Computerized Mirror Therapy with Augmented Reflection Technology for Stroke Rehabilitation

A Feasibility Study in a Rehabilitation Center

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***Abstract*—New rehabilitation strategies for post-stroke upper limb rehabilitation employing visual stimulation show promising results. Cost-efficient ways to provide these techniques are still a challenge. Virtual and Augmented Reality Technologies could be suitable for this endeavor. Recent technological advances often are not translated into therapeutic practice and improved outcomes for patients because of a lack of research on their practical usage, coupled with the inexistence of appropriate guidelines and protocols.**

Here we present a novel and affordable augmented reality system that was developed and evaluated in combination with a validated mirror therapy protocol for upper limb rehabilitation after stroke. We evaluated the components of the therapeutic intervention from both the patients' and the therapists' points of view. In particular, we provide evidence that the combination and application of the *Berlin Protocol for Mirror Therapy* together with Augmented Reflection Technology is feasible for clinical use. This paves the way to a broader use of technically-supported mirror therapy with the possibility of higher therapy frequencies and enhanced recovery for patients.

Keywords—Stroke, Augmented Reality, Virtual Reality, Usability, User Experience, Upper Limb, Visual Illusion

I. INTRODUCTION

Stroke is a leading cause of adult disability and causes significant negative socio-economic impacts. Patients with stroke are often affected with motor impairments of the upper limb, which can prevail long after discharge from the hospital. Only a small number of patients regain full functionality of their limb and many are dissatisfied with their regain of motor function [1], [2].

Despite recent improvements in the acute and post-acute phase treatments, stroke is still predicted to be a leading cause of disability worldwide in 2030 [3]. The costs related to stroke are estimated to be more than 4% of the entire health-care costs in western countries [4].

Engaging patients in therapeutic exercises early after the onset of a stroke has been shown to improve functional outcomes. The challenge therefore is to provide as much therapy as possible especially for the arm and upper limb [5]. To support this, various technological approaches have been proposed. Virtual reality (VR) technology is one such approach, and early evidence has indicated its usefulness for stroke rehabilitation to improve motor function [6]. Furthermore, the use of VR could result in higher therapeutic intensity, which further benefits patients [7].

Generally there are two main categories of VR systems. The first are robotic systems where VR is merely used as an add-on to the robotic device that supports the execution of movements [8]. The second form is when VR itself provides the meaningful therapeutic intervention. This could be either in the form of an (a) ecological valid simulation of everyday task(s) with the possibility to dynamically adapt the difficulty of the task based on the patient's performance [9]–[11], or (b) by providing the visual output itself necessary to simulate neural activity and possibly trigger recovery processes in the brain to overcome impairments after stroke [12], [13]. A detailed review on the various therapeutic possibilities with VR has been carried out by Cameirao et al. [14].

Of particular interest for the research in this paper is the second type of VR system where the essential part of the therapy is through visual stimulation and interaction. Various approaches to visualize movement have been presented with (a) the use of virtual avatars of users or their extremities [15] and (b) the use of abstract feedback, mostly in the form of schematic computer graphics, as the most dominant ones. Additionally, several systems also use augmented reality (AR) technology where they integrate video captured images of the user or their extremities in the virtual world [16]. A more detailed review on the various types of visualization in VR is provided by Ferreira dos Santos et al. [17], whereas an overview of the various possibilities to provide feedback in Virtual Rehabilitation systems and the resulting implications can be found in Schüler et al. [18].

Although there is no clear evidence on which form of visual stimulation and representation of limbs is most efficacious in stimulating recovery, benefits of limb visualizations that closer resemble reality have been reported. Abstract virtual reality representation might make it harder for participants to identify with the representation and to realize that the movement of their actual limbs is mapped on the virtual limb. This was reported by Dukes et al. who found that their patients had problems in realizing that the movement of their arms, tracked with a MS Kinect sensor, were mapped to virtual arms [19].

In addition, the rubber hand illusion [20], where participants take ownership of a rubber hand and perceive it as their own after a period of sensory stimulation, was shown to only elicit insignificant effects when the hand was replaced with a virtual arrow instead of a anthropomorphic representation in an immersive VR setup [21]. The effects were also negligible with unmediated direct vision, when the rubber hand was replaced by a wooden stick [22].

