaired hand at their impaired side. The therapeutic effects of MT are speculated to be due to increased activation in brain areas (e.g. precuneus, posterior cingulate cortex) functionally connected to the stroke affected area in the motor cortex (Mehnert, Brunetti, Steinbrink, Niedeggen, & Dohle, 2013; Michielsen et al., 2011). MT was originally proposed as an intervention to manage phantom limb pain (Ramachandran, Rogers-Ramachandran, & Cobb, 1995). However, its efficacy as a therapeutic intervention for motor rehabilitation after stroke was soon after investigated (Altschuler et al., 1999) and was recently confirmed in a systematic review and meta-analysis (Thieme, Mehrholz, Pohl, Behrens, & Dohle, 2012).

In MT with ART, computer manipulated visualisations of the patient's hand(s) are shown on screen. The unimpaired hand is mirrored to the other side of the screen to give the patients the impression of actually using their impaired hand. Patients are verbally instructed by a therapist to carry out exercises (hand movements) from a predefined category depending on the stage of the therapy. The therapist has to be present to provide verbal instruction and feedback to the patients.

A systematic review to explore the requirements of autonomous training for adults was conducted by Jettkowski, Morkisch, & Dohle (2013). They found that many principles of motor rehabilitation such as intensive and active execution of exercises, relevance of exercises to daily activities, adequate selection of exercises and consideration of the context can be integrated into autonomous training. However, providing feedback during therapy was not achievable without the presence of a therapist. Nevertheless, the use of technology to provide feedback was suggested as a possible solution.

This research project extends the existing ART system with the functionality to: a) automatically generate instructions for the user to carry out therapeutic exercises as prescribed in the MT protocol for ART and b) to provide automatic feedback during the therapy session. The viability of the computer generated instructions to allow unsupervised execution of the therapeutic exercises was evaluated, as well as how automatic real-time feedback affected the exercise execution and user experience.

A user study was conducted with healthy participants. The study combined quantitative and qualitative measures to determine user performance and experience. Validated questionnaires were used alongside a semi-structured interview at the end of the experiment. This research contributes towards current stroke rehabilitation approaches by evaluating the effectiveness of automatic feedback in an autonomous computer mediated therapy scenario. This research will help with the refinement of how computer generated feedback can be used in therapeutic applications, and how the addition of feedback causes a change in user performance and experience. The possibility to provide an enhanced therapeutic experience could lead to higher levels of patient motivation and therefore positively contribute to the efficiency and effectiveness of therapy (Maclean & Pound, 2000). In addition, the findings on the viability of the computer generated instructions can inform the use and development of therapeutic systems for unsupervised autonomous use by patients either at home or in a clinical context.

2. SYSTEM

The system used consisted of three main components: (1) An off-the-shelf webcam with a HD 720p RGB image sensor (Creative Senz3D, Creative Technology Ltd), (2) tailor-made software to process the image data using OpenCV from the webcam and deliver to the application, and lastly (3) the application itself created using Unity3D which provides the environment in which users will interact with and see on screen. In addition, another screen was used by the experimenter to start and stop the application and configure the various settings.

The hardware of the system consisted of a monitor (Dell Widescreen Full-HD 22″ Monitor) mounted on a monitor arm attached to the desk. The arm allows for users to place their hands under the monitor. The webcam was mounted on a stand attached to the monitor arm and was pointed towards the area where users place their hands. The desktop was covered with a blue curtain placed behind the monitor and under the webcam, to be used as part of the background subtraction performed on the camera image data. A detailed description of how the ART system is used can be found in Hoermann et al. (2015).

2.1 Interaction Capture

To display only the hands of a user on screen, background subtraction was performed on each frame of the webcam stream. The colour image was converted from RGB colour space to HSV. Each pixel was checked to ensure that the hue was within a predetermined range which represented the colour blue. If the pixels were within this range, they were set to transparent. This left the pixels which represented the hands, which were set as opaque.

The reason for using the colour blue was because of the contrast it provides to the skin colour. The placement of the blue fabric in the interaction supports the subtraction of everything but the hands.