An important discovery related to the capability of the brain to integrate the ownership of an alien limb occurred through Mirror Therapy. In Mirror Therapy, the recovery from unilateral motor impairments after stroke is stimulated by the observation of the mirrored unimpaired hand beside the impaired hand. This creates an illusion for the patient that the impaired hand is moving again at its full range by "fooling" the brain. In this way the observation of the mirrored hand stimulates neuromodulation and leads to the improvements of various impairments of a central origin [23], [24]. Evidence confirming the therapeutic efficacy of Mirror Therapy for the rehabilitation of motor impairments has been shown in a Cochrane review [25]. This form of therapy seems to be particular promising for severe arm pareses [26].

Based on the principle of Mirror Therapy, for the last five years a technology known as Augmented Reflection Technology (ART) was conceptualized and developed [27]–[29]. ART includes all the capabilities of traditional Mirror Therapy, but allows a wider range of computer-mediated visual illusions and exercise possibilities [30]. In particular, it was shown that the 'fooling' capability of the ART outperforms the Mirror Box by up to three times [28]. Furthermore, ART also allows the users to develop a strong sense of ownership of the displayed limb [31].

Additional evidence pointing towards the therapeutic potential of the ART approach can be drawn from two other studies. A brain imaging study showed that computer mediated mirror visual illusions, such as used in the ART, elicit similar brain activation as in optical mirroring (e.g. the traditional Mirror Box) [32], [33]. An ART system was also used in a study conducted in a physiotherapeutic setting with patients suffering from motor impairments after stroke and found to be feasible for clinical use [34].

The optimization of the intervention protocol for the use of Mirror Visual Illusion is still a challenge. Several protocols exist for use in the management and therapy of Complex Regional Pain Syndrome, such as the "St Gallen protocol" [35], the "Bath protocol" [36] and "Graded Motor Imagery" [37], [38]. The last protocol, despite being positively evaluated in two RCTs, showed only negligible efficacy in clinical practice [39]. The approaches for the intervention post-stroke are less formal, with many studies applying different intervention routines. To the best knowledge of the authors, only two formalized protocols exist: a protocol for autonomous use without the presence of a therapist [40], and a protocol for

the use with a therapist [41], also known as the "Bonn protocol".

This "Bonn protocol" was successfully applied in a randomized controlled trial, where it demonstrated its clinical efficacy [26]. Later, that protocol was further improved based on the behavioral data gathered during clinical application [42] and the results of brain imaging studies [33], [43]–[46], leading to the current Berlin Mirror Therapy Protocol (BeST, which is its acronym in German) [47]. Furthermore, a standardized self-training Mirror Therapy (BeSTEP), which stroke patients can use at home without the permanent presence of a clinician, was developed [48].

Here we present a study on the combination of the BeST protocol with ART as a therapeutic intervention for patients in their firsts months post stroke. A new version of the ART system that is more transportable and cheaper in its assembly was tested together with a first tailored subset of the BeST protocol, with stroke patients in their early stage of rehabilitation, in a rehabilitation clinic. In particular the combination of the Berlin Mirror Therapy protocol together with the ART was evaluated. The experiences of patients with different degrees of impairments as well as three therapists varying in their level of experiences with the BeST protocol and the ART system were gathered. Impairment levels of patients were assessed pre and post intervention and their experience during each therapy session was rated by the therapists.

II. METHODS

The background of the intervention is the clinical application of mirror visual illusions with the ART system based on the BeST protocol. Instead of using a mirror placed perpendicular in the midline in front of the patients and observing the hand from the side, here the hand(s) are placed naturally on a table in front of the patient and covered by a screen on which only the mirrored unimpaired hand is shown (see Fig 1). For example, a patient with a right side impairment would observe the left side mirrored to the right side of the screen, aiming to eliciting the impression that the left hand moving on the screen is the right hand.

The experience of the therapists as well as that of the patients with the system and the protocol was captured using various questionnaires for each intervention session as well as at the end, for the overall evaluation.

A. Subjects

Five patients in their first three months after stroke were recruited from the inpatients of a rehabilitation center. They had different levels of impairments but none was affected by pain in their upper limb. Table I lists the details about the patients, their type of stroke and impairments. All participants gave written informed consent to participate in the study, which was approved by the local ethics commission.

TABLE I. PATIENT CHARACTERISTICS

Code	Age	Sex	EHI[a]	Stroke Aetiology	Time since stroke	MRS[b]	MAS wrist & fingers[c]	FGM UL[d]	Strength Grip /Pinch	Neglect[e]
P1	64y	M	R	right MCA ischemic (cerebral microangiopathy)	1m	4	0/0	11	L(0/1) R(28/10)	No
P2	65y	M	R	Stroke Right MCA, genesis cardioembolic	1m	4	0/0	0	L(0/0) R(30/8)	1: Visual
P3	47y	F	R	intracerebral hemorrhage loco typico right, genesis hypertensive; Stroke MCA left, genesis embolic	2m	4	4/4	0	L(0/0) R(15/6)	1: Tactile
P4	70y	M	R	Stroke MCA left, genesis arterial	2m	4	1+/1	15	L(26/8) R(0/3)	1: Tactile
P5	64y	M	R	frontal subcortical paracentral hemorrhage left, cerebral edema	3m	4	4/2	0	L(32/9) R(0/2)	No

[a]Edinburgh Handedness Inventory, [b]Modified Ranking Scale, [c]Modified Ashworth Scale, [d]Subset Fugl-Meyer Upper Limb Assessment, [e]NIH-Stroke Scale – Subtest 11;

In addition to the therapeutic intervention of this study, patients received their regular Motor Rehabilitation (MR, e.g. physiotherapy and occupational therapy) and non-Motor Rehabilitation (nonMR, e.g. speech therapy, brain training or consultations with specialists). Sessions for these activities were mostly half an hour long and took place during the working days in the two weeks of the study: P1 (27× MR & 11× nonMR), P2 (12× MR, 9× nonMR), P3 (26× MR & 13× nonMR), P4 (28× MR and 12× nonMR) and P5 (28× MR and 19× nonMR).

B. ART System

1) Hardware

We used a 22 inch screen (Dell UltraSharp 2208WFP, 1650×1080 @ 60Hz) mounted in front of the user with a monitor arm (Dell MSA14). This allowed the users to put their hands underneath while blocking their direct line of sight. A Creative Senz3D webcam (resolution: 1280×720 at 30fps, 72º field of view) was mounted directly behind the screen positioned perpendicularly to the users' hands. The camera was attached to a standard camera stand fixed with a universal mount on the table (both Manfrotto). The computer was a Dell Optiplex 9020 with an Intel Core i5 4670 CPU (Quad Core, 3.4GHz with a HD4600 GPU), 8 GB RAM. A blue cloth covered all the areas visible to the camera.

2) Software

The software was based on Unity3D (v4.5.3) as the 3D-engine, on Windows 7 Enterprise 64bit SP1. For the processing of the camera-image, a customized plugin was developed. It used Intel Perceptual SDK (v1.8.13842) to interface with the Senz3D webcam and OpenCV (v2.4.9) for further image manipulations. The image captured by the webcam was cropped and split into two images sized 640×480 for the left and the right hand respectively. The system

performed with about 19 frames per second, with a small but noticeable end-to-end latency.

Fig. 1. Augmented Reflection Technology System showing the mirror functionality for a person with an impairment on the right side: the left hand is mirrored to the right side

C. Intervention Protocol

The intervention exercises were based on the updated Berlin Mirror Therapy Protocol.

The difference was that instead of progressing from one movement per two days, here patients had to change movements every day. This was in order to cover all three basic movements that the protocol included: (1) showing the numbers one till five with the fingers, (2) thumb oppositions with the other four fingers, and (3) various grips (e.g. lumbrical grip, fist, fingers extended etc.). In addition therapists were, as in the original protocol, free to increase the difficulty of the exercise by increasing the frequency or by adding instructions for additional movement modifications: for example, for the basic movement of showing the number five with the finger, a further instruction to bring the forearm at a different level of pronation/supination could be added.