2.2 Instruction

The system provided instructions by displaying an image of the current exercise on the screen on the same side as the hand (Fig. 1). The pixels in that image that represented the hand were semi-transparent so that the user was still able see their own hand when they overlapped, and all other pixels were completely transparent.

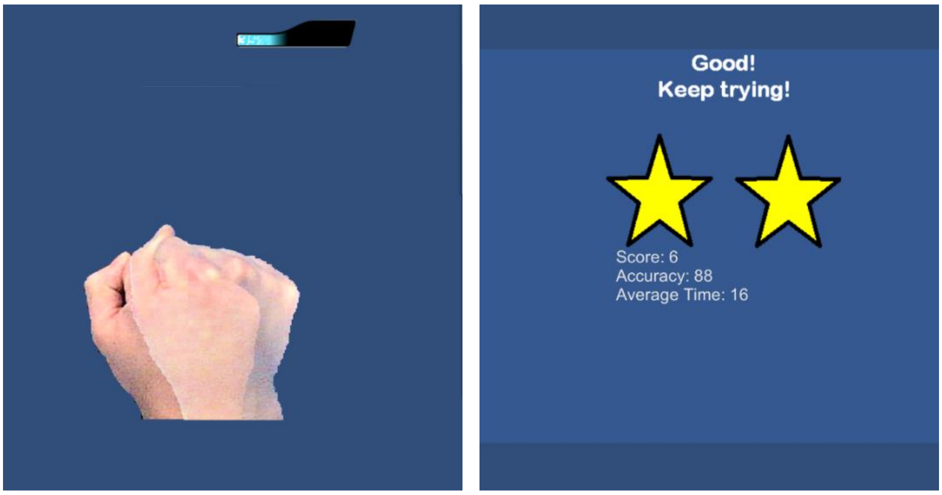

Figure 1. *The half-transparent image of the exercise and the actual hand of the user (left), post-phase feedback (right).*

If the user was able to complete an exercise, another exercise was randomly selected from a list of specific exercises without consecutive repetitions of the same exercise. When a new exercise was displayed, a short audio clip was played to inform the user.

2.3 Evaluation

The current exercise is displayed on screen for a user to follow, while another image of the same exercise is also used by the system for comparison with the images from the video-stream of the actual user's hand. This comparison image is exactly the same as the displayed image except that the transparent pixels are set to black. The system then performs a count of the non-black pixels of the image, which gives a quantitative value for how much space the exercise occupies. This value is referred to as the maximum accuracy for that exercise. When the system performs the background segmentation of the camera data, it also checks the pixels against the corresponding pixels of the comparison image. If this check finds that there are pixels in the camera data that are not empty and also pixels in the image that are not empty, it then assumes that a user has their hand in an area where the exercise is being displayed.

When pixels are found where expected then an accuracy score is incremented, and if non empty pixels are found in the camera data where there are empty pixels, the score is decremented. This approximates how well a user is matching the exercise. The current accuracy score is constantly updated, and then calculated to determine the percentage it is of the total. This percentage is used as the input for the real-time feedback bar (Figure 1, left, right upper corner).

The evaluation of an exercise is done in two steps: first the accuracy score must be above the pre-set threshold, and second the user must maintain this accuracy above the threshold for a pre-set time. If at any point the accuracy drops below the threshold, then the hold time timer is reset and will start once the threshold is reached again. The threshold and hold time are read in from an eXtensible Markup Language (XML) file at system start and can be changed to a custom value to meet required performance. Data is automatically saved into an XML file for each user. The threshold value used for the user study was 80% and the hold time 3 seconds. This means a user must maintain a hand shape at 80% or above similarity to the reference image for 3 consecutive seconds to progress to the next exercise.

2.4 Feedback

The feedback bar (Fig 1, left image, upper right corner) displays the accuracy score in real-time, and states the percentage currently achieved. When an exercise is completed, this accuracy score is saved into the user's XML file, along with the time taken to complete the exercise as well as the exercise ID.

When a phase is completed, the performance information is used to evaluate user performance. The current evaluation method is based on the average accuracy score, which will fit into one of three levels, each indicating an increasing level. The levels are calculated by: 100 minus threshold divided by three. The chosen feedback is then displayed on the screen, on the same side of the screen where the hand is displayed. There is a different feedback screen for each of the three levels, each displaying the number of stars to represent the feedback level achieved and a motivational message. Additionally, performance data from the phase is displayed, showing the score: number of completed exercises, average accuracy, and average completion time. The threshold value used in the experiment is 80, hence an average accuracy of 80 to 86.7 would result in one-star feedback, 86.7 to 93.3 in two stars and above 93.3 in three stars.

3. METHOD

3.1 Participants

Twenty-eight participants were recruited from the University of Otago and Dunedin area. The sample consisted of 20 males and 8 females working in a range of disciplines, between the ages of 21 and 62 years with an average age of 33.79 (*SD* = 12.96). All participants reported to have normal vision and no impairments that could affect their performance during the experiment. Twenty-four participants were right-handed, two left handed and two ambidextrous as measured with the Edinburgh Handedness Inventory (Oldfield, 1971). All participants provided written informed consent and received a chocolate bar as compensation for their time.

3.2 Measures

The experience questionnaire consisted of questions taken from a Mixed Reality Experience questionnaire (Regenbrecht, Botella, Banos, & Schubert, 2013), and was filled out six times, once after each phase was completed. The questions asked participants to rate the ease of performing the exercises, their performance, performance satisfaction, motivation, concentration, and enjoyment. The rating-scale ranged from 0 to 10.

After each condition, participants completed a satisfaction questionnaire, which was a subset (questions 1, 2, 3, 4, 6, 7, 10, 11, 16, and 17) of an IBM Usability Satisfaction Questionnaire (Lewis, 1995). This questionnaire comprised of ten questions on a rating-scale of 1 to 9, on how participants felt about the system while performing the task and the task itself.

Once both conditions had been completed, three different questionnaires were used. The first was a suitability questionnaire containing fourteen questions specifically related to virtual rehabilitation systems (Gil-Gomez, Manzano-Hernandez, Albiol-Perez, & Aula-Valero, 2013). The response-scale was increased from the original 5-point scale to a scale ranging from −5 to 5. The second questionnaire was a usability questionnaire to evaluate the perceived usability (Brooke, 1996). The final questionnaire contained four self-created questions asking participants to pick between each condition on a scale of −2 to 2 for their overall preference, ease of use, motivation, and concentration.

3.3 Design

The experiment used a within-subject design, with the 28 participants pre-randomised and counter-balanced for the feedback and non-feedback conditions, and for the hand used in the experiment. The hand used in the experiment was randomly predetermined and hand dominance was not taken into account but was recorded as part of the demographic questionnaire. The independent variable was "feedback" with levels (i) system will give feedback and (ii) no feedback is provided by the system. In both conditions the instructions were provided automatically by the system. The dependent variables were participant satisfaction, motivation, enjoyment, concentration, and perceived usability. The performance data collected was the exercise execution time, exercise accuracy, and score.

3.4 Procedure

Experiments were conducted in a controlled lab environment to reduce unnecessary distraction for the participants. Two conditions were evaluated: MT with automated instruction and feedback, and MT with automated instruction but without feedback.

Upon arrival, participants were greeted and given an information sheet detailing the experiment and what they should expect. After reading this, they were presented with a consent form to give their formal written consent. Participants were asked to complete a demographic questionnaire once they had consented to taking part in the experiment.

Before starting with the conditions, an initial setup step was required. This involved the experimenter verbally guiding the participant through the exercises and using the ART system to capture a photo of the participant's hand for each exercise. The 16 hand movements used were the same as used in a previous study (Hoermann et al., 2015) and were based on the Mirror Therapy Manual by Morkisch & Dohle (2015). During the experiment, the ART system would use these images to display the current exercise to the participant and perform a comparison of that image to the participant's hand movements. Some image processing was applied to the images to ensure they met the requirements expected of the system. The images were then loaded into the designated folders for the system to use.