D. Procedure

All patients were seen 5 times, three times for the intervention and twice for the assessment. Assessments were performed before the first and after the last intervention with one week in between for the three intervention sessions. The therapist protocolled each intervention session on the standard form for mirror therapy including details on the movement exercise, times of exercise and rest, and the observed state of the patient during the execution of the exercises.

In addition, a form was provided where therapists could report any adverse events during the session. Patients were instructed to place their hands under the screen and observe the mirrored movement of their unaffected hand.

E. Assessment

The patient's impairments were assessed before the first and after the last intervention using the following procedure:

1) Patients estimated their current pain in the affected arm and hand on a scale from 0 to 10, where 0 was the rating for "no pain" and 10 for the "strongest conceivable pain".

2) The general level of the patient's impairment was rated by the therapist using the Modified Ranking Scale [49].

3) Spasticity in the hand and fingers were assessed with the Modified Ashworth Scale [50]

4) Extinction and Inattention (formerly Neglect) were assessed as described in the 11th item of the Stroke Scale of the National Institutes of Health (www.nihstrokescale.org).

5) UL Motor Impairment was measured with the Fugl-Meyer Assessment [51]. Only the parts for wrist and hand were used, allowing a maximum total score of 24 (10 for wrist and 14 for hand). This procedure was based on the instructions provided by Platz et al. [52]. Patients unable to transfer themselves to a chair were assessed in their wheelchair.

6) Handedness was assessed with the Edinburgh Inventory [53].

7) Grip strength was assessed with the Southampton protocol using a mechanical dynamometer [54].

8) Pinch strength was assessed between thumb and index (PIP joint) using a pinch-gauge and the same procedure as for the grip strength.

F. Questionnaires

Three questionnaires were used in the study: one for each session filled in by the therapist, one for the therapists who had to rate the system and the overall intervention session, and one for the patients. The latter two questionnaires were filled in at the end of the intervention sequence whereas the session questionnaire was filled in immediately after each session. All questionnaires were in German, which was the primary language spoken on the premises. The questionnaires for the therapist were filled in by the therapist directly whereas the patient's questionnaire was filled in by one of the researchers based on the verbal answers given by the patient.

1) Therapy Session Questionnaire: This was about the intervention itself and related to the patient's experience, their engagement with the exercises, concentration, effort, attitude, aptitude, motivation and possible problems during the session.

2) Post Interventions Therapist Questionnaire: With this questionnaire, the experience and judgement of the therapists about the system and its use for the intervention was assessesd.

The first part of this questionnaire was based on the meCUE questionnaire, which assesses User Experience (UX) in four different modules: product perceptions, user emotions, consequences of use, and overall evaluation [55]. The original

questionnaire was slightly changed by the authors. Items of the "commitment" factor of the non-instrumental product perception module were excluded since the authors considered them to be inappropriate in a clinical context. In all items the word "product" was substituted with "therapy system".

The second part was about the specific hardware components and their arrangements e.g. the placement of the screen and seating position of the patients. In the third part, the therapists were asked about their judgement on the patients' improvements and if and how they would suggest the further use of the system. Spaces to include extra comments and to list possible problems were also provided.

3) Post Interventions Patient Questionnaire: In this questionnaire, the overall patient experience across the series of sessions was evaluated. Questions relating to their ability and motivation to execute the exercises and participate in the intervention were queried. In addition, their attitude towards the therapeutic intervention with the system was also evaluated. Furthermore, an adaptation of the meCUE based questionnaire similar as for the therapist, was used, again, the word "product" was substituted with "therapy". This questionnaire also contained questions regarding the possible further use of the system and spaces for extra comments.

III. Results & Discussion

A. Motor Function & Perception of Improvement

Of the five patients, three (P1, P4 and P5) had some improvements, especially P1 and P4, who improved considerably in their Fugl-Meyer Hand scores, whereas P5 only had a small improvement. Noticeably, the same three patients had also a slight increase in the spasticity of their fingers, whereas the spasticity in the wrist did not change for any of these patients. No adverse event was reported.