Once the setup was complete, participants were asked to place their hands under the screen and instructed on what to expect from the system. Then, the first pre-selected condition with their pre-determined hand was initiated. Each condition comprised of three two-minute phases. The participant's task was to perform the hand exercise shown on screen and to try to complete as many exercises as they could within each of the two-minute phases. The instructions given to the participant were that they should move their hand to best match the displayed exercise and maintain their hand position in place. The system would then evaluate and progress the exercises automatically. Before starting their first condition, the participants were told that the instruction and evaluation would be the same for both conditions, but in one condition there would be feedback based on their performance. All exercises were carried out by showing a mirrored display of the hand on the other side of the screen.

After each two-minute phase, participants completed a user experience questionnaire. After completing the first condition (three two-minute phases), they filled out the satisfaction questionnaire. When both conditions had been completed, participants completed the suitability, usability, and final comparison questionnaires. After that, participants were thanked for their time and rewarded with a chocolate bar.

3.5 Statistical Analysis

Post-phase feedback data from the three phases with feedback was compared to the data from the three phases without feedback. A two-tailed paired-sample t-test was used to compare the performance of participants between the two conditions. A Related-Samples Wilcoxon Signed Rank Test was used to compare the data from the two satisfaction questionnaires completed after each condition. A One-Sample Wilcoxon Signed Rank Test on the medians of the scales with their neutral midpoints was used. Where indicated, values for negatively worded questions were inverted. Analyses for parametric tests were carried out with Microsoft Excel 2013, and non-parametric tests were conducted in SPSS 22.0.0.2. For all analyses, p-values below .05 were considered as statistically significant.

4. RESULTS & DISCUSSION

4.1 Suitability

The results of the suitability evaluation questionnaire (SEQ) were statistically significant ($p < .001$) with the averages of all questions above the neutral midpoint “0”, showing that overall, participants perceived the system as suitable (Fig. 2 left). The ratings of negatively phrased questions Q7–Q10 and Q12 were inverted.

The first seven questions of the SEQ measured enjoyment (Q1), sense of being in the system (Q2), feeling of success (Q3), control (Q4), virtual environment realism (Q5), system information clarity (Q6), and general discomfort (Q7). The high ratings obtained indicated that overall participants enjoyed their experience with the system. However, Q7 had a reasonably low value, indicating that overall participants did not experience a high level of comfort while using the system.

The results obtained for questions Q8–Q10, related to the issues frequently associated with virtual rehabilitation systems, show that participants on average experienced no serious adverse effects such as dizziness (Q8), eye discomfort (Q9) or confusion (Q10). Out of these three questions, Q10 which asked whether a participant felt confused or disorientated had the lowest average value. This was an expected result as many of the participants were initially confused by the mirroring of their hand.

Q11 asked participants whether they believed that the system would be useful for rehabilitation. Although participants may not have knowledge on the field of rehabilitation, this question could still indicate opinions on the suitability of the system. The results were uniformly high and suggested that participants believe the system would be helpful for rehabilitation.

Questions Q12 and Q13 were related to the perceived difficulty. Q12 was the difficulty of the task, which here had a value close to zero. Therefore, the difficulty of the tasks performed by the participants appeared to be neither too difficult nor too easy. As part of the task creation, we would not want to make the task too easy or too difficult. Ideally, the task should feel achievable, engaging, and challenging. Q13 evaluated the perceived difficulty related with the physical interface used in the system and was again positively rated; this was expected as our system only required a participant to move their hands.

Q14 was an open ended question that participants could use to report if there was anything during the experiment that made them feel uncomfortable. Eight participants (28.57%) indicated that they felt uncomfortable in some way when using the system. The written responses included participants feeling uncomfortable sitting so close to the screen, their unused hand feeling sore from holding it still, and specific exercises were causing some soreness.

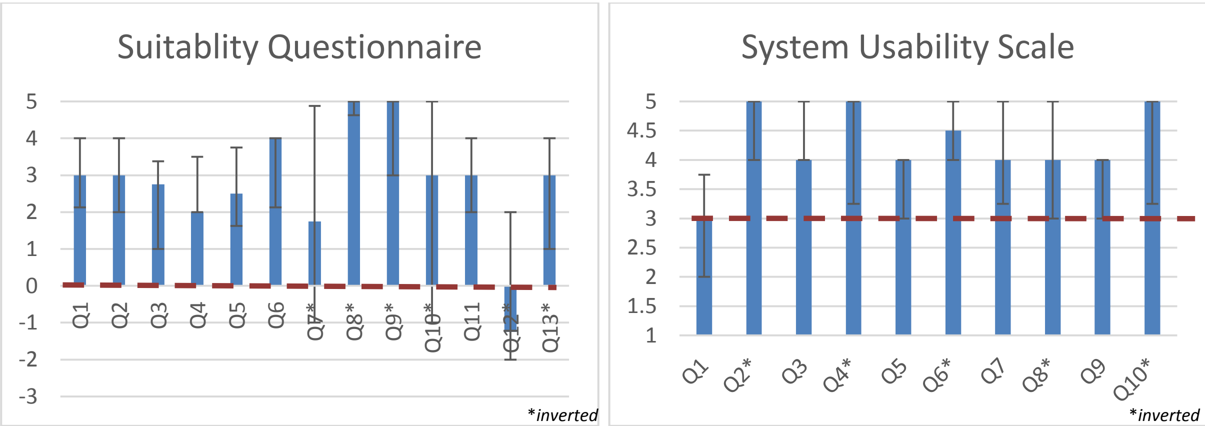

Figure 2. *Suitability Evaluation Questionnaire (left), System Usability Scale (right) (Median and IQR bars).*

4.2 Usability

The results of the usability questionnaire were significantly positive ($p < .001$) with a mean rating of 4, clearly above the neutral midpoint (Fig 2, right). Note that the ratings of negatively phrased questions (Q2, Q4, Q6, Q8 & Q10) were inverted. The SUS score, calculated using the method proposed by the author of the scale, was 75/100. This was above the pooled average of 68 calculated from more than 3,500 prior applications of the SUS and suggest that participants thought the system has good appropriateness for its purpose, although no strong clinical implications can be made as we conducted the study with healthy participants (Brooke, 2013).

Q1 asked how frequently the participant would like to use the system. As the participants were healthy, it was not likely that they would expect to use a rehabilitation system, thus values near the midpoint were not of concern. Participants uniformly rated the complexity of the system (Q2) positively, meaning that the majority of the participants found the system to not be unnecessarily complex. Similarly, participants indicated that the system was not cumbersome (Q8). The system's ease of use (Q3) was also highly rated. The need for a technical person to be able to use the system (Q4) was rated low (i.e. high inverted values), suggesting that overall, participants felt they would be able to use the system on their own. The integration of functions (Q5) was above midpoint, and the inconsistency of the system (Q6) was also positively rated. The learnability of the system was explored in questions Q7 and Q10. Regarding the learnability for other people (Q7), participants indicated that other people would learn to use the system very quickly. For personal learnability (Q10), participants reported similarly high values, suggesting they believed that they did not need to learn a lot before using the system. Participant confidence when using the system (Q9) was also above the neutral midpoint.

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4.3 Satisfaction (post-condition)

The satisfaction questionnaire was completed twice, once after the feedback condition and once after the non-feedback condition. The results (Fig. 3) for both conditions show that participants were very satisfied, with medians clearly above midpoint ($p < .001$). The differences between the two conditions (feedback: *Median*=7.25, *IQR*=1; no-feedback: *Median*=7, *IQR*=2) however did not reach significance ($p = .071$).