TABLE II: POST INTERVENTION ASSESSMENT AND SUBJECTIVE EXPERIENCE

Code	Side of Impairment	MRS[a]	FGM UL[b] change	Strength Grip / Pinch change	MAS[c] Wrist / Fingers change	Patient noticed improvements
P1	L	4	**+8**	L(0/+1.5) R(0/-0.5)	0/**+1**	**Yes**
P2	L	4	0	L(0/0) R(2/+0.5)	0/0	No
P3	L	4	0	L(0/0) R(0/-0.5)	0/0	No
P4	R	4	**+4**	L(+6/0) R(+4/0)	0/**+1**	No
P5	R	4	**+1**	L(0/0) R(0/+1.5)	0/**+1**	**Yes**

[a]Modified Ranking Scale, [b]Subset Fugl-Meyer Upper Limb Assessment, [c]Modified Ashworth Scale;

B. Intervention Protocol

On average, patients had 10.57 minutes of active therapy with the system per session, ranging from a minimum of 6 minutes to a maximum of 16. The breaks where patients were sitting at the system but did not practice (screen off) were around 6 minutes on average. No increase of active therapy time or decrease of break time was observed from the first to the last session.

All patients were able to perform the required exercises in each session. In session one, where patients were instructed to show the numbers from one to five, all patients were able to show the appropriate number with their hand. In addition for two patients (P3 & P5), the "b" modification (change between neutral, pronated and supinated forearm) was also selected. In session 2, in which patients had to touch the tips of the fingers with their thumb, again all patients were able to execute this basic movement and four patients (P1, P3, P4 & P5) were additionally given the modification to increase the challenge. In the third and last session, requiring patients to show five different grips with their hand, again all patients were able to perform the basic movement and they were also all successfully able to perform the modification.

The therapists also reported in their reporting sheet that the patients concentrated their attention in observing the mirror image of their hand with an average close to 1 out of 4 for all but P2 who had an average score of 2.4 out of 4, where 1 was the highest rating possible. The vigilance of patients was also rated high with an average rating of 1.3, and no patient was above 1.6 on average out of 3.

The level of difficulty of the exercises for the patients was never rated as too challenging and was on average at 1.7, on a 4 point scale ranging from 0 to 3, with the ratings for P3 close to "1" (i.e. normal) and the ratings for the other four patients were closer to "2" (i.e. challenged).

C. Therapist Experience & Feedback

Therapists had to rate the system from their point of view as therapists using the system, as well as for the patients.

Therapists rated the components of the ART system directly used by them, uniformly positive on a scale from "−5" to "5": Table and Seating position (Mean: 4.2), Screen with User Interface (Mean: 4.2), Handling of the User Interface (Mean: 4.2), and Instruction Manual (Mean: 3.5). Ratings related to the therapeutic intervention were also positive: Virtual Reality Therapy Components (Mean: 2.7), Exercises (Mean: 3), Duration (Mean: 3.5), and possibility to engage with patients (Mean: 3.7). Much lower were the ratings for the seating of the patients (Mean: 0.5) and the placement of screen for the patients was negatively rated (Mean: −2.5) with all three therapists giving uniformly negative ratings.

In the comments, this negative rating was clarified, suggesting that for some movements there was a lack of space on the display which resulted in situations where the hands of the patients where outside the field of view. One therapist also suggested decreasing the delay with which the movement was displayed on the screen. The therapists did not perceive that the motor functions of the patients improved in general.

The meCUE questionnaire results (on a 7-point-Likert scale) showed that the therapists had a positive product

perception (average ratings of the meCUE factors "effectiveness": 6.4, "efficiency": 6.1, "aesthetic": 5, and "status": 5.7). Questions on positive and negative emotions towards the product can be differentiated between the two dimensions - arousal and valence in the meCue questionnaire. Therapists in the study stated rather low positive emotions towards the therapy system for high arousal items (HP: 3.5) and low arousal items (LP: 3.2) as well as for high and low arousal negative emotions (HN: 1.3, LN: 1.5), suggesting that the therapy is rather neutral to the therapists. Furthermore, therapists stated a moderate to high "intention to use" (average 5) and "product loyalty" (average 4.2). The overall judgement assessed with one question at the end was clearly positive, with two therapists rating it 3 and one rating it 3.5 on a scale from −5 to 5.