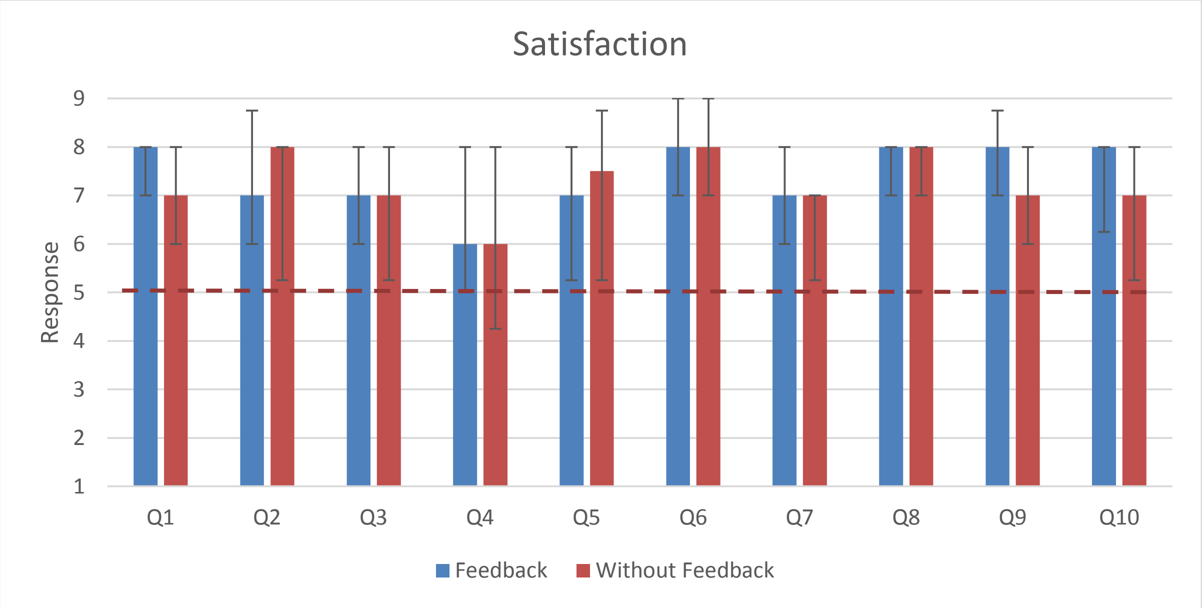

Figure 3. *Satisfaction (Median with IQR bars) and redline to highlight neutral midpoint.*

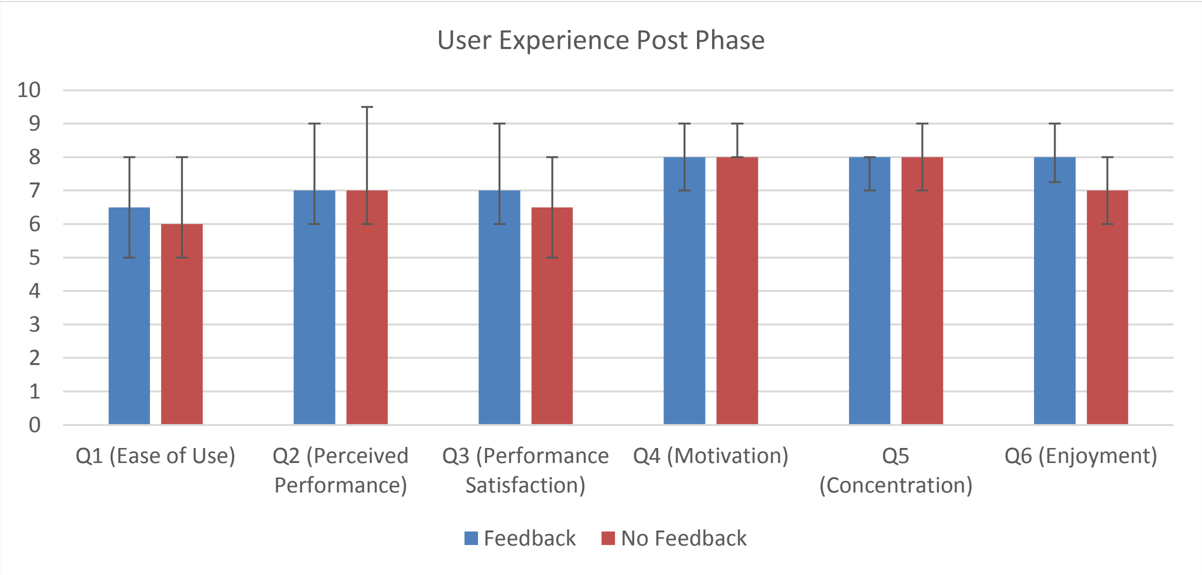

Figure 4. *Average user experience across three measurements for each condition (Median and IQR bars).*

4.4 Performance

Analyses of the performance data did not reveal any significant difference between the feedback and non-feedback conditions, across all three phase. The differences in the amount of performed exercises per phase (no-feedback: *M*=8.1, *SD*=4.69; feedback: *M*=8.11, *SD*=4.77) ($p = .38$), the accuracy of the execution (no-feedback: *M*=88.46, *SD*=3.83; feedback: *M*=88.02, *SD*=4.98) ($p = .35$) and the average time required per exercise (no-feedback: *M*=8.58, *SD*=8.12; feedback: *M*=8.50, *SD*=7.18) ($p = .10$) were not statistically significant.

All participants were able to complete at least one exercise in one of the three phases per session. At 11 instances (6.5%), 6 times in one of the three phases during the first session and 5 times in the second session, a participant finished a phase without successfully completing at least one exercise per phase.

4.5 User Experience (post phase)

Levels of user experience were measured after each phase, a total of 6 times, 3 times after phases with feedback and 3 times after phases without feedback. The difference of the overall median of the 6 questions' median was not statistically significant (p = .289) with differences for Q1 (p = .172), Q2 (p = .395), Q3 (p = .930), Q4 (p = .430), Q5 (p = .171) and Q6 (p = .172) all not significant.

4.6 Final Comparison

The final questionnaire asked participants to directly compare the two conditions on a five-point scale with the feedback condition on the left side of the scale ("−2") and the no-feedback condition on the right side ("+2"). Across all four questions, the data were significantly in favour of ART with feedback (*Median*=−1.5, *IQR*=2) (p = .002). The data for the individual question Q1 (general preference) indicated that participants preferred using the system with feedback (*Median*=−2, *IQR*=1.75) ($p < .001$). The results for Q3 (motivation) also showed that participants felt more motivated with feedback (*Median*=−2, *IQR*=2) (p = .002). The ease of use (Q2) was also perceived to be better in the feedback condition (*Median*=−2, *IQR*=2) (p = .001). Q4 (ability to concentrate) was also significant (*Median*=0, *IQR*=3), although not as highly as the other questions (p = .034).

5. CONCLUSION

In this study, we have shown that automated mirror therapy with the ART can be performed with healthy participants and that it is perceived as usable and suitable for rehabilitation by healthy non-clinical participants. We evaluated two versions of the system where we either provided feedback or did not, in addition to giving instructions for the exercises.

Although we could not find a statistical difference on the satisfaction and general user experience between the two conditions, the data indicates that enjoyment was higher in the condition with feedback. When participants had to directly compare the two conditions, strong and significant preferences for the feedback conditions were found.

As part of the suitability questionnaire and when queried informally after the experiment session, some participants reported that they experienced discomfort due to their seated position when using the system. This is already an identified area in which further refinement is required, and is not just specific to the version of the ART system presented here. The discomfort specific to this version of ART is the angle in which participants were required to place their hands to align with the on screen image. Some participants found that they had to place themselves at an unnatural position that was sometimes difficult to achieve or hold still for a prolonged time. Possible use with a patient population could be limited due to the identified problems with seating and hand positioning and improving this will be a focus for future development of the ART system.

The number of times a participant was not able to complete an exercise per phase was low, however it provides some room for improvement especially to ensure a smooth experience for a clinical population. For example, the system could switch to a new exercise or lower the required accuracy when a user is not able to accurately perform an exercise for an extended time. With this study, further progress towards an automated system for the provision of mirror therapy was achieved and preparations for clinical evaluations using this system with stroke patients can now be initiated.

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