The therapists also stated that they would recommend the system to other therapists. They were however not of a uniform opinion whether the system could be used by a patient autonomously with ratings ranging from "probably not" to "definitively yes". The consideration for patients to use the system at home however was clearer towards the negative side with two therapists rating it as "probably no".

D. Patient Experience & Feedback

Patients reported, on a scale from 1 to 6, to have:

a) had a clear understanding of the instructions (Mean: 6)

b) were almost always able to carry out the movements in adequate form (Mean: 5.2)

c) actively participated at the sessions (Mean: 5.6)

d) made an effort to successfully execute the activities (Mean: 5.6)

e) had a positive attitude towards the therapy (Mean: 6)

f) understood the necessity of the therapy (Mean: 6)

g) understood the benefit of the therapy (Mean: 5.2)

h) been motivated to carry out the activities (Mean: 6)

These results aligned very well with the ratings provided by the therapists on the patients' performance after each session. Patients themselves reported that they:

a) had a clear understanding of the instructions (Mean: 5.7)

b) were almost always able to carry out the movements in adequate form (Mean: 5.7)

c) actively participated at the sessions (Mean: 5.7)

d) made an effort to successfully execute the activities (Mean: 2.9)

e) had a positive attitude towards the therapy (Mean: 5)

f) understood the necessity of the therapy (Mean: 5.1)

g) understood the benefit of the therapy (Mean: 5.1)

h) been motivated to carry out the activities (Mean: 5.5)

The only exception where the patients' rating deviated from the therapists was on d) rating the effort of the exercises for the patients. This could be due to the ambiguous interpretation of the question by therapists who might have rated the actual exertion of the patients to carry out the exercises.

Moreover, the product perception rated with the meCUE was on average very high (average meCUE factors "effectiveness": 6.3, "efficiency": 6.3 and "aesthetics": 5.7 on a 7-point-Likert scale). Only the "status" factor of non-instrumental product perception was rated rather low (Mean: 3.0).

Within the meCue questions on user emotions towards the therapy high arousal items with positive valence (HP: 5.6) were rated on average higher than low arousal items with positive valence (LP: 3.7). On the other side low arousal items with negative valence (LN: 2.3) were rated higher than high arousal items with negative valence (HN: 1.5). This is not surprising since high arousal is a desirable condition in a therapy context. Therefore, the labels "positive" and "negative" emotions are not fully applicable in this clinical context. The overall ratings of the patients indicate that the therapy was considered to be positively activating and to a smaller extent exhausting.

All patients stated they would do the therapy again in the future (average meCUE factor "intention to use": 5.6). However, the loyalty was rated lower (average meCUE factor "product loyalty": 4.6). This was to be expected since in a clinical context different therapies are not competitive products. The overall ratings were very positive with two patients rating the intervention a "5" on a scale from "−5" to "5", one patient rating it a "4" and two rating it a "3".

Of the three patients who had a small improvement in their motor abilities, two actually also perceived themselves to have improved.

Apart from positive comments, one patient voiced an improvement suggestion of increasing the size of the screen that displays the hand(s). In general, patients also suggested that this system should be used early in stroke rehabilitation.

In the part of the questionnaire on the usage of the therapy, the following was found:

a) All patients would suggest the therapy to other patients,

b) 4 out of the 5 patients cannot imagine conducting the therapy without the (permanent) presence of a therapist,

c) but most could imagine using the system at home (4 out of 5 patients).

The general feedback and comments were very positive with one patient calling it a sensational event that in some sessions he could feel a slight tickle in his affected hand, whereas another stated that if it would be possible he would continue with this therapy the whole day.

IV. CONCLUSION

In this study we have successfully demonstrated a novel combination of a therapeutic system with an established intervention protocol. Therapists were able to use the protocol and device, and patients were able to execute the exercises, concentrate and observe the movement. Patients were

positively challenged with the difficulty of the exercises. Minor improvements could be considered in the hardware settings especially to increase the space for interaction behind the screen and the display area for the hands on the screen.

This feasibility study opens the way to a broader use of technically-supported mirror therapy with the ultimate goal of applying higher therapy frequencies in order to further support the recovery of severely affected patients.

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